Californian and Danish Study on Acoustic Aging of Road Pavements

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ABSTRACT

It is the experience by noise technicians that the traffic noise emission of a given asphalt pavement changes over time. Knowledge on acoustical aging is important for road administrations when developing policies and strategies for noise abatement. It is important to know how noise reducing as well as "normal" pavements performs over time. Acoustical aging is important information in order to achieve good accuracy when noise is predicted with methods like the American TNM method or the Nordic NORD2000 method or the like. Noise performance models for road pavements are necessary if noise is to be integrated as an active parameter in Pavement Management Systems. The purpose of this current paper is to contribute to the ongoing international development in the field of acoustical aging by performing a comprehensive analysis of four existing Californian and Danish results from long time noise measurement series on asphalt pavements. For porous pavements (built in air void over around 15 %) it is a known phenomenon that the voids of the pavements tend to clog and that this increases the noise generated from air pumping. But for other dense and open graded (but not real porous) pavement types there is not much knowledge on which changes in the surface structure that causes this increase in noise in the period in between when the bitumen film is warn off and when the pavements begins to deteriorate with distresses like raveling, cracking etc. The objective is to analyze and compare trends in the development of noise over time. A comparison of the actual nominal noise levels is not the main objective of this study but rather the change in levels over time. The development of the noise spectra over the years is also analyzed in order to investigate which mechanisms of noise generation might be changed over time. The increase of noise has normally been analyzed in relation to the age of pavements. In this paper this is supplemented by also using the traffic load as well as an artificial indicator defined as the change of noise predicted as a combination of actual physical age and traffic load.

INTRODUCTION

The purpose of this paper is to contribute to the ongoing international development in the field of acoustical aging of tire/pavement interactions by performing a comprehensive analysis of some Californian and Danish results from long time noise measurement series on asphalt pavements. The main focus is asphalt concrete pavements applied on highways. Cement Concrete Pavements have not been included in this study. This paper is based on extracts of the results from the report "Acoustic aging of asphalt pavements. A Californian Danish comparison" [1] where detailed documentation and analyses can be found.

An international literature survey has been conducted in [1]. It shows that the noise level generally increases as the pavement gets older. For porous pavement (built-in air void content of more than 15 % or so) it is a known phenomenon that air voids tends to clog in some facilities and that this increases the noise generated from air pumping. But for other dense and open graded (but not really porous) pavement types there is not much knowledge on which are the changes occurring in the surface structure causing this increase in noise in the period from when the bitumen film is worn off and when the pavements begins to deteriorate with distresses like raveling, cracking, etc.

The most common measurement methods used today for detailed analyses of road traffic noise are the wayside Statistical Pass-By method (SPB) [2] or the "close to source" methods like the On Board Sound Intensity method [3] (OBSI) or the Close Proximity method (CPX) [4]. This project [1] focuses on the trend in noise levels measured in the same way– the relative changes of noise over the years – and not on the actual noise levels. The objective is to analyze and compare trends in the development of noise over time. Therefore it is not so crucial if noise results have been measured by different methods or by the same method applied by different measurement teams/organizations. These factors might influence the actual noise levels and can complicate direct comparison, but when only trends are compared these differences in measurement methods are not that important. The average vehicle in the fleets of California and Denmark may differ, for example with smaller passenger cars in Denmark. This might influence the comparison of actual noise levels but will presumably be less important when comparing trends in noise emission over the years measured at the same site. Only changes in the noise levels happening over time are included in this project. Other factors relevant for the description of the development of the physical structure of the pavement surface like texture, porosity, visual signs of wear and tear etc have not been considered.

Two well documented long time noise measurement series from California and two from Denmark have been analyzed in this project [1]. The results have already been documented in detail in separate national reports. The objective of the current report is to perform a comparison study of the trends for acoustical aging found in these four projects. The University of California Pavement Research Center (UCPRC) finalized in 2009 the third year report on annual On Board Sound Intensity noise measurements on 65 to 76 pavement sections of different ages and mix types in California. Some results from this project are also included. The two Californian measurement series and the UCPRC study have all been carried out for California Department of Transportation (Caltrans) and the two Danish measurement series have been carried out for the Danish Road Directorate. The following five measurement series are included:

1. Open graded pavement (OGAC) on I 80 near Davis, California (10 years), one pavement type [5].
2. 5 test sections with dense and open graded pavements on LA138 in the Mojave Desert, California (5 years) [6].
3. 65 to 76 pavements in the UCPRC/Caltrans monitoring project (3 years and pavements in different age groups and of different mix types) [7].
4. 3 single layer porous (PAC), one dense graded (DGAC) and one open graded (OGAC) pavement at "Viskinge", Denmark (8 years) [8].
5. 5 thin open graded (OGAC) and one dense (DGAC) pavement at M10 ("Solrød") near Copenhagen, Denmark (5 years) [9].

The pavements included in this project were grouped in the following four main types:

1. Dense Graded Asphalt Concrete (DGAC).
2. Open Graded Asphalt Concrete (OGAC) including open graded rubberized pavements (RAC-O).
3. Porous Asphalt Concrete (PAC).
4. Thin Asphalt Layers (Thin Open) including different types of Stone Mastics Asphalt pavements (SMA) and an open graded pavement, optimized for noise reduction.

SOME RESULTS FROM A CALIFORNIAN TEST SECTION

In this section some selected results from the one of the Californian test sections are presented as examples. All the detailed results can be seen in [1]. Figure 1 to 4 show the results including the frequency spectra's from SPB noise measurements on a DGAC and an OGAC pavement constructed on highway LA138 in California 2002.

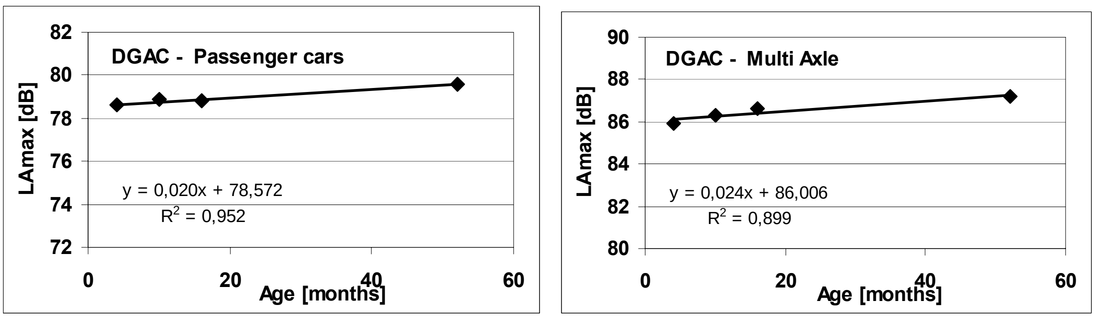


FIGURE 1: Maximum SPB noise level for passenger cars to the left (reference speed 96 km/h (60 mph) and for multi axle vehicles to the right (reference speed 88 km/h (55 mph)) for the DGAC pavement) [1, 6].

Detailed wayside SPB measurements have been carried out by Volpe Center for Acoustics 4 times in a 5 year period [6]. The microphone position used was 7.5 m (25 feet) from the centerline of the lane and at a height of 1.5 m (5 feet). The results are reported as L_{Amax}. The SPB measurements have been carried out when the pavements were 4, 10, 16 and 52 months old. The noise increase in the figures is reported per month. It therefore has to be multiplied by 12 to get the yearly noise increase. In Figure 1 the development of noise for the DCAC pavement at the LA138 test section can be seen. The noise increase fits quite well with a linear regression with Residual Standard Errors of 0.1 and 0.2 dB (see Table 1). The yearly increase for passenger cars was 0.24 dB/year and for multi axle vehicles it was 0.29 dB/year. According to Figure 2 the increases take place in the whole range of the frequency spectrum.

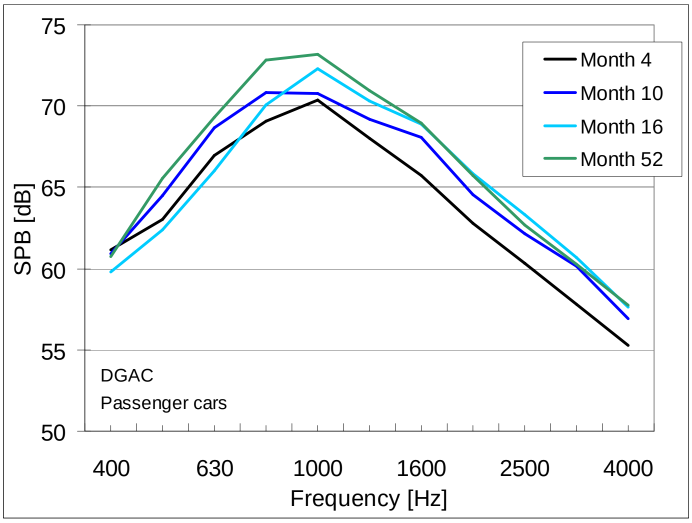


FIGURE 2: SPB noise spectra for passenger cars for the DGAC pavement (reference speed 96 km/h (60 mph)) [1, 6].

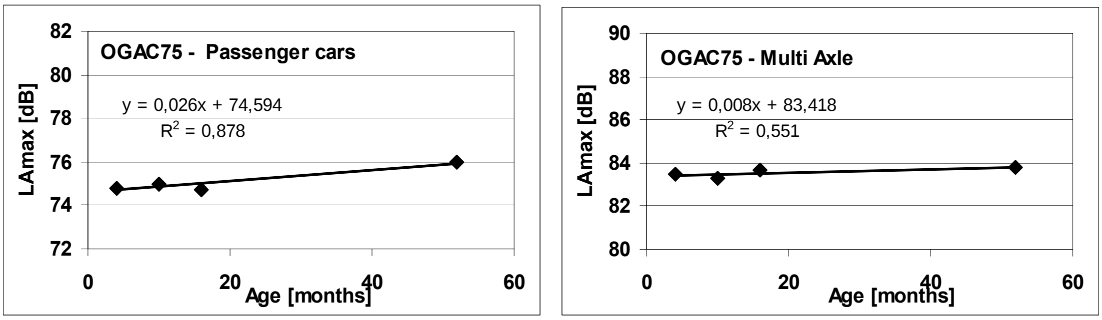


FIGURE 3: Maximum SPB noise level for passenger cars to the left (reference speed 96 km/h (60 mph) and for multi axle vehicles to the right (reference speed 88 km/h (55 mph)) for the OGAC75 pavement [1, 6].

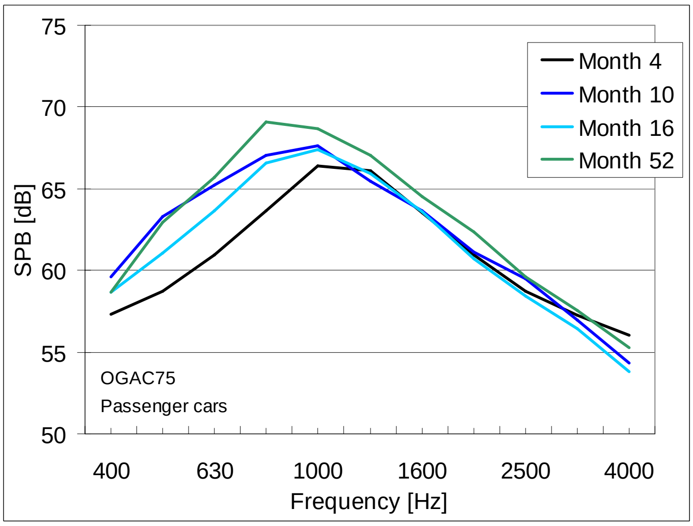


FIGURE 4: SPB noise spectra for passenger cars for the OGAC75 pavement (reference speed 96 km/h (60 mph)) [1, 6].

The development of noise over the years for passenger cars for the open graded OGAC75 pavement was 0.31 dB/year (see Figure 3) where as it was lower for multi axle vehicles (0.10 dB/Year). The noise increase fits quite well with a linear regression (the Residual Standard Error of 0.3 and 0.2 dB [see Table 1]). Figure 4 show that the increase basically happens in the low frequencies indicating that the pavement surface becomes rougher.

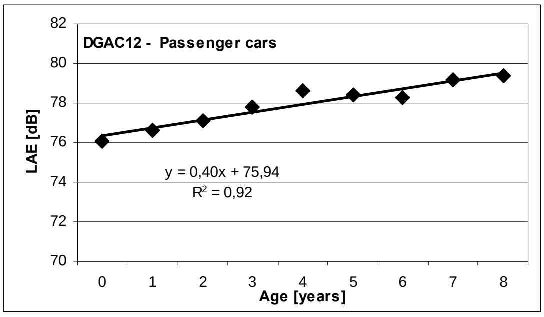
Table 1 gives an overview of the noise trends for the four LA138 pavements and also shows the Residual Standard Error for the linear regressions. For passenger cars the dense graded OGAC30 pavement has the lowest increases of 0.20 dB/year. For the other three more open graded pavements the increases vary between 0.24 and 0.40 dB/year. The increases for multi axle vehicles are generally less than for passenger cars with the DGAC pavement as an exception; here the trend for multi axle vehicles is slightly higher than for passenger cars.

TABLE 1: Average noise increase per year for passenger cars and multi axle vehicles and the Residual Standard Error for the four test pavements on LA138 (reference speed 96 km/h (60 mph) for passenger cars and 88 km/h (55 mph) for multi axle vehicles) [1].

Pavement	Passenger cars	Residual Standard Error Passenger	Multi axle vehicles	Residual Standard Error Multi axle
DGAC	0.24 dB/year	0.1 dB	0.29 dB/year	0.2 dB
OGAC75	0.31 dB/year	0.3 dB	0.10 dB/year	0.2 dB
OGAC30	0.20 dB/year	0.2 dB	0.12 dB/year	0.2 dB
RAC-O	0.40 dB/year	0.3 dB	0.36 dB/year	0.2 dB

SOME RESULTS FROM A DANISH TEST SECTION

In this section some selected results from the one of the Danish test sections are presented as examples. All the detailed results can be seen in [1]. Figure 5 to10 show the results including the frequency spectra from SPB noise measurements on a DGAC (with 12 mm maximum aggregate size) and a PAC pavement constructed at Viskinge in Denmark in 1990. SPB noise measurements have been conducted over a period of 8 to 9 years [8]. The microphone position used was 7.5 m (25 feet) from the centerline of the lane and at a height of 1.2 m (4 feet). The results are reported as LAE values and not L_{Amax} which is now common for SPB measurements. There is a linear correlation between LAE and L_{Amax} for SPB traffic noise measurements [10].



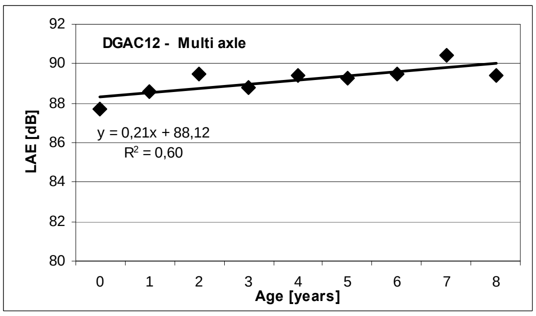


FIGURE 5: LAE SPB noise level from passenger cars (reference speed 80 km/h (50 mph)) to the left and the maximum SPB noise level for multi axle vehicles to the right for the DGAC12 pavement [1, 8].

Figure 5 shows the development of noise over the years for the dense graded DGAC12 pavement. The noise increase fits quite well with a linear regression with a Residual Standard Error of 0.3 and 0.5 dB (see Table 2). The yearly increase for passenger cars was 0.40dB/year and the double than for multi axle vehicles with 0.21 dB/year increase. The noise for passenger cars generally increased over time at all frequencies above 630 Hz (see Figure 6). In the first one to two years the noise increased 1 to 2 dB at frequencies above 1000 Hz. This could indicate that the dense surface structure of the pavement has become even denser causing an increase in the high frequency air pumping generated noise! This might be caused by the pavement being "post compacted" by the tires driving on the pavement! Heavy raveling occurred on the DGAC pavement in year 8. The results show a noise increase of 1.0 to 1.5 dB in the frequency range from 800 to 1600 Hz. The spectra for multi axle vehicles (Figure 7) generally show the same trends. From the third year the spectra is nearly unchanged to year 8. This could indicate that the truck tires are not as sensitive to changes in the openness of the pavement surface structure as passenger car tires. The raveling in year 8 does not have any significant effect on the noise emission from the truck tires.

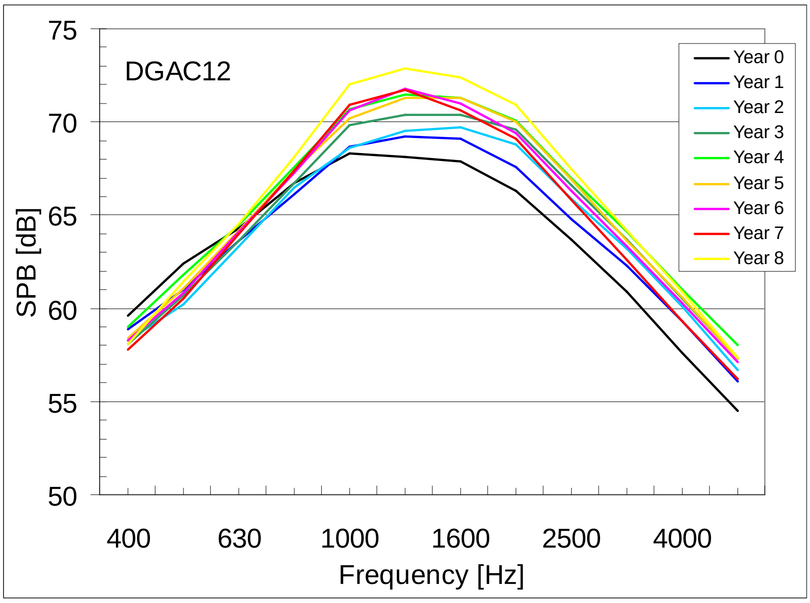


FIGURE 6: The SPB spectra for passenger cars at the different ages for the DGAC12 pavement (reference speed 80 km/h (50 mph)) [1, 8].

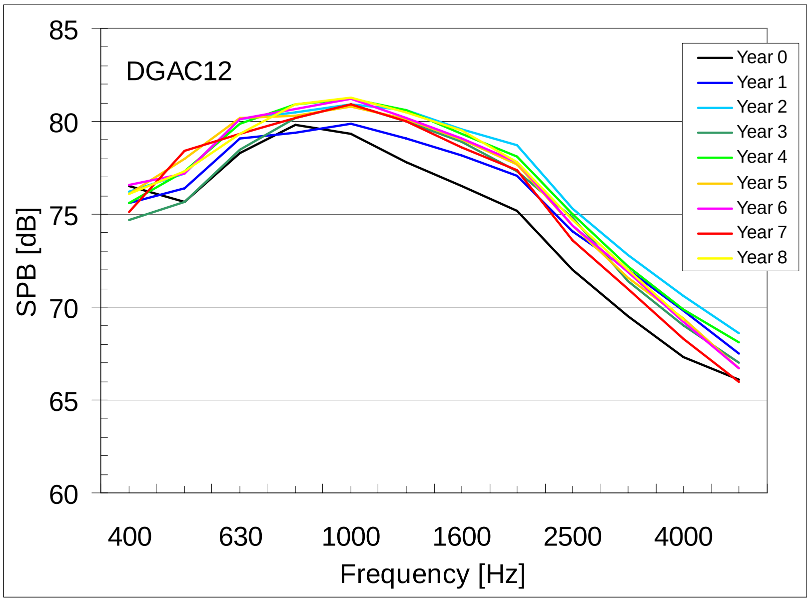


FIGURE 7: The SPB spectra for multi axle vehicles at the different ages for the DGAC12 pavement (reference speed 80 km/h (50 mph)) [1, 8].

One of the three porous pavements at the Viskinge test site is called PAC8 Type A. The development of noise can be seen in Figure 8. The yearly increase for passenger cars was 0.87 dB/year and for multi axle vehicles the increase is 0.37 dB/year. These increases are twice as high as for the dense DGAC12. The Residual Standard Error has increased for this porous pavement and is 0.6 dB for both vehicle categories (see Table 2).

But in the first year a decrease of noise of 0.3 dB for passenger cars and 0.7 dB for multi axle vehicles were observed. The frequency spectra for passenger cars in Figure 9 give an indication on what might be happening. This spectrum is significantly different from the spectra of the dense DGAC pavement. The noise decreased by 2 dB in the frequency range 800 to 1000 Hz, which is important for the total A-weighted noise level. A new open porous pavement absorbs noise reflected on the pavement at frequencies typically below 1000 Hz (engine noise) depending on the thickness of the porous layer. It seems like this absorption effect was improved over the first year. But at the same time the noise over 1250 Hz increased indicating an increase in the noise from air pumping. This might be caused by post compaction of the pavement

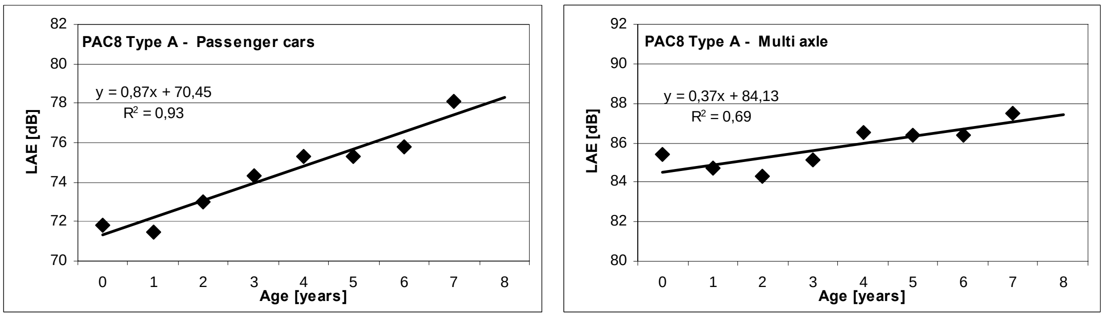


FIGURE 8: LAE SPB noise level for passenger cars to the left and the maximum SPB noise level for multi axle vehicles to the right for the PAC8 type A pavement (reference speed 80 km/h (50 mph)) [1, 8].

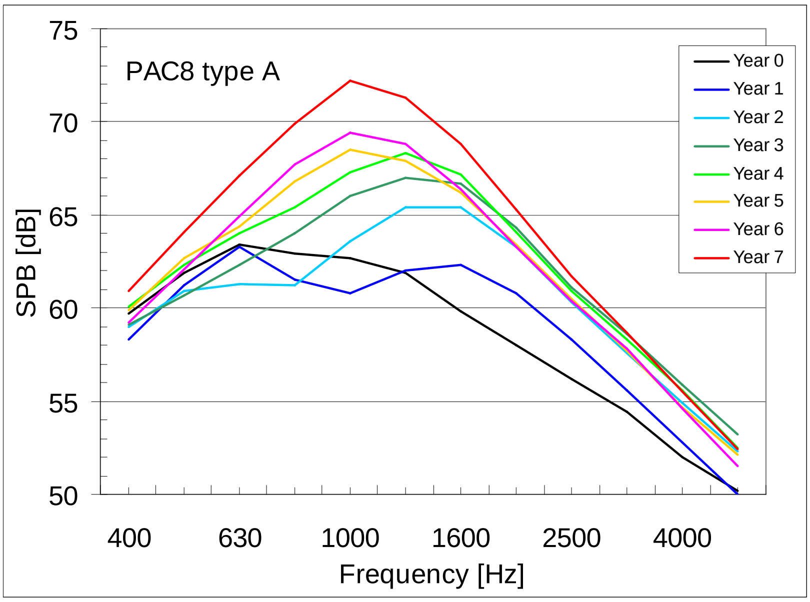


FIGURE 9: The SPB spectra for passenger cars at the different ages for the PAC8 type A pavement (reference speed 80 km/h (50 mph)) [1, 8].

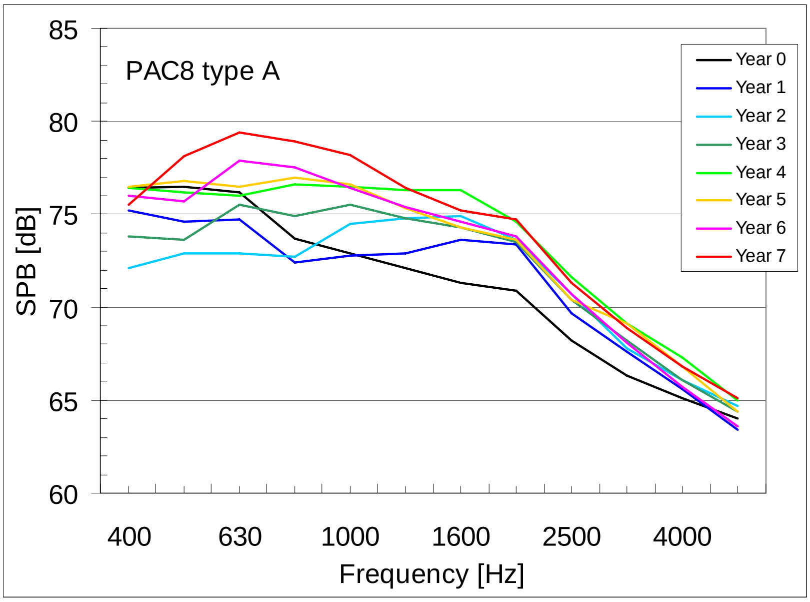


FIGURE 10: The SPB spectra for multi axle vehicles at the different ages for the PAC8 type A pavement (reference speed 80 km/h (50 mph)) [1, 8].

From the first to the second year the noise increased by 2 to 3 dB at frequencies above 1000 Hz indicating an increase in air pumping noise reflecting that the open pores of the pavement were beginning to clog! The noise also increased at 800 to 1000 Hz indicating that the noise absorption effect was reduced significantly! This is also an indication of clogging. In year 7 heavy raveling was observed on this pavement. In this year there was a significant increase of around 2 to 3 dB of low frequency noise below 1600 Hz. This reflects that the pavement has become rougher because of the raveling. Figure 10 shows the spectra for multi axle vehicles. The trends are generally the same as for passenger cars. Here the noise increases around 2 dB in the frequencies below 1600 Hz from year 6 to 7 when raveling occurs. This is different than for the dense DGAC pavement where the raveling did not increase the truck tire noise.

TABLE 2: Average noise increase per year for passenger cars and multi axle vehicles and the Residual Standard Error for the five test pavements as measured at Viskinge (reference speed 80 km/h (50 mph)) [1].

Pavement	Passenger cars	Residual Standard Error Passenger	Multi axle vehicles	Residual Standard Error Multi axle
DGAC12	0.40 dB/year	0.3 dB	0.21 dB/year	0.5 dB
OGAC12	0.51 dB/year	0.3 dB	0.27 dB/year	0.2 dB
PAC8 type A	0.87 dB/year	0.6 dB	0.37 dB/year	0.6 dB
PAC8 type B	0.81 dB/year	0.8 dB	0.20 dB/year	0.9 dB
PAC12	0.83 dB/year	1.1 dB	0.44 dB/year	0.8 dB

Table 2 gives an overview of the noise trends on the five Viskinge pavements. For passenger cars the dense graded DGAC12 pavement had the lowest increases of 0.40 dB/year, followed by the open graded OGAC12 pavement with 0.51 dB/year. For the three porous pavements the increases were around twice as high with 0.81 and 0.87 dB/year. The increases for multi axle vehicles were generally around 50% of the increase for passenger cars with the PAC8 Type B pavement as an exception; here the trend for multi axle vehicles were only a fourth of the trend for passenger cars.

The intention of the Viskinge experiment was to perform a "fast" life cycle testing of porous pavements. For this reason the five pavements were deliberately built to break down faster than would normally be the case. Modifiers were not added to the bitumen. New Dutch results show that porous pavements built for long structural lifetime (with modified bitumen) can be constructed, so they have a lifetime of around 11 years [11]. The acoustical performance of the five pavements is "stretched" to a lifetime of 11 years by multiplying the yearly increases by 7/11. Table 3 shows the expected noise increases of new durable porous pavements with modified bitumen. The dense and the open graded asphalt concrete now for passenger cars gets a noise increase of respectively 0.25 and 0.32 dB/year and the porous pavements an increase of 0.52 to 0.55 dB/year. This "stretching" of the noise increases makes it possible to compare the results with the results from the other test sections included in this project [1] and will be used in the following.

Table 3: Predicted average noise increase per year for passenger cars and multi axle vehicles for five pavements like the Viskinge test sections but constructed for long structural lifetime with modified bitumen assuming a lifetime of 11 years (reference speed 80 km/h (50 mph)) [1].

Pavement	Passenger cars	Multi axle vehicles
DGAC12	0.25 dB/year	0.13 dB/year
OGAC12	0.32 dB/year	0.17 dB/year
PAC8 type A	0.55 dB/year	0.24 dB/year
PAC8 type B	0.52 dB/year	0.13 dB/year
PAC12	0.53 dB/year	0.28 dB/year

ANALYSES

Different parameters have been used to describe the increase of noise. The increase in noise is often expressed as dB per year. Two main factors are considered to affect the changes on the noise properties of a pavement. One relates to the physical/chemical changes in the materials caused by the weather elements, and the other has to do with the wear and tear caused by traffic. It can be argued that the combined effects of both the physical age of a pavement as well as the wear and tear from traffic are determining the increase of noise. The age reflects an accumulated effect of changing weather conditions like sun radiation, rain, ice freeze/thaw etc. In order to try to define an indicator that combines these two very different factors age and traffic load, two artificial indicators called "Mixed

Indicator" ($\Delta L_{Mix50/50}$ and $\Delta L_{Mix25/75}$) have been defined [1]. The noise increase has been analyzed for five different indicators:

1. ΔL_{Age}: The change of noise per year (actual physical age of the pavement).
2. ΔL_{ADT}:The change of noise per 1 million vehicles (all types) passing per lane.
3. ΔL_{Hvy}: The change in noise per 0.1 million heavy vehicles passing per lane.
4. $\Delta L_{Mix50/50}$: An artificial indicator as the change of noise predicted as a combination of actual physical age and traffic load where the age counts for 50 % and the traffic load counts for 50 % called "Mixed Indicator 50/50".
5. $\Delta L_{Mix25/75}$: An artificial indicator as the change of noise predicted as a combination of actual physical age and traffic load where the age counts for 25 % and the traffic load counts for 75 % called "Mixed Indicator 25/75").

The results for three of these indicators are shown in Figure 11 to 13.

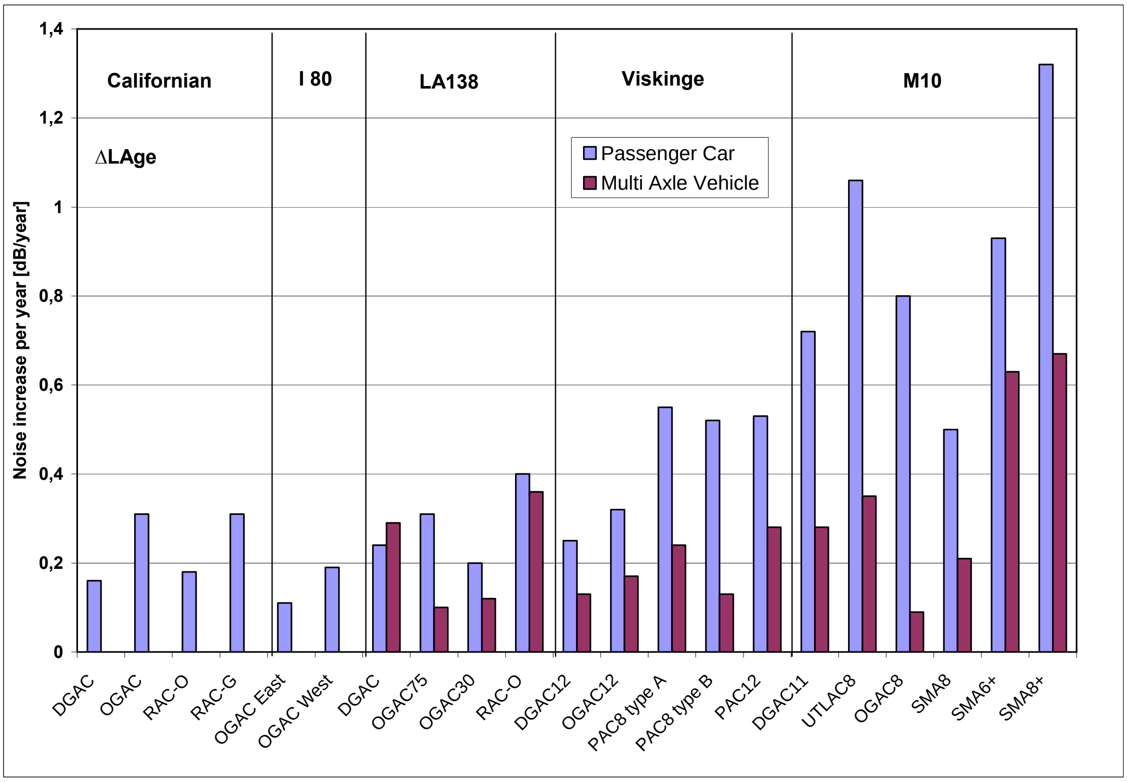


FIGURE 11: ΔL_{Age} noise increase per year of physical pavement age for all pavements in four all test sections passenger cars and multi axle vehicles [1].

Figure 11 shows an overview of the trends for noise increase per year for all the pavements included in the four test sites plus the Californian investigation. For passenger cars the two Danish test roads (Viskinge and M10) have generally significantly higher yearly noise increases than the two Californian test roads (I 80 and LA138). For multi axle vehicles the noise increases are not that different. Figure 12 shows the noise increase per 1 million vehicles (all types of vehicles) passing the test pavement. The noise increase per 1 million vehicles ($\Delta L_{ADT)}$ is calculated as follows:

$$\Delta L_{ADT} = (\Delta L_{Age} \times 10^6) / (ADT \times 365/N) \quad (1)$$

Where:
ΔL_{Age} = Increase per year in dB
ADT = Average Daily Traffic
N = Number of lanes

When taking traffic volume into consideration instead of age the ranking of the test sites changes significantly. The M10 sections with a high traffic load now have very low trends for noise increase, significantly lower than the LA138 and Viskinge test sites.

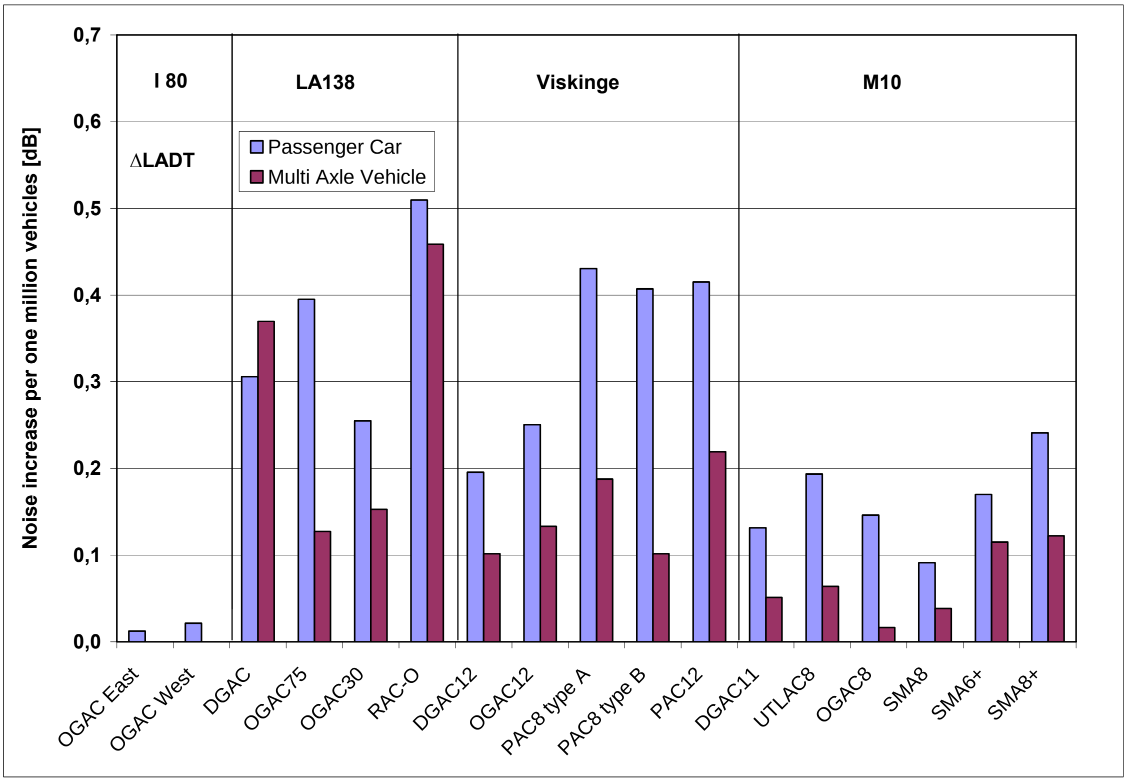


FIGURE 12: ΔL_{ADT} noise increase per 1 million vehicles passing the actual lane for all pavements in four all test sections passenger cars and multi axle vehicles [1].

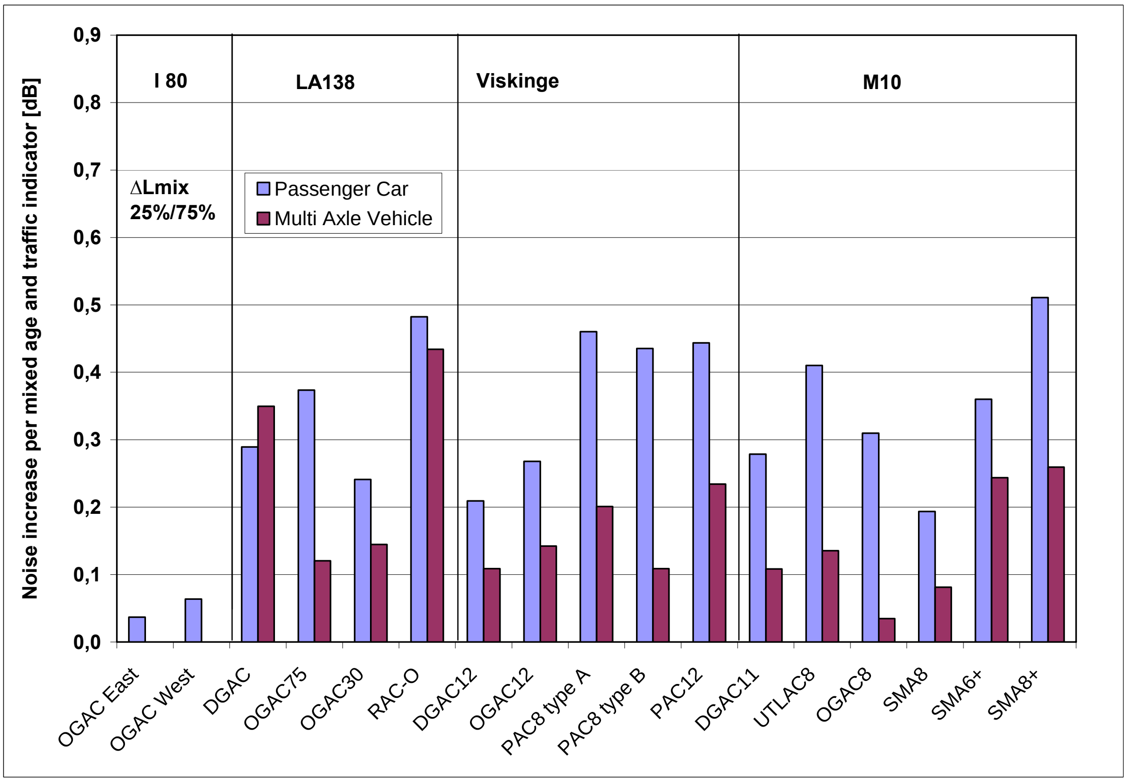


Figure 13: $\Delta L_{Mix25/75}$ noise increase per Mixed Indicator as the change of noise predicted as a combination of physical age and traffic load where the age counts for 25 % and the traffic load counts for 75 % [1].

It is believed by the authors that the porous pavements at Viskinge should have a higher noise increase than the thin open pavements at the M10 test site because of the tendency of clogging of these porous pavements which are not seen on the open but not porous thin layers. Therefore it has been decided also to try out a model where the psychical age counts for just 25 % and the traffic volume for 75 % of the noise increase. The ΔLMix25/75 indicator is calculated as follows:

$$\Delta L_{Mix25/75} = \Delta L_{Age} \text{ x } 0.25 + \Delta L_{ADT} \text{ x } 0.75 \qquad (2)$$

Figure 13 shows the Mixed Indicator $\Delta L_{Mix25/75}$ for all 17 pavements. By using $\Delta L_{Mix25/75}$ the ranking of the LA138, Viskinge and M10 test sections is now changed. The porous pavements at Viskinge now generally have a higher noise increase than the thin layers at M10.

In Table 4 and 5 the average results for each pavement group is predicted and compared. The average noise increase per year for passenger cars (ΔL_{Age}) is 0.58 dB/year. The DGAC pavements have the lowest increase of 0.40 dB/year followed by OGAC with 0.41 dB/Year. The two pavement types with the highest increase are the PAC and the Thin Open pavements with respectively 0.53 and 0.84 dB/year.

When instead of ΔL_{Age} the traffic volume (ΔL_{ADT}) is taken into consideration as an indicator for noise increase, the ranking of the pavement types changes significantly.

The average $\Delta L_{Mix25/75}$ for passenger cars is 0.32 dB. The $\Delta L_{Mix25/75}$ indicator ranks the four pavement types in the following way. DGAC has the lowest increase of 0.26 dB followed by OGAC with 0.30 dB. Next comes the Thin Open pavements with an increase of 0.39 dB. The porous pavements have the highest increase of 0.45 dB using the $\Delta L_{Mix25/75}$ indicator.

TABLE 4: The average noise increase for passenger cars for the four pavement groups expressed as the three indicators ΔL_{Age}, ΔL_{ADT} and $\Delta LMix_{25/75}$.

Pavement type	ΔL_{Age} [dB/year]	ΔL_{ADT} [dB/1 mil vehicles]	$\Delta L_{Mix25/75}$ [dB/mix]
All average	0,58	0.28	0.32
DGAC	0.40	0.21	0.26
OGAC	0.41	0.26	0.30
Thin open	0.84	0.24	0.39
PAC	0.53	0.42	0.45

TABLE 5: The average noise increase for multi axle heavy vehicles for the four pavement groups expressed as the three indicators ΔL_{Age}, ΔL_{ADT} and $\Delta L_{Mix25/75}$.

Pavement type	ΔL_{Age} [dB/year]	ΔL_{ADT} [dB/1 mil vehicles]	$\Delta L_{Mix25/75}$ [dB/mix]
All average	0.27	0.15	0.18
DGAC	0.23	0.17	0,19
OGAC	0.12	0.11	0.11
Thin open	0.44	0.16	0.23
PAC	0.22	0.17	0.18

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions on general tendencies for highways can be indicated on the background of this study on acoustical aging of asphalt pavements:

- The noise level on asphalt pavements normally increases with time.
- The increases occur continuously and before significant pavement deterioration with raveling and cracks etc. begins.
- There are exceptions where the noise is reduced over the first year of porous pavement lifetime.
- A linear regression gives a good fit of the relation between pavement age and noise both for passenger cars and multi axle vehicles using existing noise data. This was also seen in the European SILENCE study [11].

- The yearly noise increase is generally around 2 times higher for passenger cars than for heavy vehicles.

Spectral analyses have been performed. The following very general tendencies are observed for the four pavement types:

- For the Dense Graded Asphalt Concrete (DGAC) the higher frequency air pumping noise increases in the first years indicating that the pavement surface becomes denser (after compaction). After some years there is also an increase in the lower frequencies below 1600 Hz indicating that the pavement surface becomes rougher with an increase in the tyre vibrating noise.
- For the Open Graded Asphalt Concrete (OGAC) the tendencies for the different pavements included in the investigation is not very clear. For some of the pavements there is a tendency that the higher frequency air pumping noise increases in the first years indicating that the pavement surface becomes denser (after compaction), and after some years there is also an increase in the lower frequencies below 1600 Hz indicating that the pavement surface becomes rougher with an increase in the tyre vibrating noise. But for some of the pavement the increase at the lower frequencies happened before the increase at the higher frequencies.
- For the Thin Open pavements the noise increases at the same time both at the lower and at the higher frequencies. This indicates both that the pavement surface becomes rougher with an increase in the tyre vibrating noise and that the pavement surface becomes denser causing increased higher frequency air pumping noise.
- For the porous pavements (PAC) the engine noise absorption effect at frequencies between 400 and 1000 Hz is significantly reduced in the first two years. In the second year clogging begins and this increases the higher frequency noise over 1000 Hz because of increased generation of air pumping noise. As the porous pavements gets older there is an increase in the low frequency noise less than 1600 Hz indicating increased tire vibration noise caused by a rougher pavement surface structure.
- When heavy raveling occur the tire vibrating generated low frequency noise less than 1600 Hz increases for all pavement types.

On the background of this project [1] the following recommendations can be highlighted:

- There is a need for further research in order to give a better understanding on which changes in the pavement surface structure that causes the noise increase. Detailed analyses of pavement structure and noise spectra etc might be a lead to follow!
- More long time measurement series are needed to get an even better understanding of the noise increases as pavements gets older.
- It is therefore important when possible to follow existing experimental road pavement tests sections from the time they are new until they are replaced in order to get more information on the acoustical aging.
- It is necessary to combine the results of noise measurements with results from measurements of other pavement properties like surface texture, built in air-void content, permeability, acoustical absorption etc.

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REFERENCES

1. H. Bendsten; E Kohler; Qing Lu. Acoustic aging of asphalt pavements. A Californian Danish comparison. Report 171, 2009. Road Directorate/Danish Road Institute. See: www.roadinstitute.dk
2. ISO 11819-1: 1997. "Acoustics – Measurement of the influence of road surfaces on traffic noise – Part 1: Statistical Pass-by method." 1997.
3. Further Development of the Sound Intensity Method of Measuring Tire Noise Performance of In-Situ Pavements. Illingworht & Rodkin, Inc. Report prepared for the California January 4, 2006. See: http://www.i80.dot.ca.gov/hq/env/noise/pub/2_Probe_SI_Report_04Jan06.pdf
4. ISO/CD 11819-2: 2000. "Acoustics – Measurement of the influence of road surfaces on traffic noise – Part 2: The close-proximity method." 2000.

5. I-80 Davis OGAC Pavement Noise Study. Traffic Noise Levels Associated With Aging Open Graded Asphalt Concrete Overlay. Illimgworth & Rodkin, Inc. for California Department of Department of Transportation, Division of Environmental Analysis. December 15, 2008.
6. Caltrans Thin Lift Study: Effects of Asphalt Pavements on Wayside Noise. United States Department of Transportation, Volpe National Transportation Systems Center, Environmental Measurement and Modelling for California Department of Transportation, Division of Environmental Analysis. February 2009.
7. Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results. Lu, Q; Kohler, E and Harvey, J. University of California Pavement Research Center, UC Davis and UC Berkeley for California Department of Transportation, Division of Research and Innovation, Office of Roadway Research. 2009.
8. Drainage Asphalt and Noise Reduction over a Long Period. Bendtsen, Hans. Euro.noise 1998. Proceedings Euro.noise in Munich, volume 1. I-ince.
9. DRI-DWW Thin Layer Project - Final Report. Bendtsen, H. et al. Danish Road Directorate/Road Institute, DRI report 159, 2008 (www.roadinstitute.dk).
10. Noise emission from vehicles on the road network (in Danish: Støjudsendelse fra biler på vejnettet with summary in English). Andersen, Bent. Danish Transport Research Institute (now DTU Transport). Rapport 2, 2003 (www.transport.dtu),
11. Ageing of Porous Pavements. Acoustical effects. Kragh, Jørgen Danish Road Institute/Road Directorate. Technical Note 56, 2007. (www.roadinstitute.dk).