The best porous asphalt pavement in Sweden so far

Ulf SANDBERG[1]; Piotr MIODUSZEWSKI[2]

[1] Swedish National Road and Transport Research Institute (VTI), Sweden

[2] Technical University of Gdańsk (TUG), Poland

ABSTRACT

In 2010 a double-layer porous asphalt concrete (DPAC) pavement was constructed in various versions on the E4 motorway through the Swedish city Huskvarna. As a result of a court decision the Swedish Transport Administration had to reduce noise emission by applying a low noise road surface that would reduce A-weighted noise levels by 5 dB, as an average. Earlier experience in Sweden indicated that it was possible to obtain a high initial reduction but due to the widespread use of studded tyres in winter, clogging and ravelling created a loss of around 2 dB per year, with an acoustical lifetime of only 3 years.

However, the improved pavement in Huskvarna has exceeded lifetime and durability expectations by at least 100 %. The first three years noise reduction fell from the initial 7-8 dB by about 1 dB, compared to an SMA 16 pavement, and now in its 4th year the main pavement still performs well.

This paper presents results of noise measurements over a 4-year period on various versions of the DPAC and single-layer porous asphalt which were tried at the site. This includes the effects of grinding, cleaning, and rejuvenation. Measurements were made by TUG using the CPX method and two reference tyres.

Keywords: Tyre/road noise, Low noise road surface, Noise reduction, Quiet pavement
I-INCE Classification of Subjects Number(s): 11.7.1

1. INTRODUCTION

Although Sweden is one of the largest countries in Europe, having a relatively small population (10 million), and with a long tradition of sensible land use planning, in many urban and suburban areas road traffic noise exposure is too high and needs substantial reduction. As a complement to the most common noise-reducing methods; i.e., exchange to noise-reducing triple- or quadruple-glass windows and building of noise barriers, the use of low noise road surfaces (LNRS) has for a long time been a desirable measure. However, until now, all attempts to use an LNRS have resulted in disappointment. The reason is that the climate in Northern Europe makes the use of studded tyres in winter time very popular and is even considered a need in order to provide good winter road friction. These studded tyres create substantially more road wear than tyres without studs. The dirt produced by this tends to clog the pores in porous asphalt pavements in addition to create a lot of rutting. Maybe even worse is that the studs need extremely strong and large aggregates (stones) in the pavement in order to avoid ravelling (loosening from the pavement) and splitting by the impact of the studs.

In exceptional cases traffic noise complaints are so intense, at the same time as the road authority considers noise reduction as unreasonably expensive or difficult, so that the disagreement has to be brought into a court for a decision. This happened recently with respect to the noise exposure from the motorway E4 located between Lake Vättern and a residential area in the city of Huskvarna (near to the bigger city Jönköping). This residential area has a scenic view over the lake; see Figure 1, and building tall noise barriers along the motorway would restrict this view, which is unacceptable to most of the residents. Therefore, the Land and Environment Court of Appeal in 2008 decided that the Swedish Transport Administration (STA) has to reduce the noise along the mentioned motorway forcing the STA to use a combination of lowered speed limit (from 110 to 90 km/h) and application of a low noise road surface. The road surface shall reduce the noise by at least 5 dB (A-weighted overall level).

Following the Court decision, the STA ordered the road contractor Svevia to repave the motorway with a low noise road surface (double-layer porous asphalt) providing at least 5 dB of noise reduction.

[1] ulf.sandberg@vti.se

Figure 1 – The motorway E4 between Lake Vättern and a residential area in Huskvarna, Sweden.

2. OBJECTIVE

The objective of this paper is to present results of measurements over a 4-year period of acoustic properties of the double-layer porous asphalt pavement laid on motorway E4 through the city of Huskvarna, Sweden. This pavement has aimed to reduce noise exposure to the residents along the motorway by at least 5 dB (A-weighted) following a Court decision requiring noise abatement along this part of the motorway, which forced the STA to use a low noise road surface.

3. PREVIOUS EXPERIENCE OF LOW NOISE ROAD SURFACES IN SWEDEN

3.1 Single-layer porous asphalt before 2000 in new conditions

The first author has published a number of measurements of tyre/road noise reduction by low noise road surfaces in Sweden since 1978, and considerable noise reductions, measured with early versions of both the CPX and SPB methods, were reported several times (up to 8 dB in 1984); see for example [1][2]. However, those measurements were made on single-layer porous asphalt pavements in new condition and compared to conventional dense asphalt concrete (DAC) pavements after some years of traffic exposure, and also with tyres and/or vehicles used more than 30 years ago. These porous pavements were consistently losing their very good acoustic performance very rapidly, and had an unacceptable durability, due to a combination of insufficient technology and studded tyre wear. Therefore, the decrease in noise reduction with time was rarely or never measured.

3.2 The SILVIA project 2002-2005 and the first trial with double-layer porous asphalt

Double-layer porous asphalt (DPAC) had already been tried in a few other European countries, most successfully in the Netherlands, but in the European project SILVIA in 2002-2005 a double-layer porous asphalt was tried the first time in a North European climate, at the same time as a single-layer porous asphalt and a thin asphalt layer. The DPAC pavement, constructed by Skanska on motorway E18 west of Stockholm (2x2 lanes with traffic 20 000 AADT), had a max. aggregate size of 11 mm in the top layer. Thanks to a new interest by the Swedish Road Administration, for the first time, it was possible to follow-up the noise measurements over a time period of 5 years. The results of CPX measurements 2003-2008 by TUG on behalf of VTI, for a test speed of 80 km/h, are shown in Figure 2. Noise reduction is calculated with the average over the time period for the two SMA 16 pavements as a reference. It appears that the noise level is reduced in a linear fashion with time; losing approx. 1 dB per year. It shall be noted that at the age of 5 years, a part of the DPAC had its top layer exchanged to a new one. This brought the noise reduction back to the initial 6 dB (not shown in the figure).

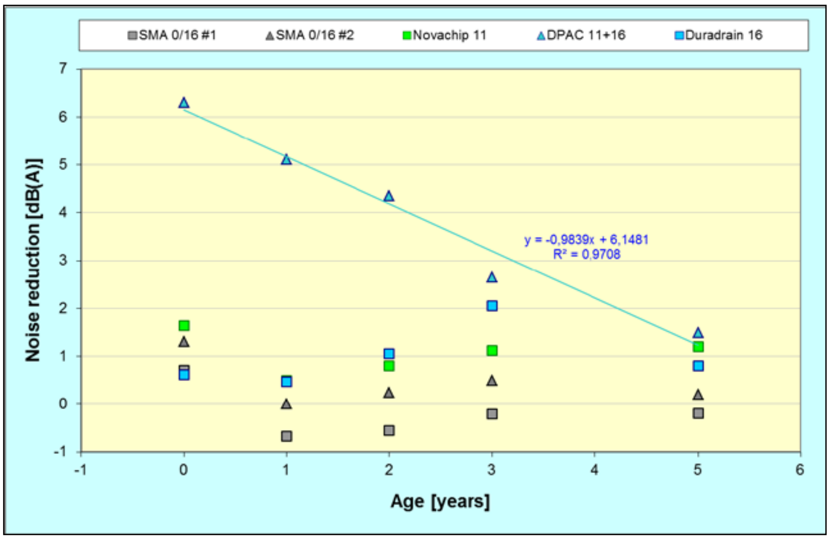

Figure 2 ─ Noise reduction measured with the CPX method at 80 km/h from 2003 to 2008 on test pavements on road E18 west of Stockholm. The regression line is for the double-layer porous asphalt concrete (DPAC). Duradrain 16 was a single-layer asphalt concrete and Novachip 11 was a thin asphalt layer.

3.3 The double-layer porous asphalt on E4 south-west of Stockholm, used from 2005

In 2005, Skanska AB was commissioned to lay a DPAC on E4 in Botkyrka/Hallunda, a south-western suburb of Stockholm, due to unacceptable traffic noise exposure in the residential areas along this part of the motorway. The aim was to achieve a 6 dB noise reduction over a 6 year period. They used the concept tried on E18, probably with minor improvements. The type is named TA 9/11. This road, with a posted speed of 90 km/h, and most of which has three lanes per direction, has one of the highest traffic volumes in Sweden (approx. AADT of 75 000).

Measurements with the CPX method at 80 km/h were made by TUG on the behalf of VTI over a four year time period (2005-2009) and the results are shown in Figure 3, which also shows a number of other measurements. The larger symbols are measurements made by a consultant company as 24-hour A-weighted Leq:s at the roadside while the smaller symbols are CPX measurements. It appeared that a very impressive noise reduction of 8-9 dB was achieved initially.

At the age of three years, the pavement had lost most of its noise reduction properties, due to raveling and clogging, and the top layer was then replaced by a new one (blue symbols in the figure). This resulted in a noise reduction of 6 dB. After this, the top layer has been replaced periodically (approx. each third year), but TUG/VTI has made measurements there only in 2011 (at an age of 6 years), when noise reduction was 4-5 dB in a lane with relatively new top layer and 1-2 dB where the surface was old and worn-out. The drop in noise reduction has been from 2.0 to 2.5 dB per year, which has been a matter of disappointment.

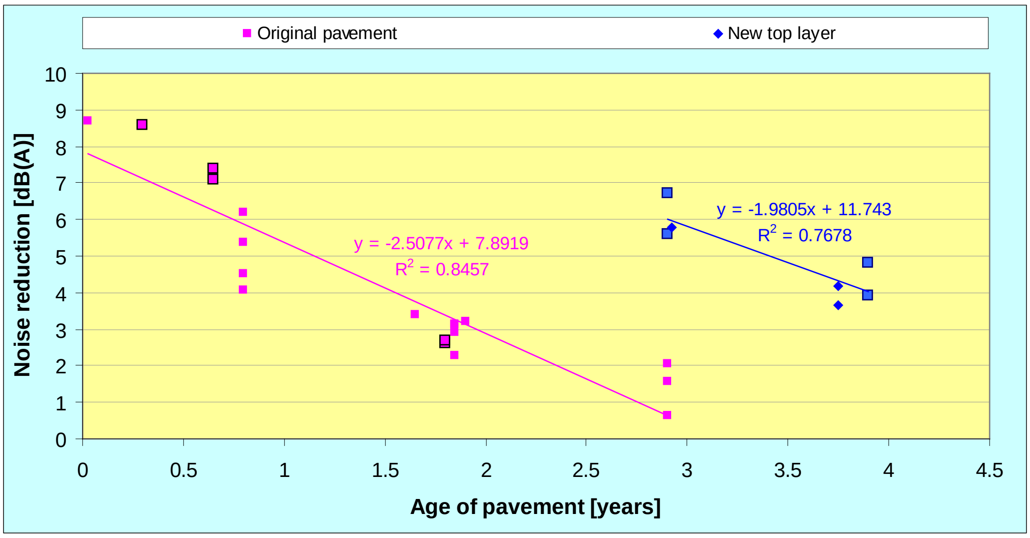

Figure 3 ─ Noise reduction measured by the CPX method at 80 km/h and as roadside Leq:s from 2005 to 2009 on test pavements on E4 southwest of Stockholm. See the text for further explanations. The reference surface (“0 dB”) is an SMA 16 laid on the same road, at an age of 2-4 years.

4. MEASUREMENT METHODS AND TEST EQUIPMENT

Unless otherwise mentioned, all noise measurements reported in this paper were made using a CPX trailer from TUG; in recent years the version marked "Tiresonic Mk4"; see Figure 4. Tests have been made in all essential details according to the ISO/DIS 11819-2. The CPX measurements have in most cases covered the entire length of the tested object, except for run-in and run-out parts, which means lengths of 100-2700 m.

During the noise measurements performed after 2005, two tyres were used: SRTT and Avon AV4, also denoted P1 and H1, respectively. See Figure 5. These are the two tyres currently considered as references for the CPX method. Before 2005, the test tyres included the four tyres A,B,C,D generally used in CPX measurements at that time. In the transition time, mainly 2005, both sets were used. The tyre load during measurements was fixed at 3200 N and the inflation pressure was adjusted to 200 kPa in cold conditions. Measurements have been performed at 50 and 80 km/h, according to ISO/DIS 11819-2, or at 50, 70 and 90 km/h. The P1 tyre is assumed to represent car tyres and the H1 tyre assumed to be a “proxy” for truck tyres.

Figure 4 ─ CPX noise tests with the TUG Tiresonic Mk4 trailer on the DPAC pavement on E4 in Huskvarna. The test tyre is mounted in the middle of the chamber.

Figure 5 ─ Tread patterns of the two test tyres used during the CPX noise tests. From left to right: SRTT (P1) and Avon AV4 (H1).

Very recently, ISO/TC 43/SC 1/WG 27 made a preliminary decision on temperature correction coefficients for three categories of pavement, using the same coefficients for both tyres P1 and H1, namely:

Dense asphalt concrete surfaces: -0.10 dB/^{o}C
Porous asphalt concrete surfaces: -0.05 dB/^{o}C
Cement concrete surfaces: - 0.07 dB/^{o}C

The corrections, based on ambient air temperature, are intended to be made to a reference temperature of 20 ^{o}C. These corrections are so far made only to the measurements in 2014.

5. THE LOW NOISE ROAD SURFACE AND THE REFERENCE SURFACES

5.1 The road and its location

The pavement which is subject of this paper is located on road E4 in Huskvarna, Sweden. The main section is 2.7 km long, of which the northern 1.7 km is shown in Figure 1. The AADT in both directions is approx. 22 000, with 18 % of heavy trucks. There are two lanes in each direction and about 70 % of all vehicles (incl. all trucks) run in the right lane and 30 % in the left lane. Posted speed is 90 km/h. The trucks run at approx. 85 km/h and most cars at 90-95 km/h. Just south of this location is a 700 m long section of the road where a single-layer porous asphalt was laid, and at the northern end there are a number of variants of the main pavement (e.g. using steel slag, and with extra binder). One day each year, part of the road is blocked-off, allowing an expert group to study the pavement in detail.

5.2 The double-layer porous asphalt concrete

The double-layer porous asphalt concrete (DPAC) pavement has a 50 mm thick bottom layer with a maximum aggregate size of 16 mm, and a 30 mm thick top layer with a maximum aggregate size of 11 mm. Figure 6 shows a close view of the surface as well as the reference surface used (see next section). In most other European countries, a maximum aggregate size of 6 or 8 mm in the top layer would have been preferred, but in Sweden and other countries that allow studs in tyres in winter time, it is considered that aggregates smaller than 11 mm would result in too much raveling and other wear. Thus, a part of the potential noise reduction must be sacrificed for durability reasons. The air voids content is assumed initially to have been higher than 20 % (up to 25 %). The binder is highly modified bitumen from Nynas. The pavement was laid in fine weather in June 2010, but at air temperatures 10-15 ^{o}C.

Figure 6 – Typical appearance of the surface of (both) the porous pavements subject of this study (on the left) and a reference pavement (on the right). The coin in the picture is 25 mm diameter.

It is interesting to note that the bottom layer was laid on one day and the top layer on the next day. The general view about the laying of DPAC is that to avoid separation of the two layers they must be laid “wet on wet”, which means that the top layer must be applied before the bottom layer has cooled significantly. However, the contractor (Svevia) laid the two layers on different days, with ambient temperatures only 10-15 ^{o}C, and to date no problem at all has been observed due to this. The DPAC laid by Skanska and mentioned above were laid with two pavers operating together in order that the two layers would be laid with only minimal cooling of the bottom layer before the top layer was applied. The experience by Svevia here proves that wet-on-wet laying is unnecessary and one can save the more expensive pavers which are needed for such operations.

5.3 The reference surfaces: SMA 16

In Sweden, the pavement dominating the paved road network is stone mastic asphalt (SMA) with a max. aggregate (stone) size of 16 mm. Swedish type designation is ABS 16, which in English corresponds to SMA 16. The reason for this dominance is that this surface has superior resistance to the wear of studded tyres. It is therefore natural that the reference surface for the measurements reported here is SMA 16. If one wants to translate the noise reductions to a reference surface corresponding to SMA 11 or dense asphalt concrete DAC 11 (the virtual reference surface in recent European prediction models) one should reduce the noise reductions reported here by approx. 1.5 dB.

In this project, the reference noise level has been an average of noise levels measured on three or more different SMA 16 surfaces of an age between 2 and 8 years. In this way, some of the natural variation within this pavement type and condition is averaged out. It has been considered so far by the authors that using this “average SMA 16” as a reference rather than a selected noise level measured by the CPX method is more stable. The reason is that the variation between reference tyres and their stability following wear and ageing has been significant source of uncertainty; something which is now changing as a result of research in recent years. An example of how an SMA 16 surface appears is shown in Figure 6.

6. RESULTS OF NOISE MEASUREMENTS ON THE MAIN ROAD SECTION

As we prefer to report the "noise reductions", in order to reduce the influence of tyre age and condition, as well as of temperature differences, it is first necessary to determine a reference noise level. As mentioned above, a number of SMA 16 pavements (usually four), the noise levels of which have been averaged, have been used each year as such references. These have not been the same each year but have varied in location according to the measurement program as a whole during that year.

The results are presented in Table 1, normalized to 80 km/h. In some cases measurements have been made at the nominal speed of 80 km/h, in other cases measurements have been made at 70 and 90 km/h; in such cases interpolation to 80 km/h has been made, based on the logarithmic relation between noise level and speed. The variations between the reference pavements, as seen in the table, reflect differences due to age (varying between two and seven years), condition, air temperature, and minor differences in construction. Also the lateral position of the test tyre on the tested road lane is a factor; even if it is generally aimed at the right wheel track, since pavements in Sweden have significant rutting.

The values which are used as reference levels for the noise reduction are those which have been calculated at the bottom of Table 1 as annual averages of the individual pavements.

Table 1 ─ A-weighted CPX noise level in dB, interpolated to 80 km/h (based on 70 and 90 km/h) or measured at 80 km/h, for measurements at six different times on different SMA 16 pavements. Tyre P1 is the SRTT and tyre H1 is the AAV4. See the text for further information.

Reference pavement	Ref. tyre	June 2010	July 2010	July 2011	July 2012	July 2013	July 2014
First	P1	101.0	100.5	100.4	100.5	100.8	100.3
	H1	100.6	100.0	99.3	100.1	100.5	100.0
Second	P1	100.7	99.0	100.5	101.5	101.9	101.3
	H1	100.1	99.1	99.5	100.2	100.9	100.2
Third	P1	101.3	99.9	100.2	101.1	101.5	100.4
	H1	100.4	99.2	99.3	100.6	100.8	99.7
Fourth	P1		100.4	101.0	101.6	99.8	100.0
	H1		99.7	99.5	101.4	99.5	99.3
Arithmetic average of above	P1	101.0	100.0	100.5	101.2	101.0	100.5
	H1	100.4	99.5	99.4	100.6	100.4	99.8

Based on the actually measured CPX noise levels on the DPAC pavement minus the reference levels of Table 1, noise reductions for the DPAC pavement are listed in Table 2. The measurements were made at 70 and 90 km/h but since there are no interesting features in the noise level difference between 70 and 90 km/h, the levels shown in the table are interpolated to 80 km/h, based on the common logarithmic relation between noise level and speed. The measurements were made in the slow (right) lane both in the right wheel track and between the left and right wheel tracks of that lane, and also in the right wheel track of the fast (left) lane. Since these different lateral positions on the road reflect different traffic loads, it is interesting to distinguish between them.

Table 2 ─ A-weighted noise reduction of the DPAC pavement in dB, interpolated to 80 km/h from 70 and 90 km/h, for CPX measurements at six different times. The noise reductions are relative to the annual average of the noise levels for the reference surfaces in Table 1. See the text for further information.

Lane & track	Ref. tyre	New June 2010	1 month July 2010	1 year July 2011	2 years July 2012	3 years July 2013	4 years July 2014
Slow (right) lane Right wheel track	P1	8.1	7.2	6.8	6.6	6.0	3.6
	H1	6.7	7.0	7.2	7.4	6.2	3.0
Slow (right) lane Between tracks	P1	8.1	7.7	7.8	7.4	6.7	4.5
	H1	6.7	7.1	7.6	7.2	6.3	3.7
Fast (left) lane Right wheel track	P1		7.5	7.0	6.8	6.5	5.9
	H1		7.0	7.0	7.3	6.5	5.3

The noise level reductions in Table 2 are shown in diagram format in Figure 7. A selection of third-octave-band frequency spectra are shown in Figures 8-10.

It appears that at the age of one month (Figure 8), the spectra show a pronounced dip at the dominating frequencies 800-1000 Hz, something which is typical of porous asphalt with maximum sound absorption at these frequencies. At the age of four years (Figure 9), this dip is gone; suggesting that sound absorption is no longer effective, most probably due to clogging. However, the fast lane (Figure 10) still shows signs of sound absorption, which is probably so since this lane is not yet fully clogged by dirt.

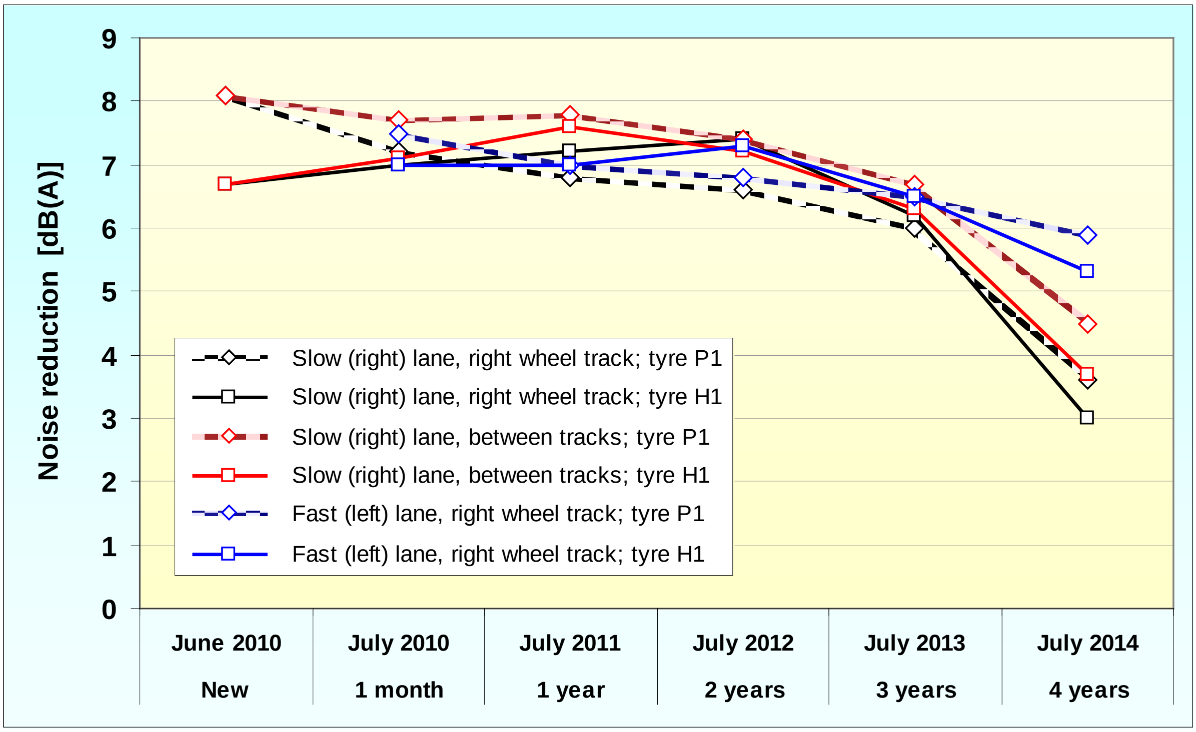

Figure 7 — A-weighted noise reductions over the first four years (2010-2014), measured with the CPX method, using tyres P1 (SRTT) and H1 (AAV4). The levels are the same as in Table 2.

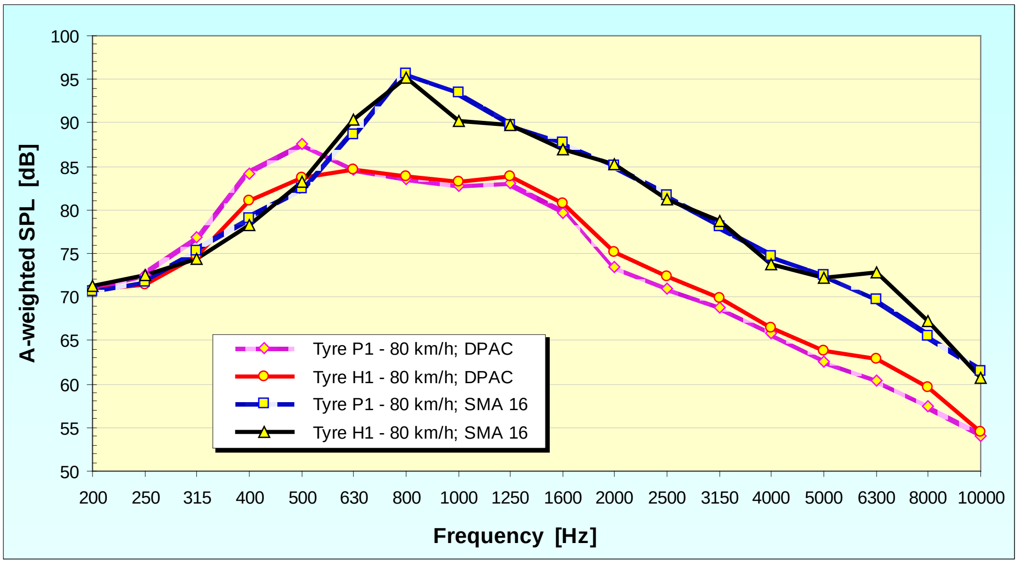

Figure 8 — A-weighted frequency spectra, interpolated to 80 km/h from 70 and 90 km/h, for the right wheel track in the slow lane, when the DPAC pavement was one month old. The reference pavement was SMA 16, 6 years old (the "third" one for July 2010 in Table 1).

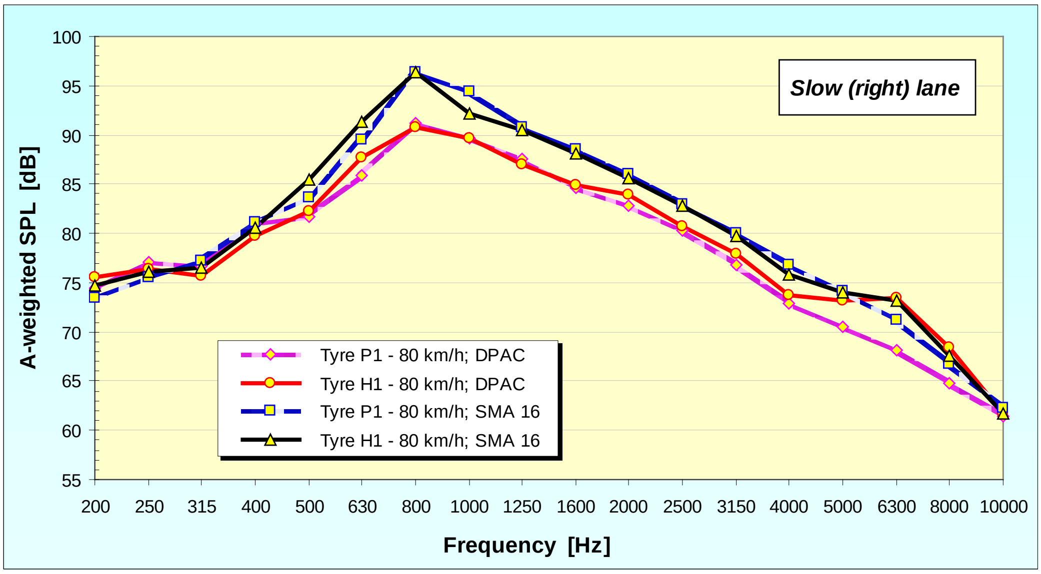

Figure 9 ─ A-weighted frequency spectra, interpolated to 80 km/h from 70 and 90 km/h, for the right wheel track in the slow lane, when the DPAC pavement was four years old. The reference pavement was SMA 16, 4 years old (the "third" one for July 2014 in Table 1).

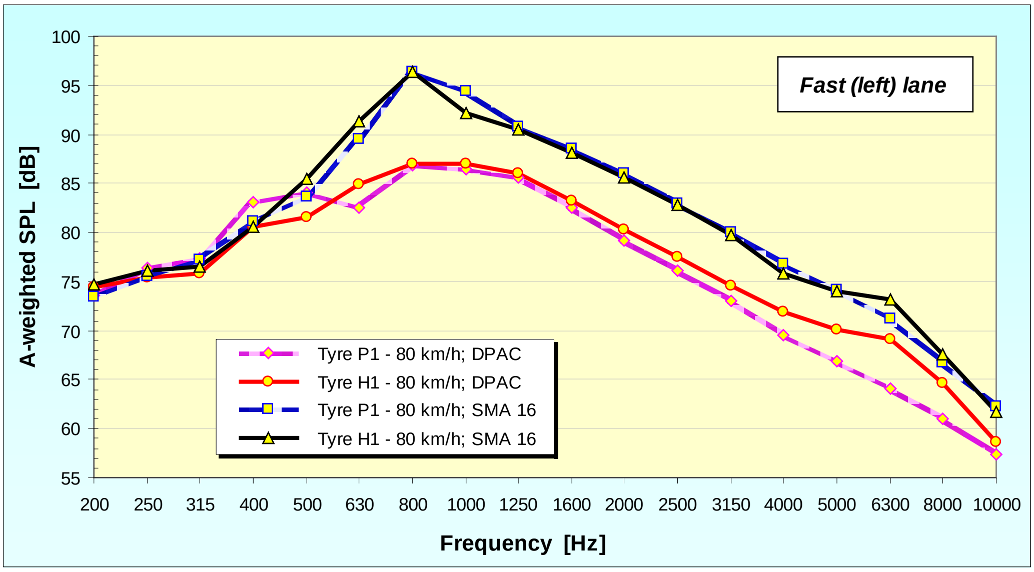

Figure 10 ─ A-weighted frequency spectra, interpolated to 80 km/h from 70 and 90 km/h, for the right wheel track in the fast lane, when the DPAC pavement was four years old. The reference pavement was SMA 16, 4 years old (the "third" one for July 2014 in Table 1).

7. RESULTS OF SPECIAL STUDIES

7.1 The effect of the bottom layer

At the same time as the DPAC was laid, also a single-layer porous asphalt pavement was laid, south of the DPAC on the same road, with exactly the same composition as the top layer in the double-layer pavement, except that it was approx. 5-8 mm thicker than the top layer. This allowed to study the effect of the bottom layer, by measuring the difference in noise emission on the single-layer versus the double-layer porous asphalt, as the only difference was the bottom layer.

A summary of the results is given in Table 3. For further information, see ref [3], which deals with this particular experiment. The following was concluded in [3]:

It is amazing how important for noise reduction the pavement at the depth between 30 and 80 mm under the surface is, provided that the layers are not clogged. The results of this study suggest that the top layer reduces noise by only 1–3 dB, whereas the bottom layer reduces noise by 5-6 dB and that the main reason is sound absorption in the pavement layers. A thickness of 80 mm tunes the maximum sound absorption to coincide with that of maximum A-weighted tyre/road noise energy, while 35 mm thickness tunes the absorption to too high frequencies.

Table 3 ─ Results of tyre/road noise measurements with the CPX method at 90 km/h, for tyres P1 and H1, expressed as A-weighted noise reductions in dB, at three occasions.

Type of pavement	July 2010		June 2011 (bef. cleaning)		July 2011 (after cleaning)	
	P1	H1	P1	H1	P1	H1
Single-layer porous asphalt	2.3	1.1	2.8	2.2	2.5	2.3
Double-layer porous asphalt	7.6	7.3	7.8	7.5	7.8	7.6
Double layer – single layer	***5.3***	***6.2***	***5.0***	***5.3***	***5.3***	***5.3***

7.2 Improving the pavement by creating a more negative texture by horizontal grinding

It is well known among tyre/road noise researchers that macrotexture of the road surface is extremely important for noise generation; and especially the way the texture is directed. A so-called negative texture means that the peaks in the vertical profile of the texture are directed downwards; i.e. there are valleys rather than ridges in the surface. A porous pavement has by its construction a rather pronounced negative texture, caused by the open but narrow spaces and pores between the chippings; a feature which is one of the major causes for the noise reduction.

The first author had earlier explored the possibility to create a more negative texture by grinding off its peaks by means of a machine grinding the surface in the horizontal plane (not to be confused with the diamond grinding commonly applied to cement concrete pavements). The DPAC here offered an opportunity to test whether this technology could provide for extra noise reduction.

Thus, the basis for the test object was already a pavement with negative texture. Nevertheless, the chippings were not flat and were not everywhere orientated in a way which gives a flat surface for the tyres to roll on. There was a potential to create an improved negative texture by grinding the surface.

The grinding was made by HTC Sweden AB. A new test section was constructed by grinding a strip 65 m long and 0.9 m wide in the right wheel track of the motorway's slow lane. Approximately 1-2 mm of the top of the chippings in the surface was ground-off, giving the already "negative texture" a flatter surface than originally; thus creating a "super-negative texture". A total of 54 kg of stone material was collected on this strip in the bag of the grinding machine. To remove remaining loose material the surface was vacuum cleaned. Figure 11 shows a comparison of the visual appearance of the non-ground and ground surfaces.

For further information, see ref [4], which deals with this particular experiment. A summary of the results appear in Table 4.

Figure 11 ─ Non-ground surface (left photo) and ground surface (right photo). The coin diameter is 25 mm.

Table 4 – Results in A-weighted dB of tyre/road noise measurements by the CPX method, comparing the DPAC before and after grinding.

Pavement/surface	Measured noise level for tyre P1			Measured noise level for tyre H1		
	50 km/h	70 km/h	90 km/h	50 km/h	70 km/h	90 km/h
Non-ground DPAC	87.9	92.1	94.7	86.3	90.6	93.6
Ground DPAC	85.2	89.5	92.8	85.9	90.2	93.0
Red. vs non-ground	**2.7**	**2.6**	**1.9**	**0.4**	**0.4**	**0.6**

The following conclusions are adapted from [4]: Measurements indicated a tyre/road noise reduction versus the not ground (similar) DPAC pavement of 2-3 dB for tyre P1 and 0.5 dB for tyre H1. This is extra in addition to the 7 dB reduction of the one-year-old DPAC versus the SMA 16 reference pavements reported above; thus resulting in a total noise reduction of up to 9 dB. Noise was reduced at low and medium frequencies but was somewhat increased at high frequencies, suggesting that the grinding products might have created some clogging of the pores in the DPAC, which probably have limited the noise reduction. The grinding also reduced rolling resistance by approximately 4-7 %.

7.3 The effect of cleaning

Trials with cleaning have been made at three times. The first time was at the age of one year, when CPX measurements were made in June 2011 before cleaning and in July 2011 after cleaning. The cleaning machine was a "regular" street cleaner truck which emitted high-pressure water and sucked up the dirt water afterwards. The results appear in Table 3. As shown in the right part of the table, the recorded differences are maximum 0.1 dB in seven cases and 0.3 dB in the eighth case; i.e., the effect is well within measuring uncertainties. A similar trial was made in 2012, with the same result as 2011.

A third trial was made in June 2014 when the surface was four years old and clogged in the slow lane. This time, much more advanced equipment was used: a special truck "VägRen" built by Skanska AB especially to clean clogged porous asphalt. A part of the DPAC's slow lane in northern direction was cleaned over a distance of approx. 100 m. TUG/VTI measured the noise reduction of this cleaned section and compared it to the rest of the pavement.

The results showed that of 11 runs over the cleaned section, for the two tyres and speeds 70 and 90 km/h, in both the right wheel track and between the wheel tracks, the difference between the cleaned section and the rest of the (uncleaned) section varied from -0.7 dB to +0.7 dB, with an average difference of 0.0 dB. Thus, it was concluded that the effect of cleaning was negligible also in this case.

7.4 The effect of rejuvenation

Rejuvenation was tried on the DPAC at three times. The first time was when the pavement was three months old, when a 100 m long test section was sprayed with a so-called Fog seal. The intention with this is to provide improved protection against oxidation of the binder and thus reduce raveling, but it may sacrifice permeability since the sprayed fluid may clog some of the more narrow pores.

When the pavement was one year old, TUG/VTI measured a difference between this sealed test section and the full non-sealed test section in the same lane and same wheel tracks to be within 0.3 dB (the average for the two tyres and the two speeds was 0.0 dB). It seems that this rejuvenation had no effect on noise. But one year later, the same rejuvenated surface was 0.6 dB quieter than the regular DPAC, for both tyres. After a new rejuvenation the next year, the rejuvenated section was approx. 0.3 dB quieter than the non-treated surface.

In September 2013, the entire slow lanes were sprayed with Fog seal. Unfortunately, no direct measurements of the effect were made. But comparing measurements in July 2013 with July 2014 (Table 2 and Figure 7) it appears that the slow lanes have lost a lot more noise reduction than the fast lanes. The average loss was 2.8 dB in the slow lane's right wheel track, 2.4 dB between the wheel tracks in the slow lane, against only 0.9 dB in the fast lane. This suggests that the spray might have clogged much of the remaining porosity. In summary, the rejuvenation effect is unclear; although the last one probably had the effect of additional clogging where clogging was not already severe.

It may also be the reason why, after the rejuvenation of the entire slow lanes, these show an increased variability from location to location along the road; as the spray intensity may have varied.

7.5 The effect of adding a single layer on top of another single layer

Since the single-layer porous asphalt provided a small noise reduction (Table 3) the road contractor tried a rather unique new option, namely to lay another (similar) single layer on top of the first one. This was made when the first layer had already been exposed to traffic for two years. Before laying the new layer, the old surface was cleaned by a regular street cleaner; then a thin “primer” was sprayed on the surface, after which the new layer was applied. Measurements by TUG/VTI showed that this new double layer, consisting of on older single layer under a new single layer, reduced A-weighted noise levels by 8 dB for tyre P1 and 7.5 dB for tyre H1. This is equally good as for the DPAC when it was new. However, there were sections at the southern end that showed 2 dB lower noise reductions. This might depend on how much the bottom layer was clogged at the time of laying the new layer on top of it.

8. DISCUSSION

8.1 Interpretation of the functional requirement of 5 dB noise reduction

The Land and Environment Court of Appeal decided that noise emission must be reduced by such an extent that the STA had to apply a low noise road surface providing 5 dB (A-weighted) average noise reduction with the additional requirement that noise reduction must not fall below 3 dB. This can be interpreted in many ways. First, it was interpreted that the STA meant 5 dB in comparison to the then existing pavement on the road section, which was a remix of SMA 16; the latter being the pavement which dominates the Swedish national road network. Second, it was discussed among the experts associated with the project whether the 3 dB minimum should apply to any part of the section or just the average over the full length of the section. The latter option was chosen. As it appears in Figs. 2-3, if an average of 5 dB and a minimum of 3 dB was required, repaving would have to be made with a period of 1-2 years, which seems to be unreasonable. Yet, this was the decision by the STA.

Finally, the interpretation of which measurement method to use was unclear. Since SPB measurements (ISO 11819-1) on the road section would be almost impossible due to the acoustic conditions, and the speeds are sufficiently high to make tyre/road noise almost totally dominating, the CPX method was chosen. Both tyres should be considered, averaged with equal weight; noting the relatively high share of heavy vehicles. It was also agreed that the measurements should include at least the right wheel track of each lane and that each lane (slow or fast) should be evaluated separately.

Functional requirements according to the above were established, with the addition that when the noise reduction had dipped below the requirements, the options for the road contractor were either to repave the lane or in another way restore noise reduction, e.g. by cleaning. In this way, the first real functional requirements for a low noise road surface that had to be met were established in Sweden.

8.2 The acoustical and technical longevity

From Table 2 and Figure 7 it appears that the noise reduction versus time has been amazingly stable, and this applies to both reference tyres; i.e. for both car and truck tyre/road noise. During the first three years, the drop in noise reduction was only 1 dB. It is first in the fourth year, and only in the slow lanes, that noise reduction dropped below 5 dB. It is tempting to speculate that in addition to "normal" clogging, a reason for the sudden drop in 2014 is the rejuvenation that was made in late 2013 and applied only to the slow lanes. Probably, the thin spray that was applied poured into the voids and contributed substantially to clogging. It is a great pity and mistake that a small section of the slow lanes was not saved from rejuvenation so we could have separated this effect.

It seems that the less traffic there is (between the wheel tracks, and in the fast lanes), the less noise reduction has been lost; i.e., the traffic load creates losses in noise reduction, but not much.

It is almost certain that in 2015, although the <u>average</u> noise reduction since the start of the project will still exceed the 5 dB requirement, noise reduction in the slow lanes will drop below the 3 dB requirement; and repaving of the slow lanes must be made. It means that this pavement will have an acoustical lifetime of 5 years, which is above the expectations and unique in Swedish conditions. Even an SMA 16 pavement is expected to have a lifetime of only 7 years on a road exposed to this traffic.

Fig. 11 is based on the results shown in Fig. 3, but with the present results for the E4 Huskvarna slow lane and right wheel track introduced; i.e. the most worn part of the Huskvarna section. First, it must be stressed that the traffic volume on the E4 Botkyrka section is probably about three times as high as in E4 Huskvarna, so the comparison is not fair. Nevertheless, the figure intends to show the advantage of a "Case I" (Huskvarna) compared to a "Case II" when the pavement noise reduction drops rapidly and steadily and exchange of the top layer is needed. Case I is of course superior.

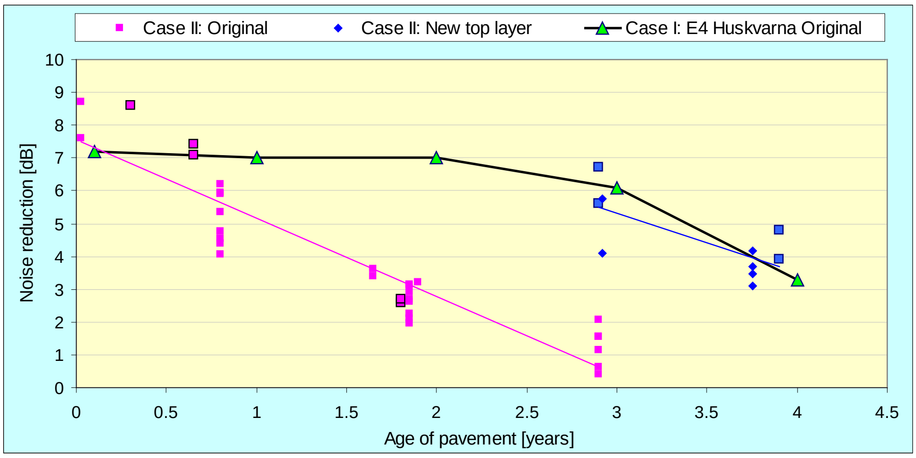

Figure 12 ─ Comparison of two cases of noise reduction versus time, with a Case I showing quite stable noise reduction, dropping off in years 3 and 4 (E4 Huskvarna), and a Case II with rapid and steady drop in noise reduction, requiring a new top layer within three years.

8.3 Concept of time-averaged noise reduction

For the noise exposed residents, as well as the road contractor or authority which pays for the pavement maintenance, the two cases illustrated above would have very different impacts. One needs to quantify them in some way. One way suggested here is to calculate the area under the curves in the diagram, to obtain an area describing the noise reduction together with the time during which it is achieved, counted over a life-cycle. Thus, the quantity could be called "decibel-years [dBy]". If one assumes that a life-cycle is five years in both cases above, in Case I the dBy would be approx. 27 and in Case II it would be approx. 19 dBy; a 45 % improvement. And it would be achieved without the cost of a new top layer. But please remember that the illustrated cases had very different traffic loads.

9. CONCLUSIONS

The following conclusions are drawn:

- The DPAC on E4 in Huskvarna has provided an excellent noise reduction: initially 7 dB
- The drop in noise reduction with time is slow; the first three years it was only 1 dB
- The average of at least four SMA 16 pavements serves as annual reference for the noise reduction
- Clogging has been observed visually and is indicated in the measured results for the fourth year
- It is suspected that a recent rejuvenation of the slow lanes has had a serious effect on clogging
- Three trials of cleaning of the voids in the pavement have failed to show any improvement
- There are indications of only light ravelling after four years of wear (incl. by studded tyres)
- The bottom layer of the DPAC is extremely effective in providing a high noise reduction
- Grinding-off the peaks of the surface texture gives 1-2 dB extra noise reduction and saves fuel
- The two layers of a DPAC can be laid on different days; "wet-on-wet" paving is not necessary
- Laying a new porous layer over an existing single-layer porous asphalt is very effective too.

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REFERENCES

1. Sandberg, Ulf, "Reduction of Tire/Road Noise by Drainage Asphalt". Presented at the International Seminar on Tire Noise and Road Construction, ETH, Zurich, Switzerland, February 1984 (also VTI Reprint No. 95, 1984, Swedish National Road and Transport Research Institute, Linköping, Sweden).
2. Sandberg, Ulf, "A new porous pavement with extended acoustical lifetime and useful even on low-speed roads". Proc. of Inter-Noise 97, Budapest, Hungary.
3. Sandberg, Ulf; Mioduszewski, Piotr, "The importance for noise reduction of the bottom layer in double-layer porous asphalt." Proc. of Acoustics 2012 Hong Kong, May 2012.
4. Sandberg, Ulf; Mioduszewski, Piotr, "Gaining extra noise reduction and lower rolling resistance by grinding a porous asphalt pavement." Proc. of Inter-Noise 2012, New York, NY, USA, 2012.