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Acoustic Aging of Asphalt Pavements: A Californian/Danish Comparison

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Abstract:

The level of noise generated by tire/pavement interaction of a pavement section changes over time. While the general consensus is that the noise level tends to increase as the pavement ages, more scientific investigation is necessary to better understand the process of acoustic aging of pavements.

For more than a decade, independent studies by Caltrans and the Danish Road Institute (DRI-DK) have included monitoring of tire/pavement noise levels on selected pavements. Using data sets collected as part of those studies, a comprehensive analysis was conducted in this study to characterize the acoustic aging properties of different types of asphalt pavements. Pavement types considered in the analysis include dense-graded asphalt concrete (DGAC), open-graded asphalt concrete (OGAC), thin open-graded asphalt layer, and porous asphalt concrete (PAC).

This report presents the results of the data analysis in terms of the relative changes of tire/pavement noise over time for the respective pavements. It also describes the development of an acoustic aging model for asphalt pavements. The model predicts the increase in noise level as a function of pavement age, traffic volume, and pavement type, primarily for highways with speeds over 50 mph. Further study is recommended to improve the prediction model and to integrate the noise model in a Pavement Management System.

Keywords: asphalt pavements, noise, tire/pavement interaction, acoustic aging

Proposals for implementation: No recommendations

Related documents:

- H. Bendtsen, H., Q. Lu, and E. Kohler. 2009. *Temperature Influence on Road Traffic Noise: Californian OBSI Measurement Study*. Reprint report: UCPRC-RP-2009-02
- Bendtsen, H. 2009. *Highway Noise Abatement: Planning Tools and Danish Examples.* Reprint report: UCPRC-RP-2010-03
- Bendtsen, H. 2009. *Noise Barrier Design: Danish and Some European Examples.* Reprint report: UCPRC-RP-2010-04
- Q. Lu, E. Kohler, J. T. Harvey, and A. Ongel. 2009. *Investigation of Noise and Durability Performance Trends for Asphaltic Pavement Surface Types: Three-Year Results.* Research report: UCPRC-RR-2009-01

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Acoustic aging of asphalt pavements

A Californian / Danish comparison

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Report 171
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Executive summary

The purpose of this project 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 noise measurement series on asphalt pavements carried out over long time. The main focus is on asphalt concrete pavements applied on highways. Cement concrete pavements have not been included in this study.

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

This project 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 absolute 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 so important. The vehicle fleet of California and Denmark may differ, for example, with smaller passenger cars in Denmark. This might influence the comparison of absolute noise levels but will presumably be less important when comparing changes in noise emission over the years measured at the same site. Only changes in the noise levels happening over time are included in this document. Changes in 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. 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 (11 years), one pavement type.
2. 5 test sections with dense and open graded pavements on LA138 in the Mojave Desert, California (5 years).
3. Around 70 pavements in the UCPRC/Caltrans monitoring project (3 years and pavements in different age groups and of different mix types).
4. 3 single layer porous (PAC), one dense graded (DGAC) and one open graded (OGAC) pavement at “Viskinge”, Denmark (8 years).
5. 5 Thin Open graded (OGAC) and one dense (DGAC) pavement at M10 (“Solrød”) near Copenhagen, Denmark (5 years).

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

- DGAC Dense Graded Asphalt Concrete.
- OGAC Open Graded Asphalt Concrete.
- PAC Porous Asphalt Concrete.
- Thin Open Asphalt Layers.

The following conclusions for highways can be made 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 during 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 heavy vehicles. This was also seen in the European SILENCE study.
- The yearly noise increase is generally around 2 times higher for passenger cars than for heavy vehicles.

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 affect the changes on the noise properties of a pavement. One relates to the physical/chemical changes in the materials caused by weather elements and time, 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 determine the increase of noise.

The age reflects an accumulated effect of changing weather conditions like sun radiation, rain, ice, freeze/thaw, oxidation, 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. The noise increase has been analyzed for five different indicators:

1. ΔL_{Age}: The change of noise level per year (actual physical age of the pavement).
2. ΔL_{ADT}: The change of noise level per 1 million vehicles (all types) passing per lane.
3. ΔL_{Hvy}: The change in noise level per 100.000 heavy vehicles passing per lane.
4. $\Delta L_{Mix50/50}$: The change of noise level 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”. This is a 50/50 % combination of ΔL_{Age} and ΔL_{ADT}.
5. $\Delta L_{Mix25/75}$: The change of noise level 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”). This is a 25/75 % combination of ΔL_{Age} and ΔL_{ADT}.

The results showed that the ΔL_{ADT} and the ΔL_{Hvy} resulted in the same ranking of the pavements presumably because there was no big variation in the percentage of heavy vehicles in the roads included. By using $\Delta L_{Mix25/75}$ instead of $\Delta L_{Mix50/50}$ the porous pavements generally have a higher noise increase than the thin layers which is believed to be correct as the porous pavements have a tendency of clogging which is not seen on non-porous thin layers. The selection of $\Delta L_{Mix25/75}$ instead of $\Delta L_{Mix50/50}$ carries implicitly the assumption (which lies beyond the scope of this study) that traffic effects dominate over climatic/time aging effects. Therefore the following three indicators ΔL_{Age}, ΔL_{ADT} and $\Delta L_{Mix25/75}$ are considered to be the most relevant for the description of the development of noise emission. The results for these three indicators for the four pavement types can be seen for passenger cars in table below.

Table. The average noise level increase for passenger cars 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	0.58	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

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 increase for the porous pavements is almost twice the increase for the dense, thin, or open graded asphalt concrete pavements.

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. The Thin Open pavements follow next 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.

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 noise increases in the first years indicating that the pavement surface becomes denser ("post compaction", increased air pumping noise). After some years there is also an increase in the frequencies below 1600 Hz indicating that the pavement surface becomes rougher with an increase in the tire vibration noise.
- For the Open Graded Asphalt Concrete (OGAC), the tendencies for the different pavements included in the investigation are not very clear. For some of the pavements there is a tendency that the higher frequency noise increases in the first years indicating that the pavement surface becomes denser ("post compaction"), and after some years there is also an increase in the frequencies below 1600 Hz indicating that the pavement surface becomes rougher with an increase in the tire vibration noise. But for some of the pavements 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 tire vibration 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 also increases the higher frequency noise over 1000 Hz presumably because of increased generation of air pumping noise. As the porous pavements get older there is an increase in the low frequency noise (below 1600 Hz) indicating increased tire vibration noise caused by a rougher pavement surface structure.
- When heavy raveling occur the tire vibration generated low frequency noise (below 1600 Hz) increases for all pavement types.

A first attempt to develop a noise emission performance model for pavements on highways has been performed. Such a model can be used as a building stone if noise is to be integrated in a Pavement Management System. The results from this project indicate that it seems most relevant to develop such an aging model taking both the physical age of a pavement as well as the traffic load into consideration. The model has been developed using the $\Delta L_{mix25/75}$ indicator.

The model predicts the increase in noise level $\Delta L_{Aging}(A)$ that has to be added to the noise emission of highway pavements when they are new (not more than one year old) as a function of the age of the pavement, the traffic load, and the pavement type.
The model is the following:

$$\Delta L_{Aging}(A) = (0.25 \cdot \Delta L_{Age} \cdot A) + ((0.75 \cdot \Delta L_{ADT} \cdot ADT \cdot 365 \cdot A) / (10^6 \cdot N))$$

Where:

ΔL_{Age}	is defined as the age component of noise level increase [dB/year].
ΔL_{ADT}	is defined as the traffic component of noise level increase [dB/10^6 vehicle per lane].
A	is the physical age of the pavement in years.
ADT	= Average Daily Traffic (total of both directions).
N	= Number of lanes (total of both directions).

This model is primarily useful for highways with speeds over 80 km/h (50 mph). This is a first version of a pavement noise performance model that can be improved and refined as more knowledge is gained.

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

- The first version of a noise emission performance model for highway pavements has been developed and can be used in Pavement Management Systems as a building stone to integrate noise as an important parameter in such systems.
- The noise emission performance model can be improved and refined like for example by including analyses of pavements on urban roads with lower speed.
- There is a need for further research in order to give a better understanding on which changes in the pavement surface structure cause 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 increase as pavements get older.

- It is important whenever possible to follow the development of noise at existing experimental road pavement test sections from the time they are new until they are replaced.
- 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.

Sammenfatning

Formålet med dette projekt er at bidrage til den aktuelle internationale udvikling angående akustisk ældning af vejbelægninger ved at udføre en sammenlignende analyse af nogle californiske og danske resultater fra langvarige støjmålinger på asfaltbelægninger på hovedlandeveje. Betonbelægninger er ikke inkluderet i denne undersøgelse.

Et internationalt litteraturstudie er blevet gennemført. Dette viser, at støjniveauet generelt stiger som belægningen bliver ældre. Hvad angår drænasfalt (porøse belægninger med indbygget porevolumen på mere end 15 %), er det et kendt fænomen, at porerne i nogle tilfælde tilstoppes, og at dette øger støj fra luftpumpning. Men for andre tætte og åbne (men egentlig ikke porøse) belægninger findes der ikke meget viden om eventuelle ændringer i overfladestrukturen i perioden fra bitumenfilm er nedslidt og til belægningerne begynder at nedbrydes på grund af stentab, revnedannelser osv.

Dette projekt fokuserer på udviklingen af støjniveauet - de relative ændringer i støj i årenes løb - og ikke de faktiske støjniveauer. Formålet er at analysere og sammenligne tendenser i udviklingen af støj over tid. Derfor er det ikke så afgørende, om støjresultaterne er blevet målt ved hjælp af forskellige metoder eller af forskellige målehold/organisationer. Disse faktorer kan påvirke de faktiske støjniveauer og kan vanskeliggøre en direkte sammenligning, men når kun tendenser bliver sammenlignet er eventuelle forskelle i målemetoder ikke så vigtige.

Den gennemsnitlige alder og størrelse af køretøjerne i Californien og Danmark kan variere, for eksempel med mindre personbiler i Danmark. Dette kunne have indflydelse på sammenligningen af de faktiske støjniveauer, men vil formentlig være mindre vigtigt, når man sammenligner udviklingen i støjemissionen over årene målt på samme strækning. Kun ændringer i støjniveauet over tid er medtaget i dette dokument. Andre faktorer som er relevante for beskrivelsen af udviklingen, som den fysiske struktur af vejbelægningen såsom tekstur, porøsitet, visuelle tegn på slitage etc. er ikke blevet taget i betragtning.

To veldokumenterede langtidsstøjmåleserier fra Californien og to fra Danmark er blevet analyseret. Resultaterne er allerede blevet dokumenteret detaljeret i særskilte nationale rapporter. Formålet med den aktuelle rapport er at foretage en sammenligning af tendenserne for akustisk ældning fundet i disse 4 projekter. University of California Pavement Research Center (UCPRC) afsluttede i 2009 den tredje års rapportering af årlige "On Board Sound Intensity" støjmålinger på 65 til 76 belægninger af forskellig type og alder i Californien. Nogle af resultaterne fra dette projekt er også inkluderet.

De to californiske måleserier og UCPRC undersøgelsen er alle udført for California Department of Transportation (Caltrans) og de to danske måleserier er blevet udført for det danske Vejdirektorat. Følgende fem måleserier er medtaget:

1. Åben asfaltbeton på I 80 nær Davis, Californien (11 år), 1 belægning.
2. 5 prøvestrækninger med tæt og åben asfaltbeton på LA138 i Mojave ørkenen, Californien (5 år).
3. 65 til 76 belægninger i UCPRC/Caltrans moniteringsprojekt (3 år og belægninger af forskellig alder og forskellige typer).
4. 3 belægninger med et lag drænasfalt samt en tæt og en åben asfaltbeton belægning i "Viskinge", Danmark (8 år).
5. 5 tynde åbne belægninger og en tæt asfaltbeton belægning på M10 ("Solrød") nær København, Danmark (5 år).

Belægningerne medtaget i dette projekt blev grupperet i følgende 4 hovedgrupper:

- Tæt asfalt beton.
- Åben asfalt beton.
- Drænasfalt.
- Tynde åbne belægninger.

Følgende konklusioner for hovedlandeveje kan drages på baggrund af denne undersøgelse på akustisk ældning af asfaltbelægninger:

- Støjniveauet på asfaltbelægninger stiger normalt med tiden.
- Støjniveauet stiger kontinuerligt og inden betydelig belægningsnedbrydning med stentab og revner osv. begynder.
- Der er undtagelser, hvor støjniveauet er reduceret i løbet af det første år af en porøs belægnings levetid.
- En lineær regression giver en god beskrivelse af forholdet mellem belægningsalderen og støj, både for personbiler og flereakslede køretøjer. Dette blev også fundet i den europæiske SILENCE undersøgelse.
- Den årlige støjforøgelse er generelt ca. 2 gange højere for personbiler end for tunge køretøjer.

Forskellige parametre har været brugt til at beskrive støjforøgelsen. Stigningen i støjniveauet er ofte udtrykt som dB/år. To vigtige faktorer påvirker ændringer af støjegenskaberne af en belægning. Den ene faktor drejer sig om de fysiske/kemiske ændringer i materialet, forårsaget af vejrets påvirkning, og den anden har at gøre med slitage forårsaget af trafik. Det kan hævdes, at den kombinerede effekt af belægningens fysiske alder samt slid fra trafik er afgørende for støjforøgelsen.

Alder afspejler en akkumuleret effekt af ændringer i vejrforholdene, som solstråling, regn, is, frost/tø osv. For at forsøge at definere en indikator, der kombinerer disse to meget forskellige faktorer, alder og trafikbelastning er to kunstige indikatorer kaldet "blandet indikator" ($\Delta L_{Mix50/50}$ og $\Delta L_{Mix25/75}$) er blevet defineret. Støjforøgelsen er i alt blevet analyseret for fem forskellige indikatorer:

1. ΔL_{Age}: Ændring af støj pr. år (faktiske fysiske alder af belægningen).
2. ΔL_{ADT}: Ændring af støj per 1 million køretøjer (alle typer) som passerer pr vognbane.
3. ΔL_{Hvy}: Ændring i støj per 100.000 tunge køretøjer som passerer pr vognbane.
4. $\Delta L_{Mix50/50}$: En kunstig indikator for ændring af støj beskrevet som en kombination af den faktiske fysiske alder og trafikbelastningen, hvor alder tæller for 50% og trafikbelastningen tæller for 50%. Kaldes "blandet indikator 50/50".
5. $\Delta L_{Mix25/75}$: En kunstig indikator for ændring af støj beskrevet som en kombination af den faktiske fysiske alder og trafikbelastningen, hvor alder tæller for 25% og trafikbelastningen tæller for 75%. Kaldes "blandet indikator 25/75".

Undersøgelserne viste, at ΔL_{ADT} og ΔL_{Hvy} resulterede i den samme rangordning af belægningerne, formentlig fordi der ikke var nogen stor variation i andelen af tunge køretøjer på de inkluderede veje. Ved at bruge $\Delta L_{Mix25/75}$ i stedet for $\Delta L_{Mix50/50}$ får drænasfalt belægningerne generelt en højere støjstigning end de tynde åbne belægninger; dette vurderes at være korrekt, da dræmnasfalt har en tendens til tilstopning, som ikke er set på ikke-porøse tynde belægninger. Ved at vælge $\Delta L_{Mix25/75}$ i stedet for $\Delta L_{Mix50/50}$ indgår der en antagelse om at trafikkens indvirkninger dominerer over klimatiske ældningsvirkninger. De følgende tre indikatorer ΔL_{Age}, ΔL_{ADT} og $\Delta L_{Mix25/75}$ anses for at være de mest relevante til beskrivelse af udviklingen af støjemission. Resultaterne for disse tre indikatorer for de fire belægningstyper kan ses i nedenstående tabel (for personbiler).

Tabel. Forøgelsen af gennemsnitsstøj for personbiler for 4 typer belægninger dom tre indikatorer ΔL_{Age}, ΔL_{ADT} og $\Delta L_{Mix25/75}$.

Belægningstype	**ΔL_{Age} [dB/år]**	**ΔL_{ADT} [dB/1 mio. køretøjer]**	**$\Delta L_{Mix25/75}$ [dB/mix]**
Gennemsnit af alle belægninger	0,58	0.28	0.32
Tæt asfaltbeton	0.40	0.21	0.26
Åben asfalt beton	0.41	0.26	0.30
Tynde åbne belægninger	0.84	0.24	0.39
Drænasfalt	0.53	0.42	0.45

Den gennemsnitlige støjstigning pr. år for personbiler (ΔL_{Age}) er 0,58 dB/år. Tæt asfaltbeton har den laveste stigning med 0,40 dB/år efterfulgt af åben asfaltbeton med 0,41 dB/år. De to belægningstyper med den højeste stigning er drænasfalt og tynde åbne belægninger med henholdsvis 0,53 og 0,84 dB/år.

Når der i stedet for ΔL_{Age} tages trafikmængden (ΔL_{ADT}) i betragtning som en indikator for støjstigninger, rangordningen af belægningstyperne betydeligt.

Den gennemsnitlige $\Delta L_{Mix25/75}$ for personbiler er 0,32 dB. $\Delta L_{Mix25/75}$ indikatoren rangordner de fire belægningstyper på følgende måde. Tæt asfaltbeton har den laveste stigning på 0,26 dB, efterfulgt af åben asfaltbeton med 0,30 dB. Dernæst kommer tynde åbne belægninger med en forøgelse på 0,39 dB. Drænasfalt har den højeste stigning på 0,45 dB når $\Delta L_{Mix25/75}$ indikatoren anvendes.

Spektrale analyser af støjen er blevet udført. Følgende, meget generelle, tendenser er observeret for de fire belægningstyper:

- For tæt asfaltbeton stiger støjniveauet i de første år pga. øget luftpumpningen som indikerer, at vejbelægningen bliver tættere (efterkomprimering). Efter nogle år er der også en stigning i de lavere frekvenser under 1600 Hz der indikerer, at vejbelægningen bliver mere ujævn med en stigning i dækvibrationsstøj.
- For de tynde åbne belægninger, stiger støjen samtidig både på de lavere og højere frekvenser. Dette indikerer både, at belægningen bliver mere ujævne med en stigning i dækvibrationsstøj og at belægningens overflade bliver tættere (efterkomprimering), hvilket forårsager en øget højfrekvent støj fra luftpumpning.
- For drænasfalt bliver absorptionen af motorstøj på frekvenser mellem 400 og 1000 Hz reduceret betydeligt i de første to år. I det andet år, begynder tilstopningen, og dette øger støj i de højere frekvenser over 1000 Hz på grund af øget luftpumpestøj. Efterhånden som drænasfalt bliver ældre er der en stigning i den lavfrekvente støj ved mindre end 1.600 Hz som resultat af en mere ujævn belægningens overflade.
- Når der forekommer stentab ses stigninger i den lavfrekvente dækvibrationsstøj under 1.600 Hz.

Et første forsøg på at udvikle en model for at beskrive støjens udvikling over tid for belægninger på hovedlandeveje er blevet udført. En sådan model kan bruges som en byggesten, såfremt støj skal integreres i et Pavement Management System. Resultaterne fra dette projekt viser, at det ser ud at være mest relevant at udvikle sådan en ældningsmodel ved at tage både den fysiske alder af en belægning samt trafikmængde i betragtning. Modellen er blevet udviklet ved hjælp af $\Delta L_{mix25/75}$ indikatoren.

Modellen beregner stigningen i støj $\Delta L_{aging}(A)$, der skal adderes til støjen, når belægninger er nye (ikke mere end et år gamle) som en funktion af alderen på belægningen og trafikmængden på af en given vej såvel som en funktion af belægningstypen. Modellen er således:

$$\Delta L_{Aging}(A) = (0.25 \text{ x } \Delta L_{Age} \text{ x } A) + ((0.75 \text{ x } \Delta L_{ADT} \text{ x ADT x 365 x } A) / (10^6 \text{ x } N))$$

Hvor:

ΔL_{Age}	er defineret som alderskomponent af støjstigningen [dB].
ΔL_{ADT}	er defineret som trafikkomponent af støjstigning [dB].
A	er den fysiske alder af belægningen i antal år.
ADT	= gennemsnitlig daglig trafik (total i begge retninger).
N	= antal vognbaner (total i begge retninger).

Denne model er primært udviklet for hovedveje med hastigheder over 80 km/t. Dette er en første version af en model, der vil kunne videreudvikles og forbedres.

På baggrund af dette projekt, kan følgende anbefalinger fremhæves:

- Den første version af en støjemissionsmodel for hovedlandsvejsbelægninger, som er udviklet i projektet, kan anvendes i Pavement Management Systemer som en byggesten, der gør det muligt at integrere støj som en vigtig parameter i sådanne systemer.
- Støjemissionsmodellen kan forbedres, for eksempel ved at inddrage analyser af belægninger på byveje med lavere hastigheder mv.
- Der er behov for yderligere forskning med henblik på at give en bedre forståelse af hvilke ændringer i belægningens overfladestruktur, der forårsager støjstigningerne. Grundige analyser af belægningsstrukturen og støjspektre etc. kan være emner at tage op!
- Flere langtidsmålingsserier er nødvendige for at få en endnu bedre forståelse for hvorfor støjen stiger efterhånden som belægninger bliver ældre.
- Det er derfor vigtigt, hvis det er muligt, at følge eksisterende teststrækninger over så lang tid som muligt for at få mere information om akustisk ældning.
- Det er nødvendigt at kombinere resultaterne af støjmålinger med resultater fra målinger af andre belægningsegenskaber som overfladetekstur, indbygget hulrum, permeabilitet, akustisk absorption osv.

Preface

It is the experience of noise technicians that traffic noise emission of a given asphalt pavement changes over time. Normally the noise level tends to increase over the years. Knowledge on acoustical aging is important for road administrations in different ways:

- When developing policies and strategies for noise abatement it is important to know how noise-reducing pavements as well as standard pavements perform over time.
- Acoustical aging is important information in order to achieve good accuracy when noise is predicted with methods like the American TNM method, 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 project is to contribute to the ongoing international development in the field of acoustical aging by performing a comprehensive analysis of some existing Californian and Danish results from long-time noise measurement series on asphalt pavements.

The project is carried out under the framework of the research technical agreement entitled “Supplementary Studies for the Caltrans Quieter Pavement Research Program” between California Department of Transportation (Caltrans) and the University of California Pavement Research Center (UCPRC) as a part of the task: “Policy documents: guidelines for Caltrans policy”. The Danish Road Institute (DRI-DK) is subcontracted by UCPRC to work on the project. The work is carried out by a project group with the following members:

- Hans Bendtsen, Danish Road Institute/Road Directorate (DRI-DK) working as a guest researcher at UCPRC in 2008 and 2009.
- Qing Lu, University of California Pavement Research Center.
- Erwin Kohler, Dynatest Consulting Inc.

This report includes selected results from three Caltrans and two Danish projects. From California the first site is the highway I-80 project near Davis, where noise measurements and analyses has been carried out by Illingworth & Rodkin, Inc. Another site is the LA138 project where noise measurements and analyses have been carried out by Volpe Center Acoustics Facility. The third site is actually a large set of sections throughout the state of California that correspond to the UCPRC project on field evaluation of tire/pavement noise, being performed by the Partnered Pavement Research Programs (PPRC) Contract as Strategic Plan Element 4.19.

Results from two Danish projects are included. The “Viskinge” project in which noise measurements and analyses have been carried out by Delta Acoustics and the M10 project where DRI-DK has carried out noise measurements and analyses.

The authors would like to thank everybody involved in these projects. Without their substantial work it would not have been possible to accomplish this aging study. Qing Lu and Erwin Kohler were responsible for data analyses of OBSI measurements from UCPRC collected in the field by Mark Hannum from UCPRC. Katrine Handberg from the DRI-DK library carried out a literature search. The report is written by Hans Bendtsen, DRI-DK. Jørgen Kragh DRI-DK has taken part in the evaluation and discussion of the results. Bent Andersen DRI-DK has performed Quality Assessment of the report.

Forord

Erfaringen blandt støjteknikere er, at trafikstøj fra en asfaltbelægning ændrer sig med tiden. Almindeligvis øges støjniveauet i løbet af en årrække. Kendskab til akustisk ældning er vigtig for vejadministrationerne på forskellige måder:

- Når der udvikles politikker og strategier for støjreduktion, er det vigtigt at vide hvorledes støjdæmpningen på støjreducerende belægninger såvel som på “normale” belægninger opfører sig i et givent tidsforløb.
- Akustisk ældning er en vigtig information for at opnå høj nøjagtighed, når støj beregnes med metoder som den amerikanske TNM metode eller den nordiske NORD2000 metode eller lign.
- Støjmodeller for vejbelægninger er nødvendige, hvis støj skal indgå som en aktiv parameter i Pavement Management Systemer.

Formålet med dette projekt er at bidrage med den løbende internationale udvikling angående akustisk ældning ved at gennemføre en omfattende analyse af nogle californiske og danske resultater fra støjmålingsserier på asfaltbelægninger.

Projektet udføres inden for rammerne af den forskningstekniske aftale med titlen "Supplerende Undersøgelser for Caltrans ”Quieter Pavement Research Program"” mellem California Department of Transportation (Caltrans) og UCPRC (University of California Pavement Research Center) som en del af opgaven: " Policy documents: guidelines for Caltrans policy”. En del af dette arbejde er kontraheret til Vejdirektoratet/Vejteknisk Institut i Danmark

Arbejdet er udført af en projektgruppe bestående af følgende personer:

- Hans Bendtsen, Vejteknisk Institut/Vejdirektoratet der arbejdede som gæsteforsker på UCPRC i 2008 og 2009.
- Qing Lu, University of California Pavement Research Center.
- Erwin Kohler, Dynatest Consulting Inc.

Denne rapport indeholder udvalgte resultater fra Caltrans og fra danske projekter. Fra Californien medtages I-80 projektet, hvor støjmålinger and analyser er udført af Illingworth & Rodkin, Inc; LA138 projektet, hvor støjmålinger og analyser er udført af Volpe Center Acoustics Facility og UCPRC projektet på evaluering af dæk/belægningsstøj, the Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.19.

Resultater fra to danske projekter er medtaget. “Viskinge” projektet, hvor støjmålinger og analyse er udført af Delta Acoustics og M10 projektet, hvor Vejteknisk Institut/ Vejdirektoratet har udført målinger og analyser. Forfatterne vil gerne takke alle som har været involveret i disse projekter. Uden deres store indsats ville det ikke have været muligt at gennemføre dette ældningsstudie.

Qing Lu og Erwin Kohler var ansvarlige for data analysen af OBSI målingerne fra UCPRC som blev udført af Mark Hannum fra UCPRC. Katrine Handberg fra Vejteknisk Institut, Danmark har gennemført en litteratur søgning. Rapporten er skrevet af Hans Bendtsen, Vejteknisk Institut. Jørgen Kragh Vejteknisk Institut har deltaget i evalueringen og diskussionen af resultaterne. Bent Andersen Vejteknisk Institut har kvalitetssikret rapporten.

1. Introduction and existing knowledge

It is known from international literature [1] that noise emission from road traffic changes over time as the road pavements age and are exposed to traffic and weather. Normally an increase in noise level is seen. This report focuses on the change in noise emission caused by changes in the pavement surface properties. Noise emission from a given road can also change because of increase in traffic volume or percentage of heavy vehicles as well as changes in average driving speed or driving pattern. The effect on noise of these traffic related changes is not the objective of this study which focuses on pavements and the generation of tire-pavement noise.

There is a lack of well documented knowledge available today that can describe the development of tire-pavement noise emission as a pavement gets older [1]. The main purpose of this project is to contribute to the ongoing international development in the field of acoustical aging of road surfaces. This is done in two ways:

1. By carrying out an international literature survey.
2. By performing a top down comprehensive analysis of existing Californian and Danish results from long-time noise measurement series.

The results can be relevant for work on integrating noise as an active component in Pavement Management Systems (PM Systems) that are often used by road authorities as a tool for planning the ongoing process of road and pavement maintenance and renewal. Parameters like skid resistance etc are normally included in PM Systems in order to optimize the traffic safety component, but noise might also be included in the future [10]. An important part of integrating noise in PM Systems is to have performance models that can predict future noise emission from pavements as time goes by. The results of this project will be relevant for developing such noise performance models for road pavements.

The main focus of this project is asphalt concrete pavements. Cement concrete pavements have not been included in this study.

The unit “dB” is used in this report and it is considered in this document to be equal to what is often denoted “dB(A)” or “dBA”.

1.1 Pavement properties and noise generation

In relation to pavement performance characteristics such as noise, skid resistance, rolling resistance etc., the surface of a road pavement is often described by the following three texture components [1] (see Figure 1.1):

1. The microstructure is the deviation of a road surface from a completely plane surface with characteristic dimensions along the surface less than 0.5 mm (wavelengths less than 0.5 mm). The microtexture of a pavement is generally created by the surface structure (sharpness and harshness) of the individual aggregates of the pavement surface. The microtexture is important for the skid resistance of a pavement, but it is not considered to have an important influence on the tire-noise generation.

2. The macrotexture is the deviation of a road surface from a completely plane surface with characteristic dimensions along the surface between 0.5 mm and 50 mm (wavelengths between 0.5 mm and 50 mm). The macrotexture is obtained by the size and proportioning of aggregates and mortar, and by the compaction of the pavement. The macrotexture is very important for the tire-pavement noise generation.

3. The megatexture is the deviation of a road surface from a completely plane surface with characteristic dimensions along the surface between 50 mm and 500 mm (wavelengths between 50 mm and 500 mm). The megatexture can be created by potholes, other larger discontinuities of the pavement surface, or unevenness of the bottom layer. Megatexture is important for rolling resistance, driving comfort etc., and can have some influence on the tire-pavement noise generation. Surface roughness with larger wavelengths (>500 mm) is normally called unevenness.

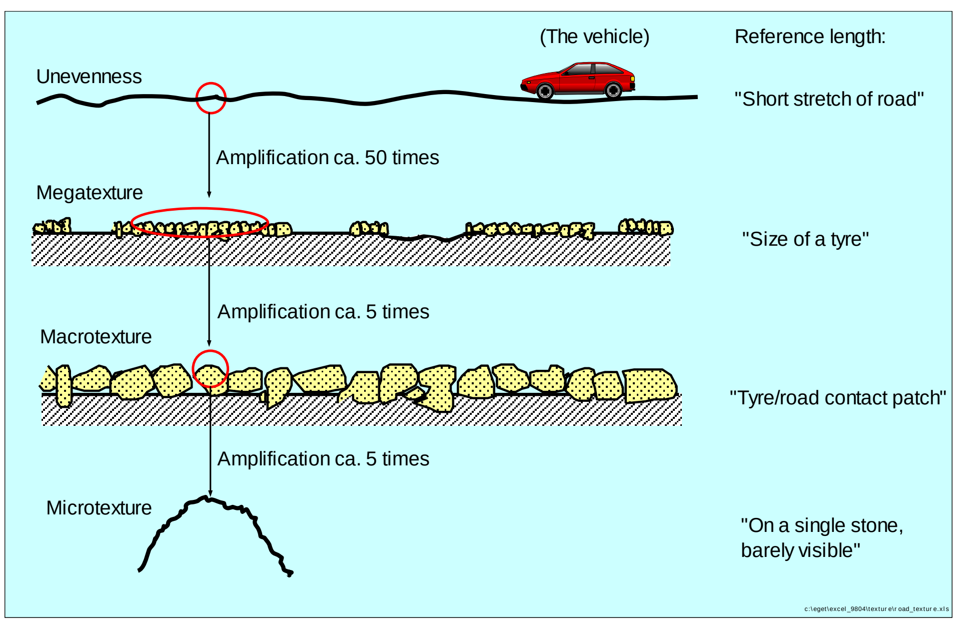


Figure 1.1. Simplified examples of microtexture, macrotexture and megatexture [1] (used with permission from Ulf Sandberg, VTI).

The generation of noise when the tires are rolling on a road surface is mainly determined by the following different mechanisms [1] even though other mechanisms might also play a minor role:

- Vibrations in the tires: The vibrations are generated by the contact between the surface of the pavement and the rubber blocks of the tread pattern of the tire. Tire vibrations generate noise in the frequencies from 500 to 1500 Hz. Macrotexture is important for this noise. The noise level increases when the road surface gets rougher. Therefore, an increase in the maximum aggregate size generally leads to an increase in the noise level.
- The air pumping effect: When the rubber blocks on the tread pattern of the tire hit the road surface, air is pressed out through the cavities between the rubber blocks and the road surface. When the rubber blocks leave the road surface air is sucked back into the cavities. This air pumping generates noise at frequencies over 1000 Hz. The macrotexture is important for the generation of this noise. If the road surface is open or porous, the air will instead be pumped down into the pavement structure and the noise level will be reduced.
- The horn effect: The curved belt of the tires and the road surface act as an acoustical horn which amplifies the road noise generated around the contact point between the tire and the road surface. This effect is highly directional and most important for high frequencies. If the road surface is porous (and therefore sound absorbing), this amplification effect will be reduced.
- Absorption during propagation: The engine and road-tire noise are propagated from the vehicle to the receiver. 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.
- The effect of stiffness: The stiffness of the pavement is important for the noise generated by the contact between the surface of the pavement and the rubber blocks of the tread pattern of the tire. If the pavement is much less stiff, less noise will be generated.

1.2 The "Tyre/Road Noise Reference Book"

The "Tyre/Road Noise Reference Book" by Sandberg and Ejsmont from 2002 [1] includes an international status on current knowledge at that time on the influence of pavement age etc. on tire/road noise generation. According to this book, a road surface changes its characteristics influencing noise over its lifetime. For some surface types the influence is small and for others it can be large. It is summarized that the age and wear influence on noise emission are caused by the following phenomena [1]:

- *"Mega- and macrotexture are changed, as particles and other materials are worn away.*
- *Mega- and macrotexture, as well as stiffness, are changed due to the pavement structure being compacted by traffic.*
- *Microtexture is changed, mainly by a polishing effect of many tires passing over the surface (studs on tires may counteract this effectively).*

- *The chemical effects of the weather, maybe assisted by road salt, creates a weathering and crumbling of the surface (loss of fine material), affecting both microtexture and macrotexture. Rain may also play a role in changing the microstructure.*
- *Cracks may be created.*
- *If the surface is porous, its pores will become clogged by accumulated dirt."*

The Reference Book concludes that for smooth and medium textured dense asphalt concrete (DGAC) and SMA, the noise levels normally increase 1 to 2 dB the first 1 to 2 years of the pavement's lifetime and then stabilizes until raveling and cracking occur at the end of the lifetime of the pavement. The increase generally occurs at the higher frequencies indicating an increase in the air pumping noise. According to [1], although macrotexture will change over time there are cases where this change cannot explain the observed increase in noise. The reason for this is (according to [1]) still unknown and the matter requires further research.

1.3 Literature survey

The library at the Danish Road Institute/Road Directorate (DRI-DK) has carried out an international literature search for references to studies on the aging effects of asphalt road pavement in relation to noise. The general result is that not very many studies have been carried out worldwide with this specific focus. As a part of the European EU funded project SILENCE [4], a large comprehensive inventory of currently available European results was performed [5]. The main results from this European study are presented in the following pages together with the results of some recent studies carried out in Arizona [20] and Washington State [21 to 24] in the US as well as in Norway [26].

1.3.1 The SILENCE inventory

The SILENCE project included a task to provide models for the effect of pavement aging on the noise reducing effect of road pavements [5]. This task was carried out by DRI-DK. Existing historical measurement data on long-time noise performance of pavements was collected from Belgium, Denmark, France, Germany, the Netherlands, Poland, Sweden, and United Kingdom. A series of data from the noise study at the UCPRC as a part of Caltrans Quiet Pavement Research (QPR) program in California was also included [11].

The scatter of all these results was quite large. The results were analyzed with the main focus of finding slopes or trends for the increase of noise level every year for different pavement types. No indication could be found that any model (polynomial, logarithmic or exponential) would yield better fit to the data than a simple linear relation between vehicle noise level and pavement age. This may be due to large scatter in measurement results. Therefore a simple linear model was selected. This study did not include spectral analyses for the noise data in relation to aging.

In Table 1.1, a summary is given of the average slopes to be expected for the linear time history of vehicle noise levels. For both light and heavy vehicles, the slope to be expected at dense asphalt pavements is in the order of 0.1 dB per year of pavement service time. This applies to high speed as well as low speed roads. For porous or open graded asphalt pavements the time history slope for light vehicles can be expected to be in the order of 0.4 dB per year at high speed roads and 0.9 dB per year at city streets with low traffic speed. Heavy vehicle noise levels can be expected to increase with 0.2 dB per year at high speed roads with open/porous pavements. Data was not available for heavy vehicles at low speed porous/open pavements.

Table 1.1. Overall time history slopes, dB per year of pavement service time [5].

Surface type	**Light vehicles**		**Heavy vehicles**	
	High speed [dB/Year]	**Low speed [dB/Year]**	**High speed [dB/Year]**	**Low Speed [dB/Year]**
Dense asphalt (DGAC)	0.1	0.1	0.1	0.1
Porous / Open graded asphalt (PAC/OGAC)	0.4	0.9	0.2	-

1.3.2 US studies

Figure 1.2. Asphalt-Rubber Friction Course (ARFC) has been used as a tool to reduce highway noise in Arizona.

Figure 1.3. Results of CPX noise measurements in Arizona on Asphalt-Rubber Friction Course at different ages [20] performed at 96 km/h (60 mph) [20].

The Arizona Department of Transportation (ADOT) has used Asphalt-Rubber Friction Course (ARFC) as a tool to reduce highway noise for a longer period. In 2002, ADOT conducted a survey where noise was measured at 20 ARFC pavements [20] with ages ranging from 3 to 12 years using the CPX noise measurement method [2]. This measurement series did not follow the same pavement over the years. The main result was that the noise increased 0.55 dB/year as can be seen in Figure 1.3.

Figure 1.4. Interstate I-5 in Washington State where noise reducing pavements were constructed in June/July 2006 with a close up photo of a pavement after being exposed to studded tires (Photo Washington State Department of Transportation).

The Department of Transportation in Washington State is carrying out a project on evaluating noise reducing pavements [23]. On Interstate I-5 three different pavement types have been constructed in June/July 2006. The pavements were a DGAC and two open graded noise reducing pavements, one polymer modified and the other rubber modified. The maximum aggregate size was 12.5 mm for the DGAC and 9.5 mm for the two open graded pavements [24]. On Board Sound Intensity (OBSI) [14] noise measurements with the SRTT tire have been performed nearly every month on these pavements since they were one month old. Studded tires are frequently used in the winter period on the test road.

The results of the OBSI noise measurements can be seen in Figure 1.5. There is a significant increase in noise level especially for the open graded polymer and rubberized pavements. The increase mainly happens in the winter month where studded tires are used. The average noise increase over the two and a half year period is 1.8 dB/year for the DGAC and 2.4 and 3.6 dB/year for the two open graded pavements; the highest increase for the rubberized pavement.

The OBSI noise measurements are not corrected for the influence of temperature on the noise levels. A recent UCPRC and DRI-DK study [27] has resulted in a suggestion of an air temperature correction factor for the SRTT tire of -0.027 dB/°C. This means that the noise level increases as the air (and the tires and pavement) gets colder. But the increase is not at all so large that it can explain the increase seen in the winter periods in these measurements. But there is a tendency that the noise level decreases a little in the summer periods. This could to some extent be caused by higher temperature in the summer.

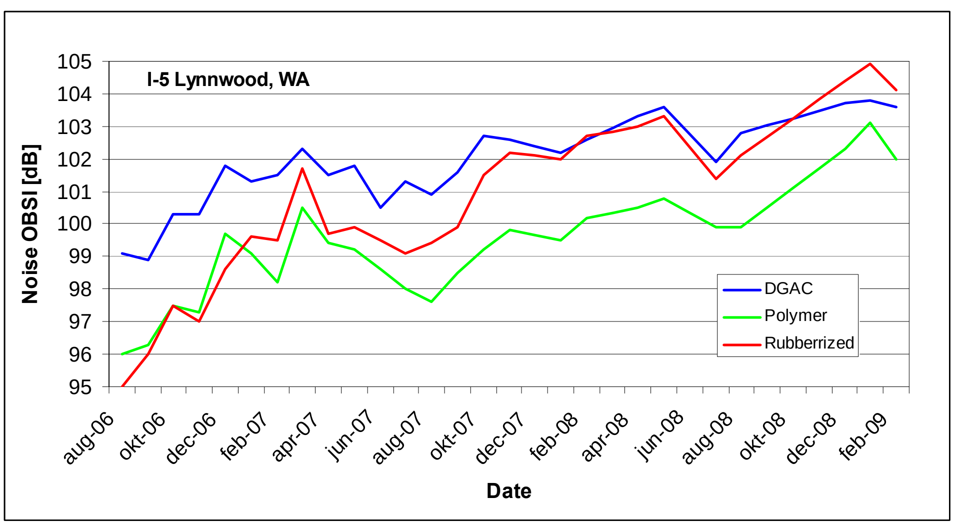


Figure 1.5. Results of OBSI CPX noise measurements on test pavements on interstate I-5 in Washington State using SRTT tire [21].

The Colorado Department of Transportation has started a study of tire-pavement noise on different pavements. The results of the first year of OBSI measurements performed in 2006 are reported in [25]. Time series are not yet available.

1.3.3 A Norwegian study

A research and development project called “Environmentally friendly pavements” has been initiated by the Norwegian Public Roads Administration in 2005. As a part of this project, the Norwegian research institution SINTEF has performed yearly CPX noise measurements on 37 asphalt pavements [26] in the period from 2005 to 2008. The measurements were carried out at 50 km/h (31 mph) and/or 80 km/h (50 mph). The CPX “A” tire was used for these measurements [2]. In Norway, studded tires are commonly used in the long winter season causing wear and tear of the pavements.

Some results from measurements performed over a four-year period are shown in Figures 1.7 and 1.8. The main results show that the noise level on a newly laid pavement increased 2-4 dB after the first winter with exposure to studded tires. There is a trend that the noise level increase was higher for pavements with a small maximum aggregate size. In the following years, the increase was around 0.5 to 1.0 dB/year. The two porous pavements are exceptions with yearly increase of 1.6 and 2.0 dB.

Figure 1.6. Road included in the CPX measurements carried out as a part of the Norwegian “Environmentally friendly pavements” (Photo Truls Berge, SINTEF ICT Acoustics, Norway).

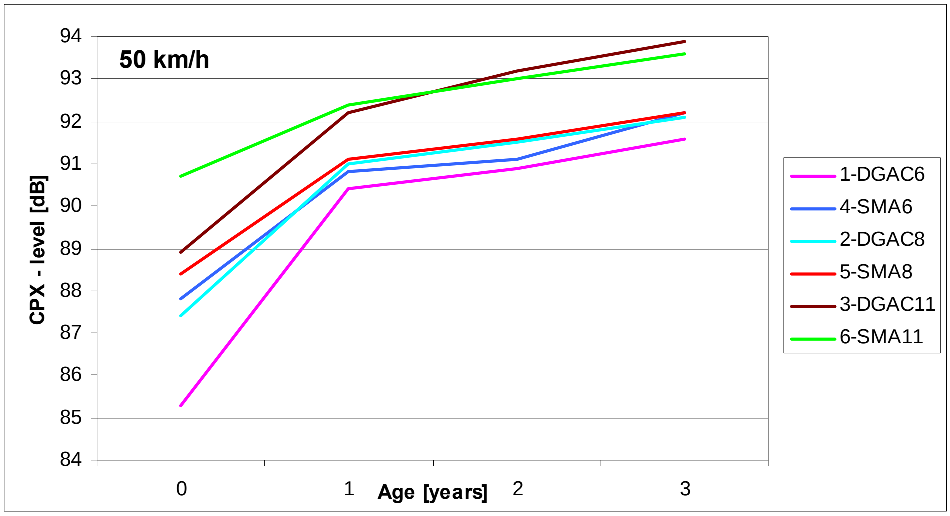


Figure 1.7. CPX measurements performed at 50 km/h (31 mph) (using the CPX "A" tire) on different pavement types in Norway [26].

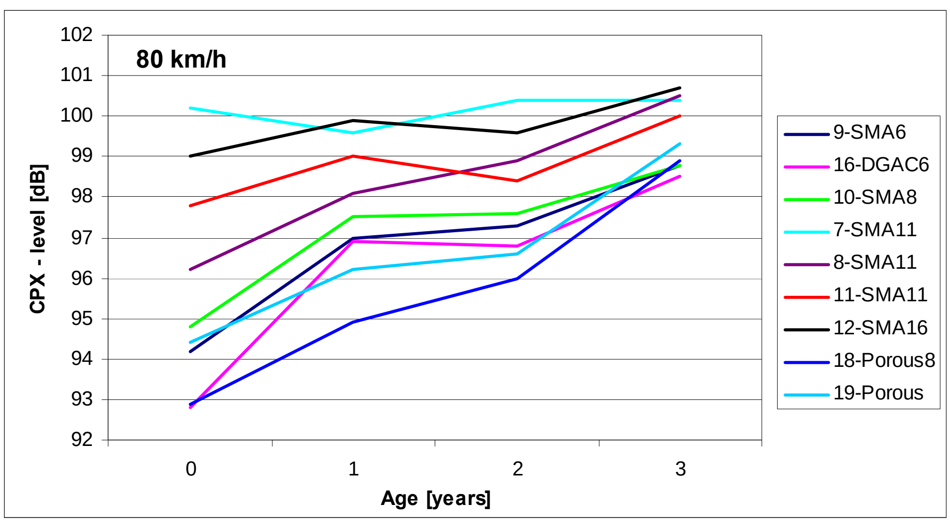


Figure 1.8. CPX measurements performed at 80 km/h (50 mph) (using the CPX "A" tire) on different pavement types in Norway [26].

1.4 Important factors affecting noise increase

1.4.1 Pavement aging and distress

The structure and condition of the surface of a given asphalt pavement changes over time! When the pavement is newly laid, a black bitumen film covers the aggregate at the surface (see Figure 1.9). This bitumen film is worn off by the traffic (the tires) driving on the road within a shorter period of up to some months (see Figure 1.10). The effect on noise of this initial bitumen film is not clearly documented as most noise measurements are first conducted when this film has been worn off.

Figure 1.9. A one day old porous asphalt concrete (PAC) with a black bitumen film covering the aggregate prior to opening to traffic.

Figure 1.10. A three years old dense-graded asphalt concrete (DGAC) where the bitumen film has been worn off and where no significant signs of wear and tear and distress can be observed.

The mix design (aggregate gradation, binder type and content, use of additives etc.) as well as the aging of the binder are important for the structural performance of a pavement as time goes by. When asphalt pavements get older, significant signs of wear and tear as well as distress on the pavement surface can be observed like for example:

- Polishing of aggregate.
- Raveling where aggregates are lost creating small holes in the surface (see Figure 1.11).
- Cracks in the pavement (see Figure 1.11).
- Development of potholes where material is missing over a larger area (see Figure 1.12).
- Fatigue cracking (see Figure 1.12).
- Bleeding where bitumen covers parts of the surface (see Figure 1.13).

Besides polishing of aggregate that generally influences the microtexture of a pavement, these types of distress generally increase the macrotexture/roughness of the surface structure and will result in an increase in vibration generated noise depending on the severity of the distress. The impact on noise is very often rather localized; a few ten meters back and in front of the area with distress, the noise level is not affected [13]. On some occasions “bleeding” occurs. This might also lead to changes in the noise emission. The level of pavement distress is reflected in the overall pavement condition index that is established on the background of visual inspection. An overview of the main influence on pavement texture on the different types of distress can be seen in Table 1.2.

In the European SILENCE project [4], a series of CPX noise measurements were performed on asphalt pavements with different kinds of distress. An increase of 2 - 3 dB was measured with the CPX method at a speed of around 50 km/h (31 mph) on a 6 m long section with severe alligator cracking relative to a section of the same pavement with no distress [13].

Figure 1.11. Raveling, loss of aggregate (to the left) and cracking (to the right).

Figure 1.12. Pothole (to the left) and alligator cracking (to the right).

Figure 1.13. Bleeding where bitumen covers part of the pavement surface.

Table 1.2. Pavement distress types and their main influence on pavement texture.

Distress	Polishing of aggregate	Raveling	Cracks	Potholes	Alligator cracking	Bleeding
Microtexture	XX					XX
Macrotexture		XX	XX	X	XX	XX
Megatexture				XX	X	

1.4.2 Acoustical aging

The literature survey shows that the noise level generally increases as the pavement gets older. For porous pavement (built in air void more than 15 % or so) it is a known phenomenon that voids tends to clog and that this increases the noise generated from air pumping [12]. But for other dense and open graded (but not really porous) pavement types there is not much knowledge on which changes in the surface structure causes this increase in noise level in the period from when the bitumen film is worn off until the pavements begins to deteriorate with distresses like raveling, cracking etc.

An example of the development of the pavement texture over a long period of time can be seen in Figure 1.14 which shows the Mean Profile Depth (MPD) on a dense graded asphalt pavement (DGAC) with 8 mm maximum aggregate size over ten years. The pavement is located on an urban road in Copenhagen with an average daily traffic (ADT) of around 7000 vehicles (7 percent heavy) and a speed limit of 50 km/h (31 mph). The figure shows a remarkable decrease of the MPD when an old worn down dense asphalt concrete pavement with distress was replaced by a new DGAC. Over the years MPD gradually increase and after 8 years the MPD has nearly reached the level of the former old pavement. No significant signs of pavement distress have been observed over the years on the “new” DGAC pavement.

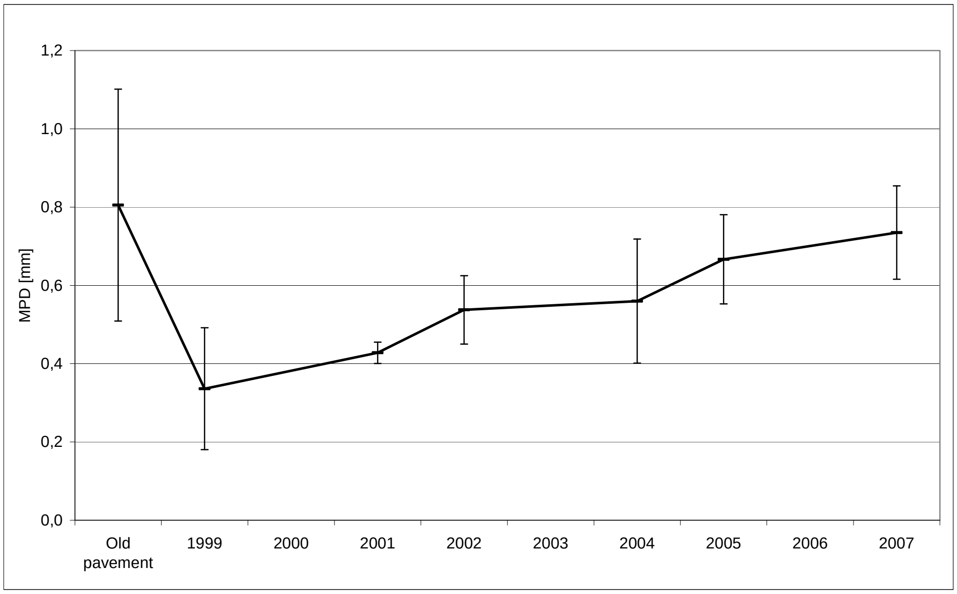


Figure 1.14. Development of MPD of a dense graded asphalt concrete (DGAC) in the Danish Øster Søgade experiment [12]. Bars show the standard deviation of the MPD measurements along the 100 m long road section.

The following are suggestions for factors that might influence the acoustical aging phenomena before significant pavement distress occurs:

- Extra "post" compaction because of traffic load.
- Aggregate is pressed further down in the mortar and the openness of the surface structure is reduced.
- Change in the orientation of the aggregate because of traffic load.
- Clogging where the open structure with communicating pores in the upper part of a porous pavement layer is more or less clogged.
- The average driving speed might have an influence on the clogging process.
- Ordinary pavement maintenance and cleaning such as sweeping etc.
- If utility works are carried out, patchwork pavement repair can change the surface structure.
- In areas with "white" winter periods, snow and ice removal procedures, salting, and plowing etc. might influence the surface structure.
- In areas where studded tires and/or snow chains are used this definitely has an effect on the surface structure creating rutting and raveling.
- Meteorological conditions like rain water, sun, snow, freeze-thaw, oxidation etc.
- Ultraviolet radiation from the sun.

On the background of the list of factors shown above which might influence the acoustic aging of a pavement, it can be discussed which indicator or indicators for aging are relevant to use. In previous investigations the pavement age has normally been used (see Section 1.3). Besides age the following indicators could be relevant:

- Accumulated traffic load on relevant driving lane (total vehicles/lane/year).
- Accumulated light vehicles on relevant driving lane (light vehicles/lane/year).
- Accumulated heavy vehicles on relevant driving lane (heavy vehicles/lane/year).
- Traffic speed and acceleration/deceleration (including curvature, gradients etc.).

Together these traffic load related indicators, the climate zone (effect of weather), the winter maintenance procedures and the use of studded tires and/or snow chains might define some basic parameters that influence the tire pavement noise emission over time.

In the current project, the indicators pavement age as well as the accumulated traffic on the driving lane will be taken into consideration in the analyses. The road sections included in the survey are all highways with a speed limit of 80 to 110 km/h (50 to 69 mph) and they are located in areas where studded tires and/or snow chains are not used (see Section 1.5). The sections in California are located in a subtropical climate zone with very little frost and long warm and sunny summers, while the Danish sections are located in a temperate coastland climate zone with many thaw/frost periods and colder and cloudier summer periods than in California.

1.5 Noise measurement methods

Some factors might "contaminate" long-time measurement series of noise emission from pavements. If wayside measurements including a large population of vehicles like the Statistical Pass-By method (SPB) [3] or L_{Aeq} measurements are used, the noise measured reflects the noise produced by the average vehicle fleet with the average tires used at the time and in the region where the measurements are performed.
The noise emission related to vehicles and especially tires might change over the years because of introduction of new types. The tire tread pattern, the rubber hardness, and the tire width etc. has an influence on this.

If "close to source" methods like the On Board Sound Intensity method [14] (OBSI) or the Close Proximity method (CPX) [2] are used, there will be no dependencies of the development of noise emission from vehicles or tires, since a standardized set of test tires are used. But over the years the specifications for the methods might be changed or new corrections applied and this might complicate comparison of results measured over long time periods. Different reference tires have also been used in US and in Europe.

This study will focus on wayside measurements because it turns out that the longest comparable time series measured in California and Denmark have been performed using these methods. The use of close by (OBSI and CPX) methods has been more common in the last 5 years in California and in Denmark. So in the future also results from long-time measurement series using these methods may become available.

This project focuses on the trend in noise levels measured in the same way – the relative changes of noise levels over the years – and not on the actual absolute noise levels. 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 absolute 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 fleet of California and Denmark may differ, for example with smaller passenger cars in Denmark. This might influence the comparison of absolute noise levels but will presumably be less important when comparing trends in noise emission over the years measured at the same site.

1.6 Layout of study

As already mentioned, this study focuses on the acoustical aging of asphalt concrete pavements on highways. 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. When possible, noise emission from light and heavy vehicles is analyzed separately. Frequency spectra will be used for detailed analyses of the changes in noise emission.

This project focuses on the development of noise levels with time. It is outside the scope of the project to include parameters describing the development of the pavement surface structure with measurements like:

- Surface profiles
- Mean Profile Depth
- Built in air-void content
- Permeability
- Acoustical absorption
- Etc.

Examples of such comprehensive measurements and analyses are the Danish "Øster Søgade" experiment on two-layer porous pavements for urban roads [12] and the UCPRC experiment in 2006 on approximately 70 pavement sections that span over various climate regions, pavement age, traffic conditions and pavement types [17].

Two well documented long-time noise measurement series from California [15 and 16] and two from Denmark [18 and 19] have been selected for this project. 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. UCPRC has finalized the third year report on yearly OBSI measurements on 65 to 76 pavements at different ages in California [17]. Some results of trends of noise emission and spectras from this project are also included in this current report. The two Californian measurement series and the UCPRC study have all been carried out for Caltrans and the two Danish measurement series have been carried out for the Danish Road Directorate. The following measurement series are included:

- **California:**
  1. Open graded pavement (OGAC) on I-80 near Davis (10 years) [15].
  2. Five test sections on LA138 in the Mojave Desert (5 years) [16].
  3. Around 70 pavements in the UCPRC/Caltrans monitoring project (3 years, pavements in different age groups and mix types) [17].

- **Denmark:**
  1. Three single layer porous (PAC), one dense graded (DGAC) and one open graded (OGAC) asphalt concrete pavements at "Viskinge" (8 years) [18].
  2. Five Thin Open graded and one dense (DGAC) pavement at M10 ("Solrød") near Copenhagen (5 years) [19].

The test sections and the pavements will be briefly described in Chapter 2 and the trends of noise emission will be analyzed in Chapter 3 with focus on both the trends of the development of the noise emission and on the development of the noise spectra over the years in order to be able to evaluate what might cause the acoustical changes of the pavements. A comparison of the results will be performed in Chapter 4, where also a noise performance model in relation to noise is developed.

2. Road sections included

Table 2.1 gives an overview of the measurement series on the five test roads/projects that are included in this study. Presentations of the projects as well as more detailed descriptions and data on the pavements at these five test roads/projects can be found in the following publications [15, 16, 17, 18 and 19]. Studded tires and/or snow chains are not used in the regions where the test roads are located though there might be a few exceptions on some of the 65 to 76 pavements in [17].

Table 2.1. Overview of the five measurement series/projects included in this comparison study.

Test road/ project	Number of pavements	Year of construction	Noise measurement method	Years of measurements	Number of lanes	Speed limit km/h / mph	Yearly AverageDaily Traffic ADT	Percentage heavy vehicles	Average ADT per lane
I-80 Cal.	1	1998	L_{Aeq}	11	6	104 / 65	146000	7.6%	24300
LA138 Cal.	5	2002	SPB	5	2	88 / 55	4300	17%	2150
Viskinge DK	5	1990	SPB	8-9	2	80 / 50	7000	12.5%	3500
M10 DK	6	2004	SPB	5	6	110 / 69	90000	13.2%	15000
UCPRC 70 Cal.	65-76	1989 - 2005	OBSI	3	variable	variable	variable	variable	variable

2.1 I-80 test section by Davis, CA

The test section with Open Graded Asphalt Concrete with a nominal maximum aggregate size of 9.5 mm was constructed in 1998 [15]. Wayside L_{Aeq} noise measurements have been performed every year over an eleven year period in the summer season.

Figure 2.1. The Open Graded Asphalt Concrete on the I-80 test section. The diameter of the US quarter dollar coin is 24 mm.

Figure 2.2. The test section on Highway I-80 east of Davis California with an OGAC pavement.

2.2 LA138 test sections in Mojave, CA

Figure 2.3. The test section on Highway LA138 in the Mojave Desert California with three open graded and two dense graded pavements.

The test sections on LA138 were constructed in 2002 [16]. The purpose was to perform full scale testing of noise properties of a series of open graded pavements. All the pavements have a nominal maximum aggregate size of 12.5 mm. The following pavements were constructed on the test road:

- A Dense Graded Asphalt Concrete (DGAC) with a specified thickness of 30 mm used as a noise reference pavement (air void around 9 %).
- An Open Graded Asphalt Concrete (OGAC 30) with a specified thickness of 30 mm (air void around 15 %).
- An Open Graded Asphalt Concrete (OGAC 75) with a specified thickness of 75 mm (air void around 12 %).

- An Open Graded Asphalt Concrete with rubber powder added to the bitumen (RAC-O) and a specified thickness of 30 mm (air void around 12 %).
- A Bonded Wearing Course (BWC). A propriety product used in California (air void around 7 %). (Noise measurements have only been performed on this pavement when it was 10 and 16 months old so it is not included in the further analyses in this project).

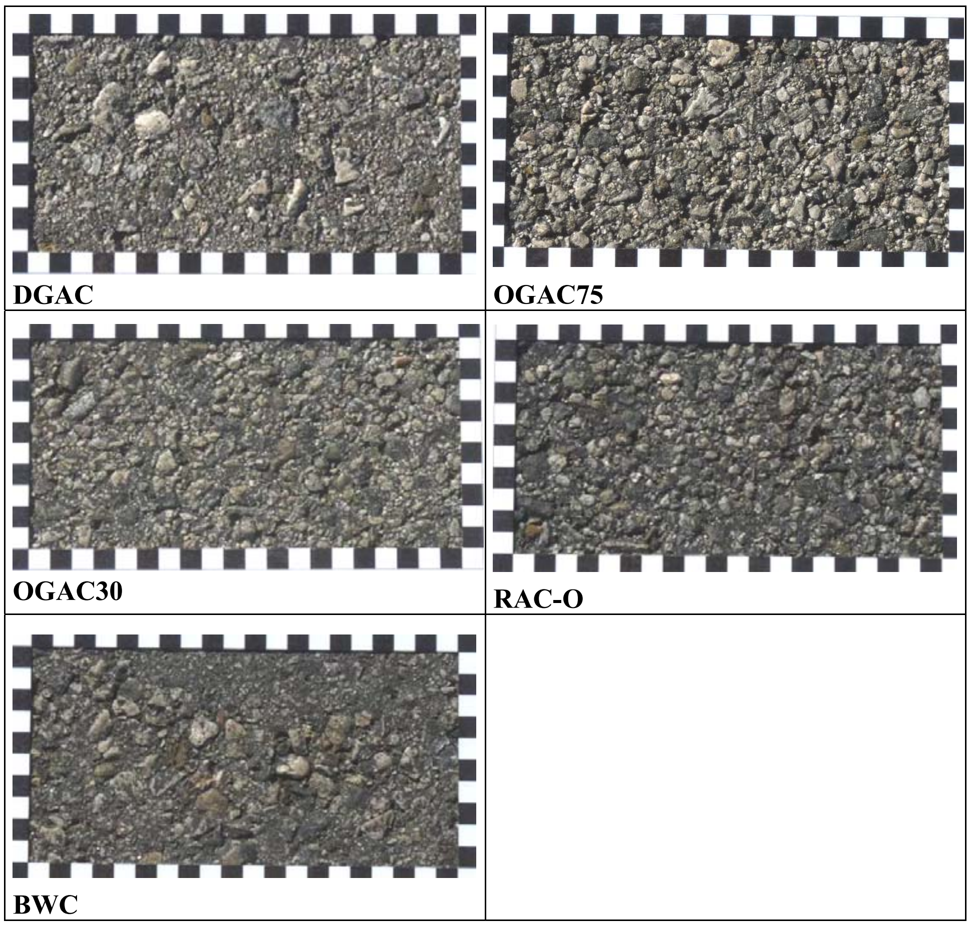


Figure 2.4. The five test pavements on the Highway LA138 test section when they were 6 years old. All the pavements have a nominal maximum aggregate size of 12.5 mm. The size of the black and white squares on the photos is 10 mm by 10 mm.

2.3 Viskinge test sections, DK

The test sections at Viskinge were built as the first Danish full scale noise experiment with porous and open graded asphalt concrete [18]. The sections were constructed in 1990 and yearly SPB noise measurements were conducted over a period of 8 to 9 years. There were five test pavements:

- PAC8 type A: Single layer porous pavement with 8 mm nominal maximum aggregate size and a built in air void between 18 and 22 %.
- PAC8 type B: Single layer porous pavement with 8 mm nominal maximum aggregate size and a built in air void of more than 22 %.
- PAC12: Single layer porous pavement with 12 mm nominal maximum aggregate size and a built in air void of more than 22 %.
- DGAC12: Dense graded asphalt concrete with 12 mm nominal maximum aggregate size.
- OGAC12: Open graded asphalt concrete with 12 mm nominal maximum aggregate size.

In order to be able to carry out a full lifecycle experiment of these porous pavements in the shortest time period possible, the five pavements were deliberately built to break down faster than would normally be the case. Therefore it was decided not to use bitumen modifiers. With this choice it was expected that the lifetime of these porous pavements would be minimized. Heavy raveling occurred when the pavements were seven years old. Then the experiment was ended and the road was repaved with other non-porous pavement types.

From recent Dutch experiences such porous pavements with bitumen modifiers have a lifetime around eleven years on highways [28]. In the further analyses in Chapter 4 of this report an estimated lifetime of eleven years is assumed for these pavements, because this is considered more realistic for such porous pavements if they were constructed today using modified bitumen. The yearly noise increase is reduced to reflect a lifetime of eleven and not seven years. By doing so it becomes more relevant to compare the results of this study started nearly 20 years ago with results from more recent studies.

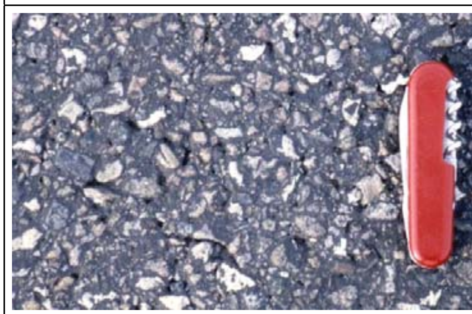
Figure 2.5. The test section at a highway near Viskinge in Denmark.

PAC8 type A

PAC8 type B

PAC12

DGAC12



OGAC12

Figure 2.6. The five test pavements on the Viskinge test sections [18] when they were 3 years old. The aggregate size varies between 8 and 12 mm. The red knife has a length of 8.5 cm.

2.4 M10 test sections, DK

The test sections on highway M10 near Solrød in Denmark were established in 2004 [19]. The purpose was to test different types of noise reducing thin open graded pavements on a motorway. Yearly SPB noise measurements have now been conducted over a 5 year period. There are six test pavements. A dense graded pavement and five noise reducing thin layers were laid (see Figure 2.8):

- DGAC11: Dense asphalt concrete with 11 mm nominal maximum aggregate size (air void when constructed 2.8 %).
- SMA8: Stone Mastic Asphalt with a nominal maximum aggregate size of 8 mm constructed as an open graded pavement (air void when constructed 12.4 %).

- OGAC8: A very open graded asphalt concrete with a nominal maximum aggregate size of 8 mm (air void when constructed 15.3 %).
- UTLAC8: An ultra thin layer pavement with a nominal maximum aggregate size of 8 mm. On the existing road surface, a thick layer of polymer modified bitumen emulsion is spread. On the top of this unbroken bitumen emulsion a very open graded mix is paved (like porous asphalt) with a built-in air void of approx. 14 % or even more. The unbroken bitumen emulsion "boils up" in the air voids of the pavement leaving only the upper part of the structure open. This reduces the built-in air voids of the pavement because the pores of the pavement are almost filled with bitumen.
- SMA6+: Stone Mastic Asphalt with a nominal maximum aggregate size of 6 mm. A small amount of 5/8 mm aggregate is added (air void when constructed 3.0 %).
- SMA8+: Stone Mastic Asphalt with a basic nominal maximum aggregate size of 6 mm. A very small amount of 6/8 aggregate and a larger amount of 8/11 mm aggregate are added (air void when constructed 5.7 %).

Figure 2.7. The Highway M10 test section near Solrød in Denmark with five open graded and one dense pavement.

UTLAC8

DGAC11

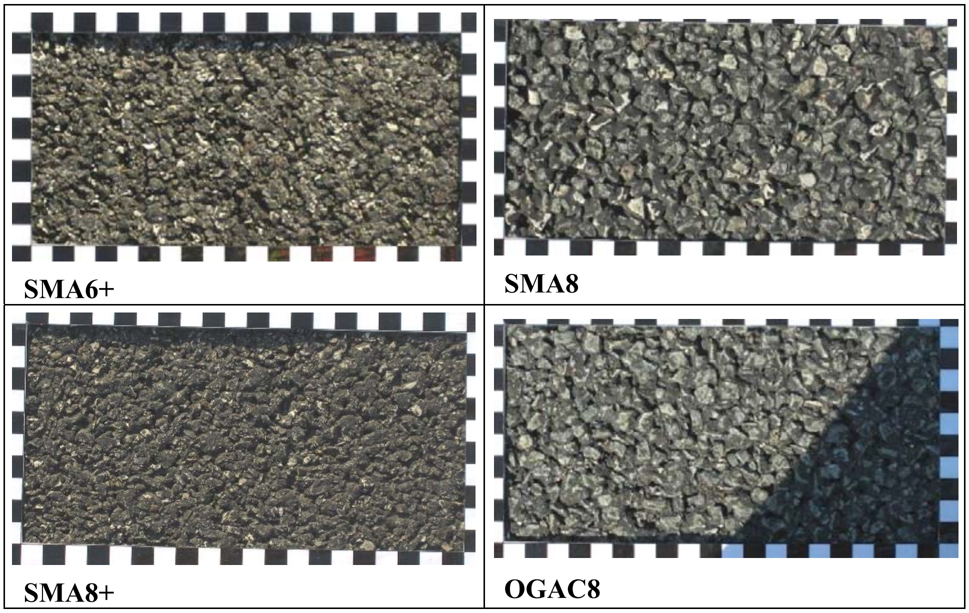


Figure 2.8. The six test pavements on the on the Highway M10 test section when they were 2 years old. The maximum aggregate size varies between 6 and 11 mm [19]. The size of the black and white squares on the photos is 10 mm by 10 mm.

2.5 Californian investigation

In 2006, UCPRC started a project where noise, durability and other pavement properties were measured on 76 selected pavements on the Californian highway network [8]. The pavements were selected in order to include both new, some years old and older pavements of the same type. The following pavement types were included (see Figure 2.10):

- DGAC: Dense Graded Asphalt Concrete.
- OGAC: Open Graded Asphalt Concrete.
- RAC-O: Open Graded Asphalt Concrete with rubber.
- RAC-G: Dense graded Asphalt Concrete with rubber.

Each of the four main pavement groups were divided into the following three age categories in 2006 when the project started: less than one year old, one to less than four years old and more than four years old. The nominal maximum aggregate size of the pavements in these three groups is 9.5, 12.5 and 19 mm. The influence on noise caused by different aggregate size is generally assumed to be an increase of noise level of around 0.25 dB per 1 mm increase in aggregate size. In this data set, the variation in aggregate size can be expected to influence the noise levels in a range of 2.5 dB. This will cause some spread in the results.

The noise has been measured by the OBSI method on all these pavements in 2006, 2007 and 2008 [17] and the measurements will be continued in 2009. Generally, the OBSI measurements were carried out at a speed of 96 km/h (60 mph). Where this for practical reasons was not possible, the noise levels have been normalized to a reference speed of 96 km/h. Due to pavement rehabilitation etc. the amount of pavements included every year has decreased. In 2007 the number was 71 and in 2008 65. An analysis of the noise from pavements belonging to the same pavement type of different ages is included in Section 3.5 of this report. Generally each of the pavements is represented three times in the data set, each time being one year older.

Figure 2.9. One of the 76 roads included in the UCPRC pavement noise study, started in 2006 in California.

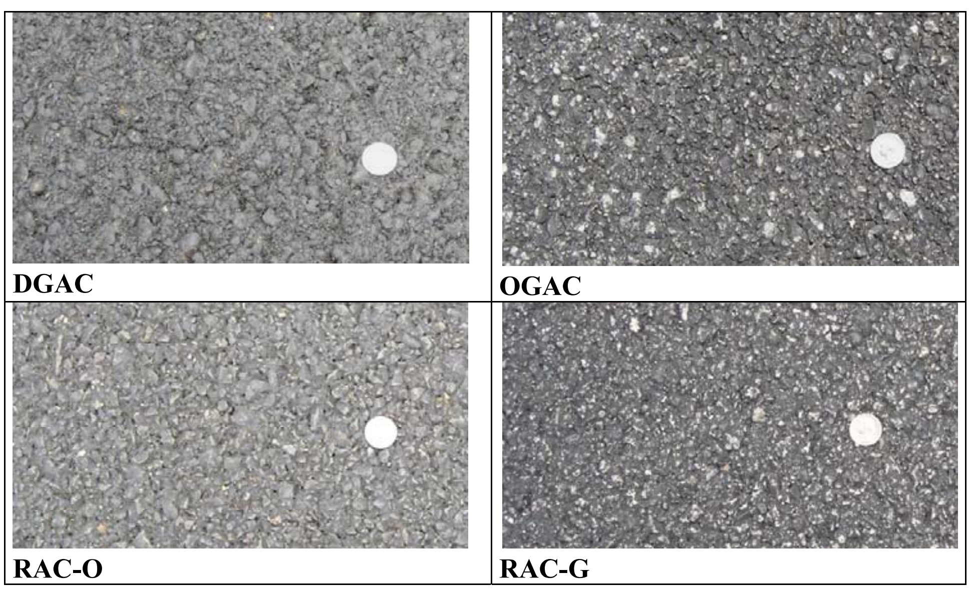


Figure 2.10. Typical pavements included in the Californian project. The diameter of the US quarter dollar coin is 24 mm.

3. Analyses of noise over time

The noise level trends from each of the five projects are presented in this chapter. The Residual Standard Error is used to describe the spread of the actual measurement data around the regression lines. Frequency spectra are presented for the frequency range from 400 to 4000 Hz important for the A-weighted noise level. The OBSI measurements used at the 76 Californian pavement sections do not include the 400 Hz frequency band. The noise trends generally range between 0.1 and 1.0 dB/year. In order to show differences between the pavements two decimals are used for noise trends even though the normal accuracy of noise measurements only calls for using one decimal.

3.1 I-80 test section by Davis, CA

The I-80 test section with an Open Graded Asphalt Concrete was constructed in 1998. Yearly wayside L_{Aeq} noise measurements have been performed for mixed traffic using the American Continuous Flow Traffic Time Integrated Method (CTIM). Noise has been measured by Illingworth & Rodkin Inc., both for the eastbound and for the westbound lanes [15]. The noise is normalized to a fixed traffic volume. The speed limit is 104 km/h (65 mph). Temperature correction has not been performed, but the measurements have all been carried out in the summer period with temperatures generally ranging between 21 and 29°C (70 to 85°F), so the temperature should not have a significant influence on the noise trend [27].

The results can be seen in Figures 3.1 and 3.2 and in Table 3.1. A linear regression gives a reasonable fit with Residual Standard Error of respectively 0.3 and 0.5 dB. The yearly increase of noise on this OGAC pavement is 0.11 dB/year in the eastbound direction and 0.19 dB in the westbound direction.

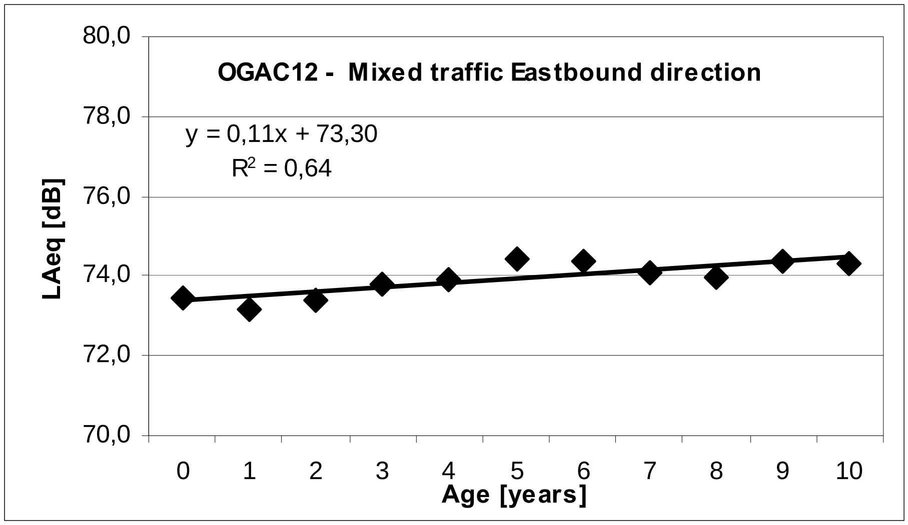


Figure 3.1. Measured wayside eastbound noise as L_{Aeq} for mixed traffic (speed limit 104 km/h (65 mph)) [15].

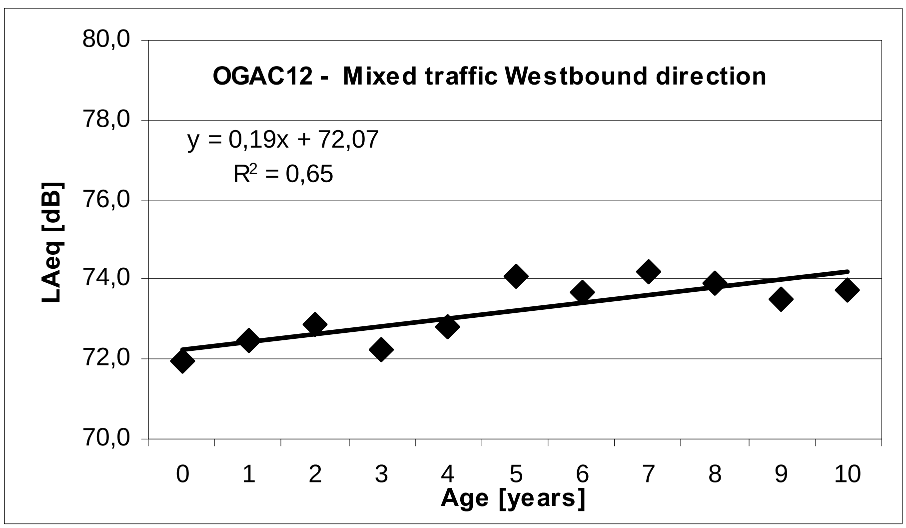


Figure 3.2. Measured wayside westbound noise as L_{Aeq} for mixed traffic (speed limit 104 km/h (65 mph)) [15].

Table 3.1. Average noise increase per year and the Residual Standard Error for mixed traffic at the I-80 test section (speed limit 104 km/h (65 mph)).

Section	Increase	Residual Standard Error
Eastbound	0.11 dB/year	0.3 dB
Westbound	0.19 dB/year	0.5 dB

The development of the noise spectra for mixed traffic over the years can be seen in Figures 3.3 and 3.4. The trend shows that the noise is generally slightly increased over the 10 year period in all frequency bands.

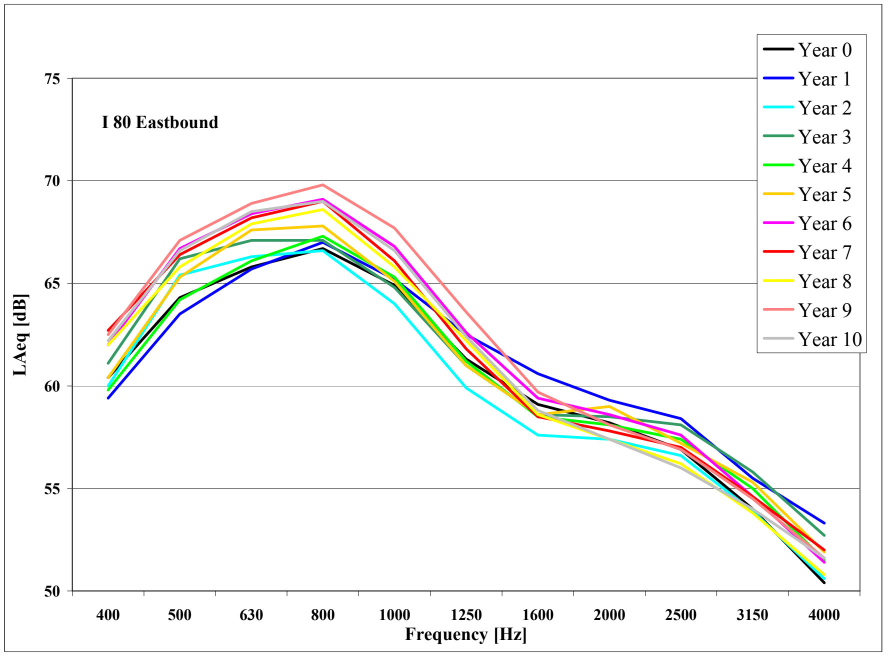


Figure 3.3. The spectra of L_{Aeq} for mixed traffic at the different ages for the OGAC12 pavement at I-80 in the eastbound direction [15].

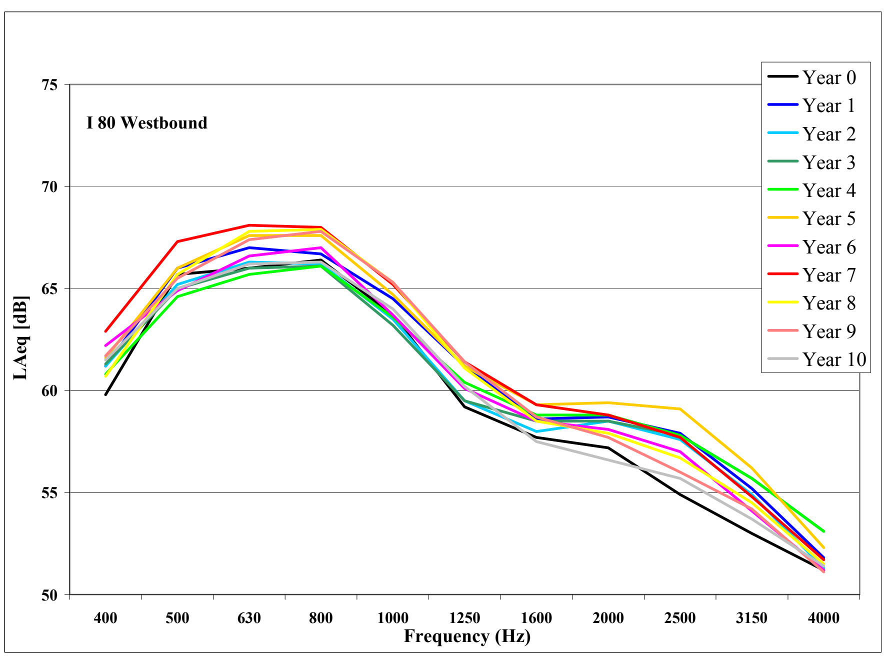


Figure 3.4. The spectra of L_{Aeq} for mixed traffic at the different ages for the OGAC12 pavement at I-80 in the westbound direction [15].

3.2 LA138 test sections in Mojave, CA

A test section with five test pavements was constructed on LA138 in 2002. Detailed wayside SPB measurements have been carried out by Volpe Center for Acoustics four times in a five year period [16] (except for the BWC pavement where data are only available from month 10 and 16). Therefore, the BWC pavement has not been included in the following analyses. The measurements were carried out at a temperature range of 16 to 28°C (61 to 83°F). Temperature corrections have not been applied to these data, but with the relatively narrow temperature range this will not have a significant influence on the trends for noise increase. 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 SPB measurements have been carried out when the pavements were 4, 10, 16 and 52 months old. Therefore, the time scale used in the analyses is months after construction and not years as in the other measurement series included in this report. The noise increase per month therefore has to be multiplied by 12 to get the yearly noise increase. The trends for the development of the noise for passenger cars as well as for multi axle vehicles and the spectra can be seen in the below figures and in Table 3.2 where also the Residual Standard Error is given.

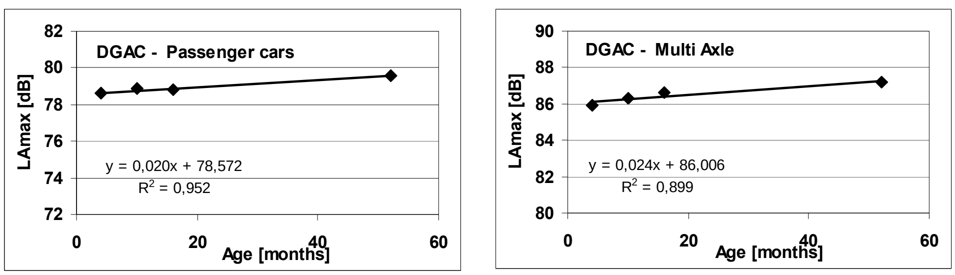


Figure 3.5. Maximum SPB noise level for passenger cars to the left (reference speed 96 km/h (60 mph) and for multi axle vehicles to the right (reference speed 88 km/h (55 mph)) for the DGAC pavement) [16].

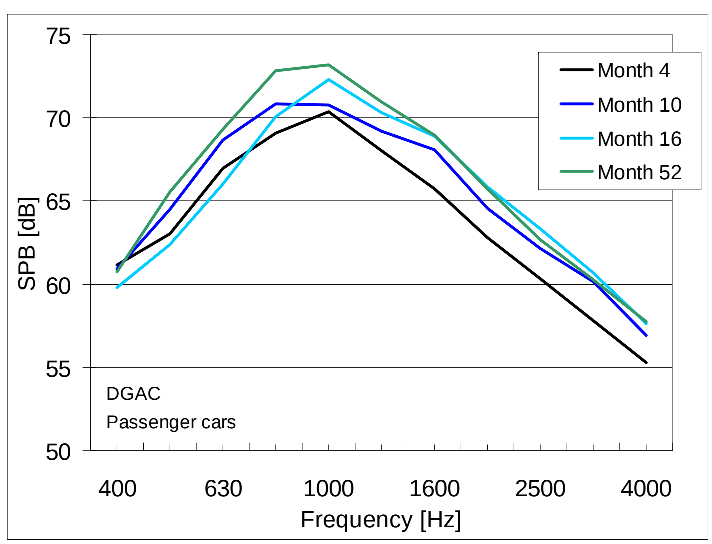


Figure 3.6. SPB noise spectra for passenger cars for the DGAC pavement (reference speed 96 km/h (60 mph)) [16].

In Figure 3.5 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 3.2). 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 3.6 the increases take place in the whole range of the frequency spectrum.

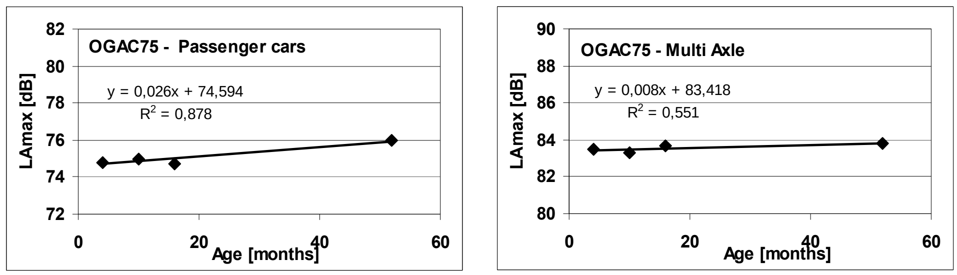


Figure 3.7. Maximum SPB noise level for passenger cars to the left (reference speed 96 km/h (60 mph) and for multi axle vehicles to the right (reference speed 88 km/h (55 mph)) for the OGAC75 pavement) [16].

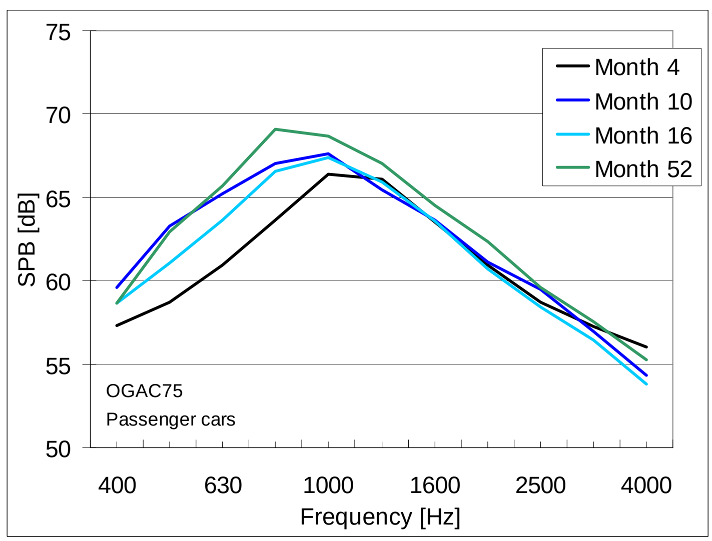


Figure 3.8. SPB noise spectra for passenger cars for the OGAC75 pavement (reference speed 96 km/h (60 mph)) [16].

The development of noise over the years for passenger cars for the open graded OGAC75 pavement was 0.31 dB/year (see Figure 3.7) whereas it was lower for multi axle vehicles (0.10 dB/year). The noise increase fits quite well with a linear regression with Residual Standard Error of 0.3 and 0.2 dB (see Table 3.2). Figure 3.8 show that the increase basically happens in the low frequencies indicating that the pavement surface becomes rougher.

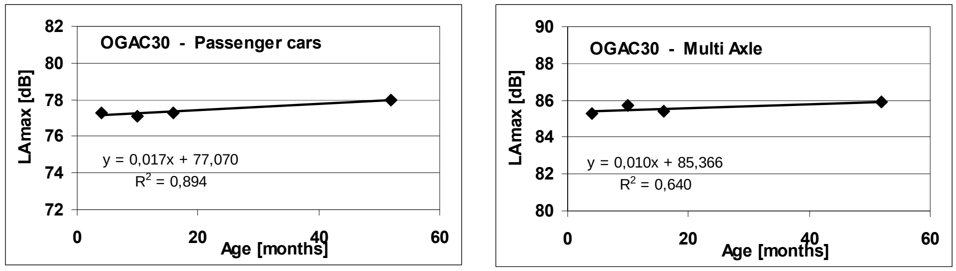


Figure 3.9. Maximum SPB noise level for passenger cars to the left (reference speed 96 km/h (60 mph) and for multi axle vehicles to the right (reference speed 88 km/h (55 mph)) for the OGAC30 pavement) [16].

Figure 3.9 shows the trends for the open graded OGAC30 pavement. The Residual Standard Error is 0.2 dB for both vehicle categories (see Table 3.2). The increase is 0.20 dB/year for passenger cars and 0.12 dB/year for multi axle vehicles. Figure 3.10 shows that the increase like for the OGAC75 pavement basically happens in the low frequencies indicating that the pavement surface becomes rougher.

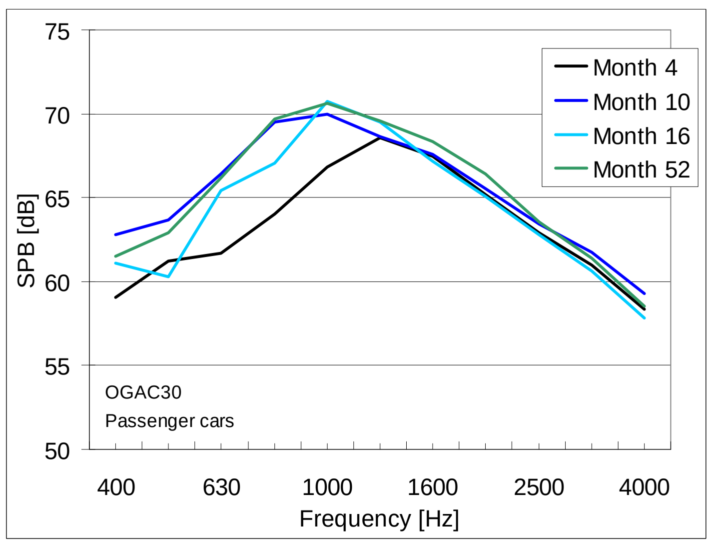


Figure 3.10. SPB noise spectra for passenger cars for the OGAC30 pavement (reference speed 96 km/h (60 mph)) [16].

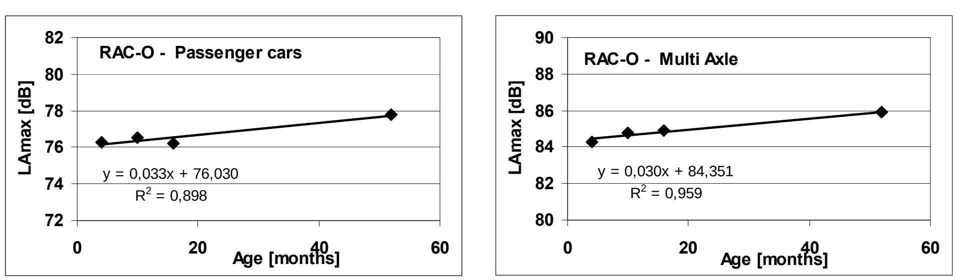


Figure 3.11. Maximum SPB noise level for passenger cars to the left (reference speed 96 km/h (60 mph) and for multi axle vehicles to the right (reference speed 88 km/h (55 mph)) for the RAC-O pavement) [16].

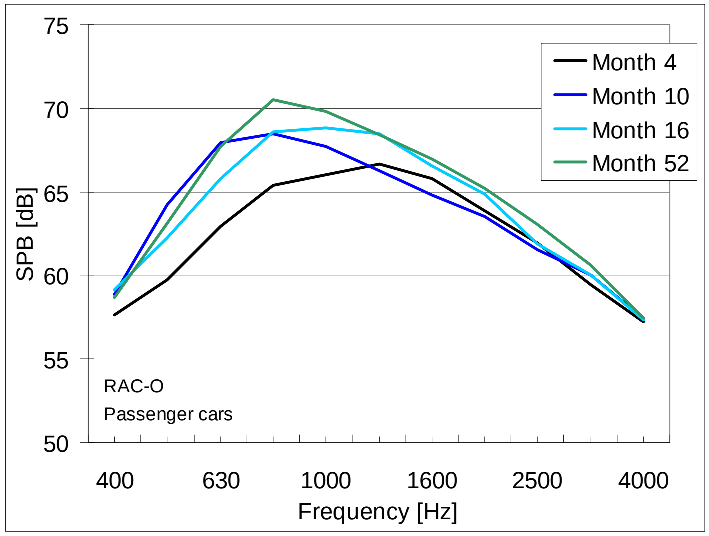


Figure 3.12. SPB noise spectra for passenger cars for the RAC-O pavement (reference speed 96 km/h (60 mph)) [16].

Finally, the trends for the open graded RAC-O can be seen in Figure 3.11. This pavement has the highest increase of the LA138 test pavements with a yearly increase of 0.40 dB for passenger cars and 0.36 dB for multi axle vehicles (Residual Standard Error of 0.3 and 0.2 dB [see Table 3.2]). The spectra in Figure 3.12 show that the highest increase happens at frequencies below 1000 Hz but there is also some minor increase at the higher frequencies.

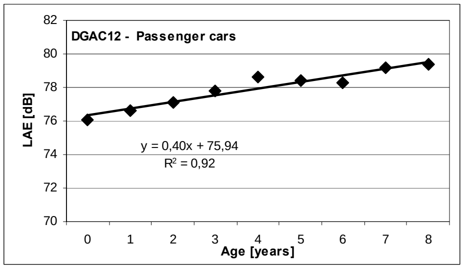
Table 3.2. Average noise level increase per year for passenger cars and multi axle vehicles and the Residual Standard Error for the four test pavements on LA138 (reference speed 96 km/h (60 mph) for passenger cars and 88 km/h (55 mph) for multi axle vehicles).

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

Table 3.2 gives an overview of the noise trends for the four LA138 pavements. For passenger cars the dense graded OGAC30 pavement has the lowest increase 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.

3.3 Viskinge test sections, DK

The five test pavements at Viskinge were constructed in 1990. SPB noise measurements have been conducted over a period of eight to nine years [18]. 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 L_{AE} values and not L_{Amax} which is now common for SPB measurements. There is a linear correlation between L_{AE} and L_{Amax} for SPB traffic noise measurements [29]. Temperature corrections have not been performed, but the measurements have all been made in periods not covering the colder winter months in a temperature range of generally 15 to 25°C (59 to 77°F) so this will not have a significant influence on the trends for noise increase. The trends for the development of the noise level for passenger cars as well as for multi axle vehicles and the spectra can be seen in the below figures. The Residual Standard Error can be seen in Table 3.3.



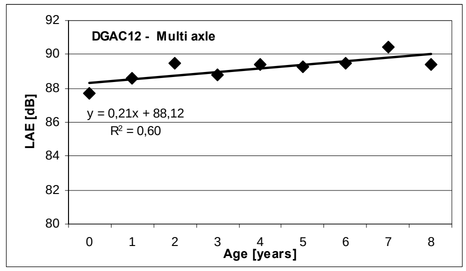


Figure 3.13. L_{AE} SPB noise level from passenger cars (reference speed 80 km/h (50 mph)) to the left and for multi axle vehicles to the right for the DGAC12 pavement [18].

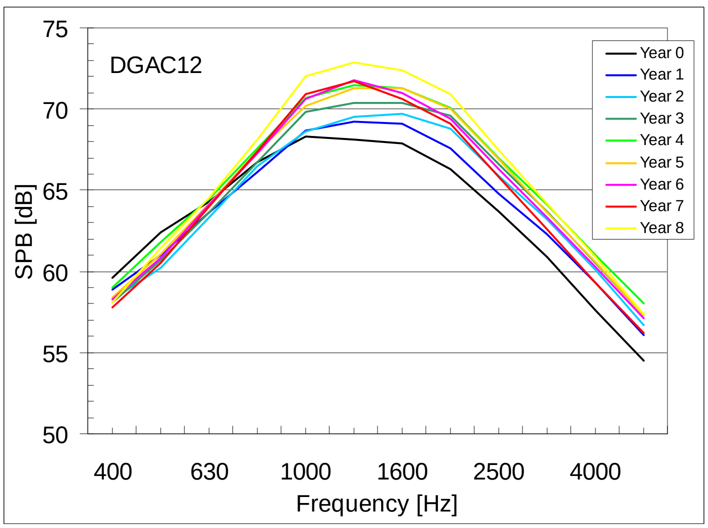


Figure 3.14a. The SPB spectra for passenger cars at the different ages for the DGAC12 pavement (reference speed 80 km/h (50 mph)) [18].

Figure 3.13 shows the development of the noise level over the years for the dense graded DGAC12 pavement. The noise level increase fits quite well with a linear regression with a Residual Standard Error of 0.3 and 0.5 dB (see Table 3.3).

The yearly increase for passenger cars was 0.40 dB/year and for multi axle vehicles 0.21 dB/year. The noise for passenger cars generally increased over time at all frequencies above 630 Hz (see Figure 3.14a). 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 3.14b) generally show the same trends. From the third year the spectra is nearly unchanged to year 8. This could indicate that 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.

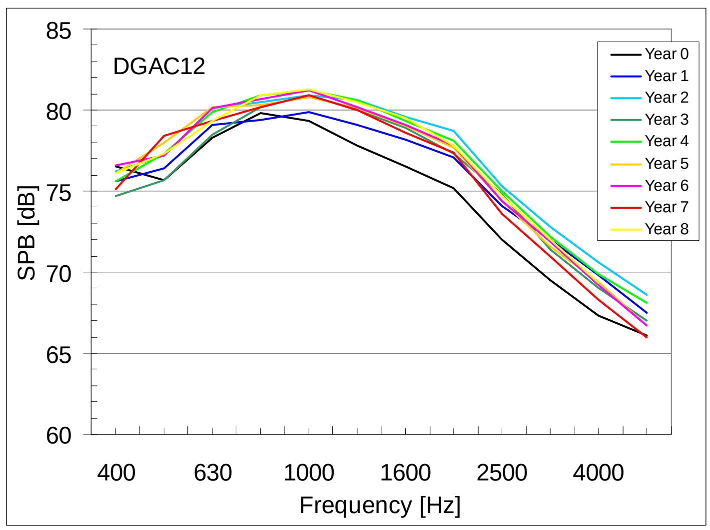


Figure 3.14b. The SPB spectra for multi axle vehicles at the different ages for the DGAC12 pavement (reference speed 80 km/h (50 mph)) [18].

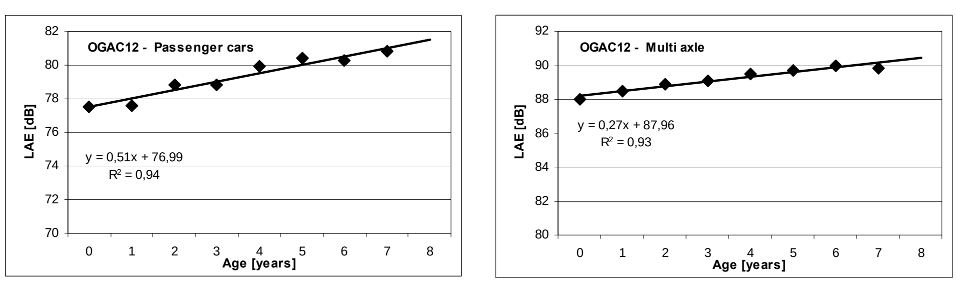


Figure 3.15. L_{AE} SPB noise level from passenger cars to the left and for multi axle vehicles to the right for the OGAC12 pavement (reference speed 80 km/h (50 mph)) [18].

The development of noise level at the open graded OGAC12 is shown in Figure 3.15. Also for this pavement the noise increase fits quite well with a linear regression (Residual Standard Error of 0.3 and 0.2 dB (see Table 3.3)). The yearly increase for passenger cars was 0.51 dB/year and for multi axle vehicles 0.27 dB/year. The noise for passenger cars generally increased at all frequencies above 630 Hz (see Figure 3.16a). Like for the DGAC12 pavement the noise increased 1 to 2 dB at frequencies above 1000 Hz in the first one to two years. Also for the OGAC12 pavement this might be caused by the pavement being "post compacted" reducing the open structure of the pavement surface. For the truck tires there is an increase of 1-2 dB over 1000 Hz from year 0 to year 1. After this the changes of the spectra are quite small.

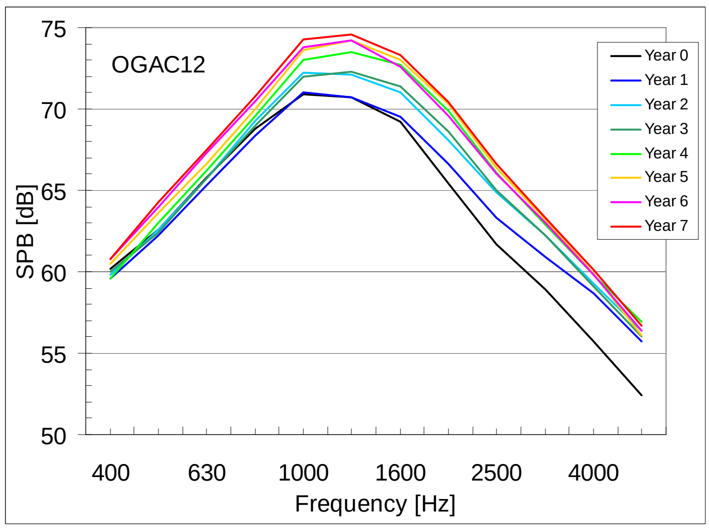


Figure 3.16a. The SPB spectra for passenger cars at the different ages for the OGAC12 pavement (reference speed 80 km/h (50 mph)) [18].

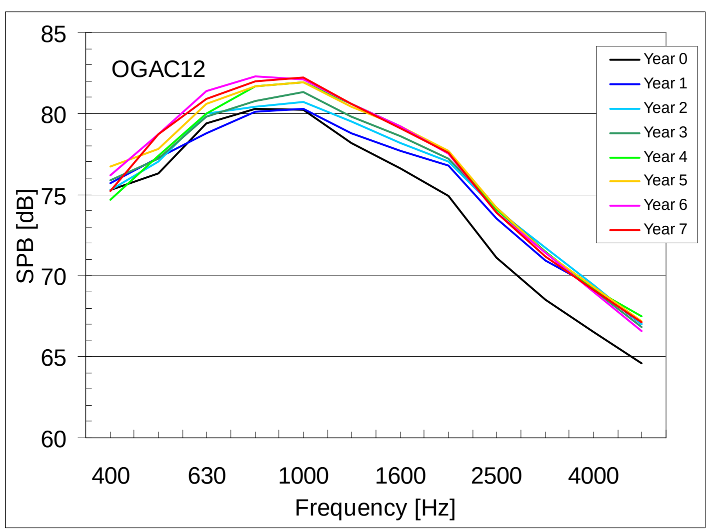
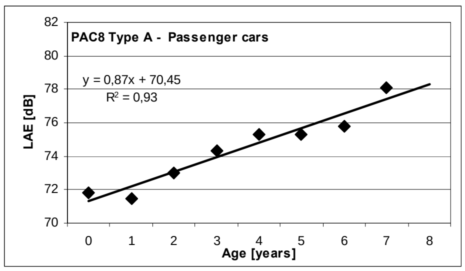


Figure 3.16b. The SPB spectra for multi axle vehicles at the different ages for the OGAC12 pavement (reference speed 80 km/h (50 mph)) [18].

The first of the three porous pavements at the Viskinge test site is the PAC8 Type A. The development of noise can be seen in Figure 3.17. The yearly increase for passenger cars was 0.87 dB/year and for multi axle vehicles the increase was 0.37 dB/year. These increases are twice as high as for the dense DGAC12 and the open but not porous OGAC12 pavement. The Residual Standard Error was greater for this porous pavement and was 0.6 dB for both vehicle categories (see Table 3.3).



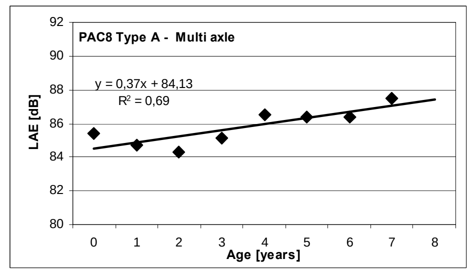


Figure 3.17. L_{AE} SPB noise level for passenger cars to the left and for multi axle vehicles to the right for the PAC8 type A pavement (reference speed 80 km/h (50 mph)) [18].

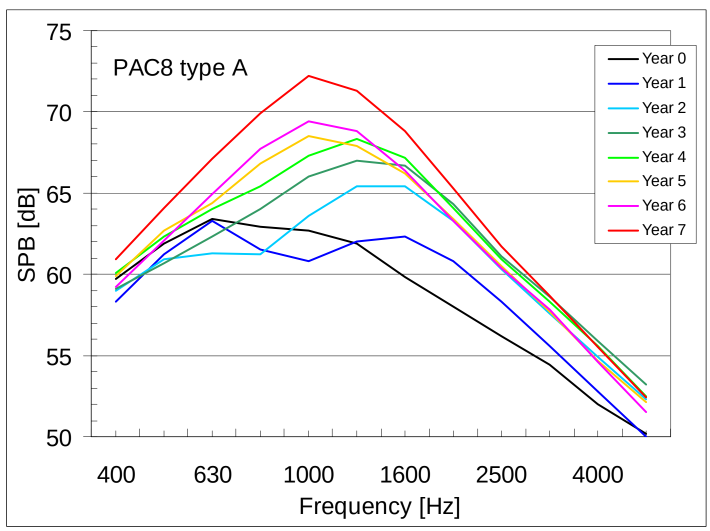


Figure 3.18a. The SPB spectra for passenger cars at the different ages for the PAC8 type A pavement (reference speed 80 km/h (50 mph)) [18].

In the first year, a decrease of noise level of 0.3 dB for passenger cars and 0.7 dB for multi axle vehicles was observed. The frequency spectra for passenger cars in Figure 3.18a give an indication of what might be happening. This spectrum is significantly different from the spectra at the two previous not porous pavements.

The noise level 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 around 400 to 1000 Hz (engine noise) depending on the thickness of the porous layer. It seems that this absorption effect 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.

From the first to the second year the noise level increased by 2 to 3 dB at frequencies above 1000 Hz giving an increase in air pumping noise indicating that the open pores of the pavement were beginning to clog! The noise level 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 indicates that the pavement has become rougher because of the raveling. Figure 3.18b shows the spectra for multi axle vehicles. The trends are generally the same as for passenger cars. Here the noise level increased 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.

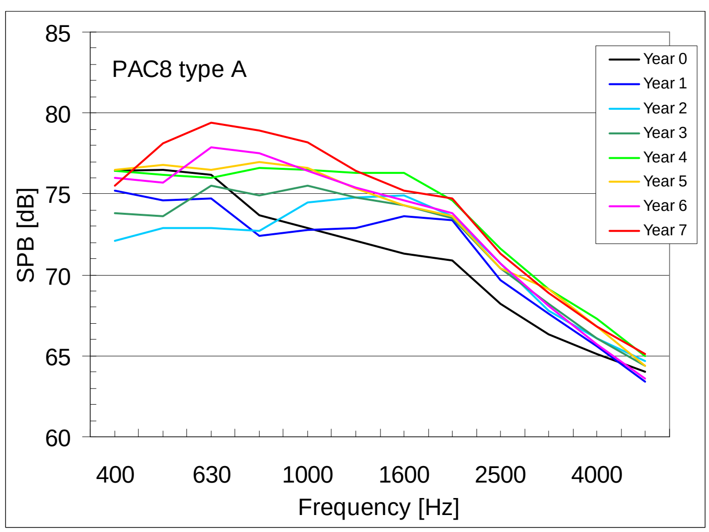


Figure 3.18b. The SPB spectra for multi axle vehicles at the different ages for the PAC8 type A pavement (reference speed 80 km/h (50 mph)) [18].

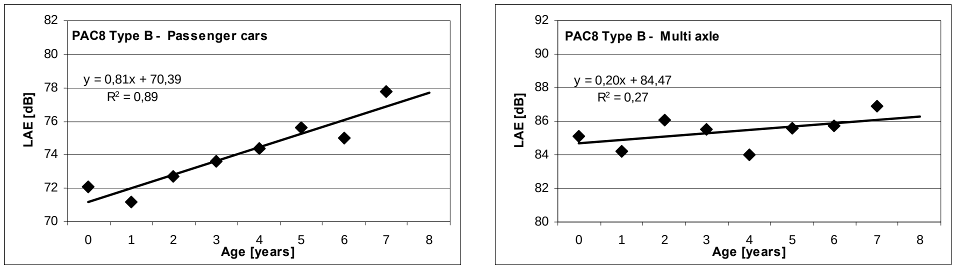


Figure 3.19. L_{AE} SPB noise level from passenger cars to the left and for multi axle vehicles to the right for the PAC8 type B pavement (reference speed 80 km/h (50 mph)) [18].

Figure 3.19 shows the development of noise level of the porous PAC8 Type B pavement (Residual Standard Error of 0.8 and 0.9 dB [see Table 3.3]). The yearly increase for passenger cars was 0.81 dB/year similar to the increase at the PAC8 Type A pavement. For multi axle vehicles the increase was only 0.20 dB/year. But in the first year a decrease of noise of 0.9 dB for both passenger cars and multi axle vehicles were observed. The frequency spectra for passenger cars in Figure 3.20a give an indication of what might be happening. The same trends as described for the PAC Type A pavement with increased absorption over the first year at 800 to 1000 Hz can be observed.

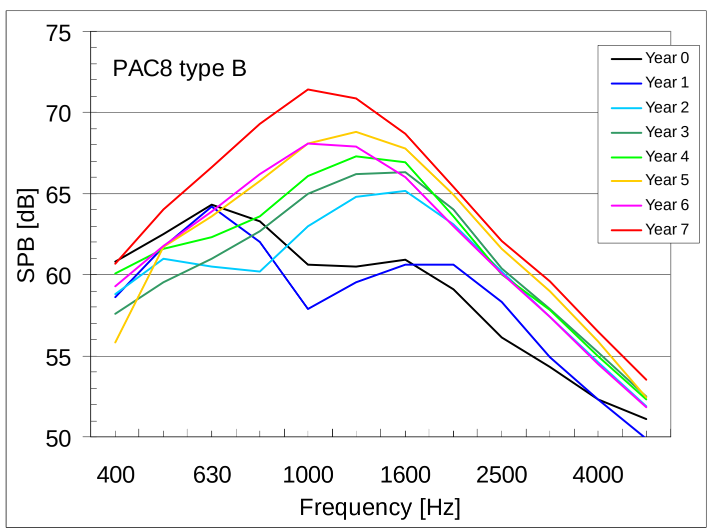


Figure 3.20a. The SPB spectra for passenger cars at the different ages for the PAC8 type B pavement (reference speed 80 km/h (50 mph)) [18].

From the first to the second year, the noise level increased 2 to 5 dB at frequencies above 1000 Hz indicating an increase in air pumping noise because 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 significantly reduced. This is also an indication of clogging.

Also for the PAC8 type B heavy raveling was observed in year 7. In this year there was a significant increase of low frequency noise level (around 2 dB) at below 1600 Hz. This reflects that the pavement has become more uneven because of the raveling.

Figure 3.20b shows the spectra for multi axle vehicles. The trends are similar to the trends seen for passenger cars.

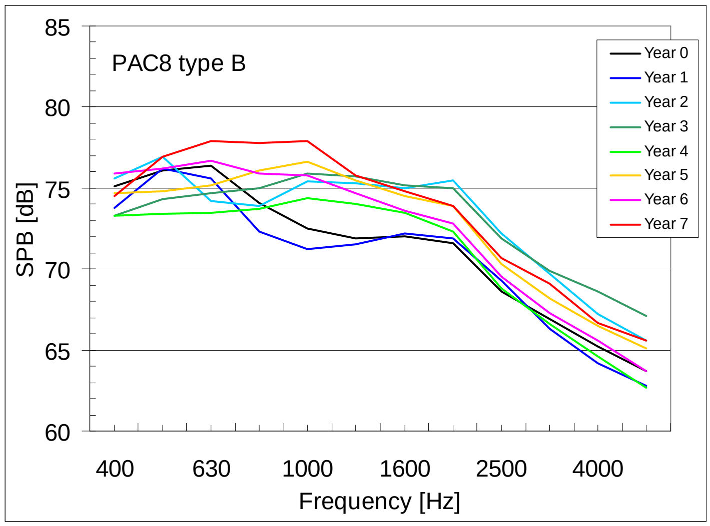


Figure 3.20b. The SPB spectra for multi axle vehicles at the different ages for the PAC8 type B pavement (reference speed 80 km/h (50 mph)) [18].

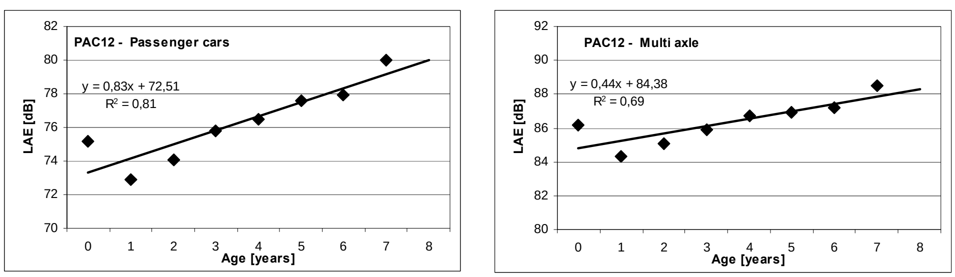


Figure 3.21. L_{AE} SPB noise level from passenger cars to the left and for multi axle vehicles to the right for the PAC12 pavement (reference speed 80 km/h (50 mph)) [18].

The results from the third and last porous pavement on the Viskinge test site can be seen in Figure 3.21(Residual Standard Error of 1.1 and 0.8 dB [see Table 3.3]). The yearly increase for passenger cars was 0.83 dB/year and for multi axle vehicles 0.44 dB/year, similar to the PAC8 Type A and B pavement. But in the first year a decrease of noise level of as much as 2.3 dB for passenger cars and 1.9 dB for multi axle vehicles was observed. The frequency spectra for passenger cars can be seen in Figure 3.22a. The same trends as described for the PAC Type A and Type B pavements with increased absorption at 800 to 1000 Hz can be observed over the first year.

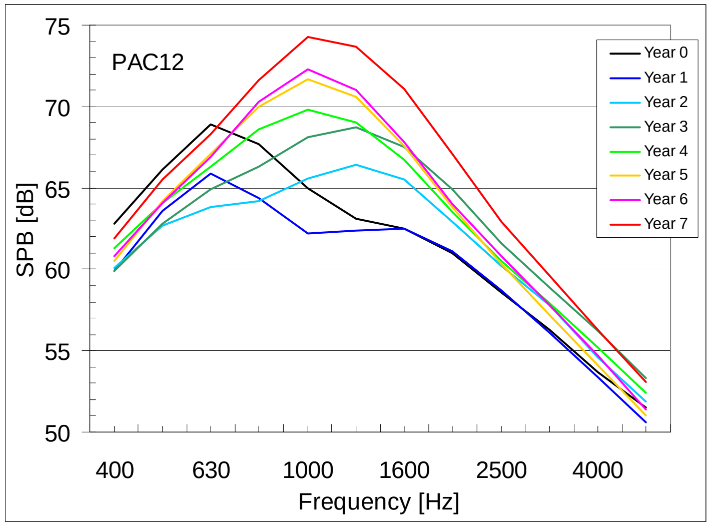


Figure 3.22a. The SPB spectra for passenger cars at the different ages for the PAC12 pavement (reference speed 80 km/h (50 mph)) [18].

From the first to the second year the noise level increased 1 to 4 dB at frequencies above 1000 Hz indicating an increase in air pumping noise, because the open pores of the pavement were beginning to clog! The noise level also increased at 800 to 1000 Hz indicating that the noise absorption effect was significantly reduced. This is also an indication of clogging.

Heavy raveling was also observed on the PAC12 pavement in year 7. In this year there was a significant increase of low frequency noise level (below 1600 Hz) of around 2 to 3 dB. This indicates that the pavement has become rougher because of the raveling.

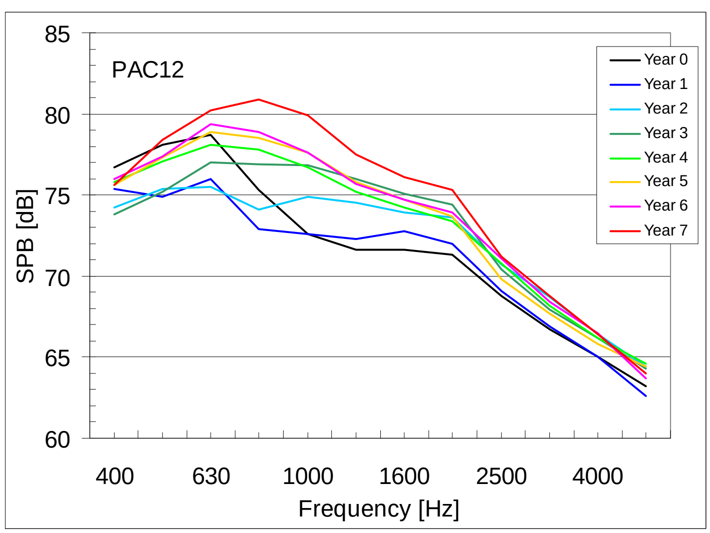


Figure 3.22b. The SPB spectra for multi axle vehicles at the different ages for the PAC12 pavement (reference speed 80 km/h (50 mph)) [18].

Also for this PAC12 pavement the same spectral tendencies as for passenger cars can be seen for multi axle vehicles (Figure 3.22b).

Table 3.3. Average noise level increase per year for passenger cars and multi axle vehicles and the Residual Standard Error for the five test pavements measured at Viskinge (reference speed 80 km/h (50 mph)).

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 3.3 gives an overview of the noise level trends on the five Viskinge pavements. For passenger cars, the dense graded DGAC12 pavement had the lowest increase of 0.40 dB/year, followed by the open graded OGAC12 pavement with 0.51 dB/year. For the three porous pavements the increase was around twice as high with 0.81 and 0.87 dB/year. The increase 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.

Table 3.4. Predicted average noise level 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 eleven years (reference speed 80 km/h (50 mph)).

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

As mentioned in section 2.3, 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 eleven years [28]. The acoustical performance of the five pavements is “stretched” to a lifetime of eleven years by multiplying the yearly increases by 7/11.

Table 3.4 shows the expected noise increases of new durable porous pavements with modified bitumen. The dense and the open graded asphalt concrete for passenger cars then get 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 increase as a function of age makes it possible to compare the results with the results from the other test sections included in this report.

3.4 M10 test sections, DK

The test sections on highway M10 in Denmark were constructed in 2004 [19]. SPB measurements have been conducted every year over a five year period and it is planned to continue these measurements. The SPB results are here reported as L_{Amax} levels. 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) according to ISO 11819-1 [3]. The data are all normalized to an air reference temperature of 20°C (68°F). The trends for the development of the noise for passenger cars as well as for multi axle vehicles, and the spectra can be seen in the below figures. The Residual Standard Error can be seen in Table 3.5.

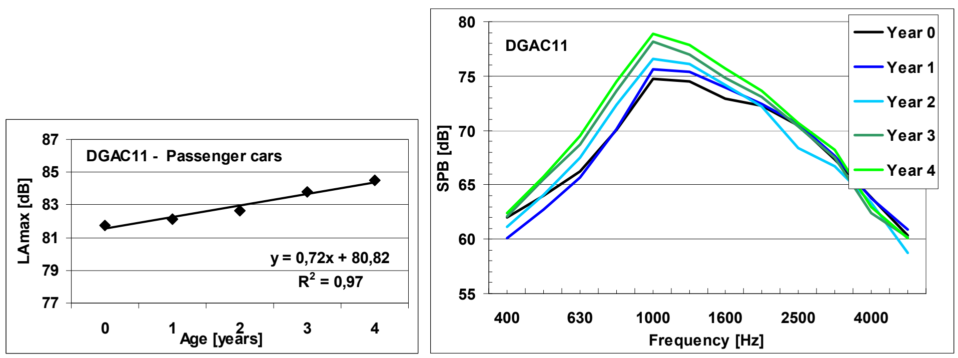


Figure 3.23. Maximum SPB noise level from passenger cars to the left and SPB noise spectra to the right for the DGAC11 pavement (reference speed 110 km/h (69 mph)).

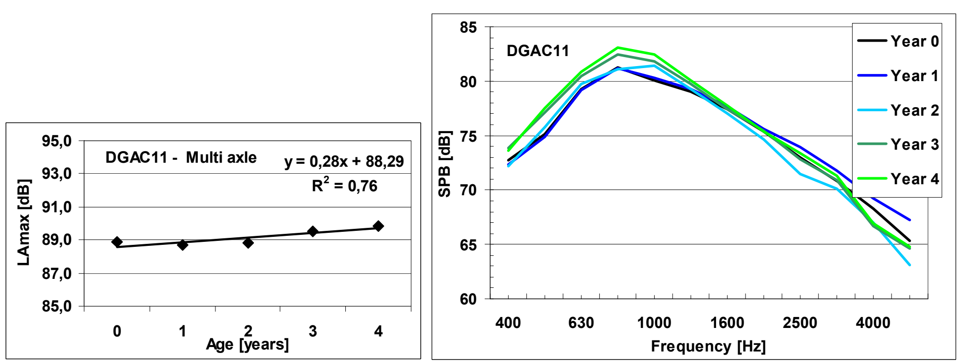


Figure 3.24. Maximum SPB noise level from multi axle vehicles to the left and SPB noise spectra to the right for the DGAC11 pavement (reference speed 85 km/h (53 mph)).

The results for the DGAC11 pavement on the M10 test sections can be seen in Figure 3.23 and 3.24. The noise level increase fits quite well with a linear regression (Residual Standard Error of 0.2 and 0.3 dB (see Table 3.5)). The yearly increase for passenger cars is 0.72 dB/year and a for multi axle trucks 0.28 dB/year increase. The noise level increases mainly at frequencies below 1600 Hz. This can indicate an increase in the vibration generated noise caused by the pavement texture becoming rougher.

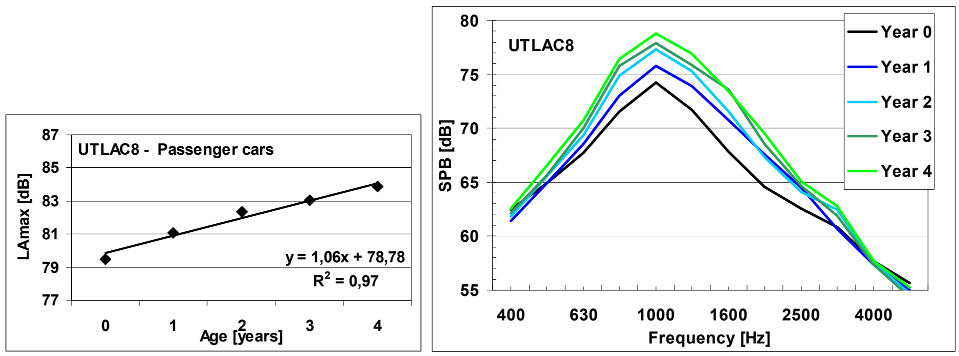


Figure 3.25. Maximum SPB noise level from passenger cars to the left and SPB noise spectra to the right for the UTLAC8 pavement (reference speed 110 km/h (69 mph)).

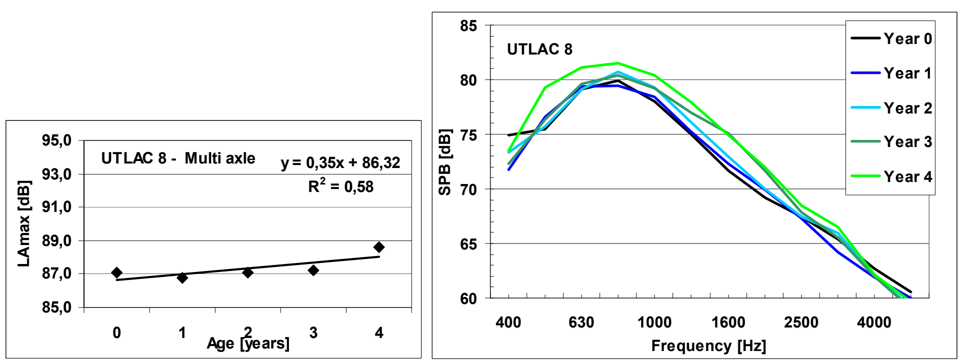


Figure 3.26. Maximum SPB noise level from multi axle vehicles to the left and SPB noise spectra to the right for the UTLAC8 pavement (reference speed 85 km/h (53 mph)).

The results for the UTLAC8 pavement can be seen in Figures 3.24 and 3.25. The noise increase from this pavement fits well with a linear regression (Residual Standard Error of 0.3 and 0.5 dB (see Table 3.5)). The yearly increase for passenger cars is 1.06 dB/year and around three times the increase for multi axle trucks which is 0.35 dB/year. The yearly increase is higher for this open graded pavement than for the dense graded DGAC11. For passenger cars, the noise level increases both in the frequencies above and below 1000 Hz. This could indicate an increase in the vibration generated lower frequency noise caused by the pavement texture becoming more rough as well as an increase in the high frequency air pumping generated noise caused by the pavement surface becoming denser.

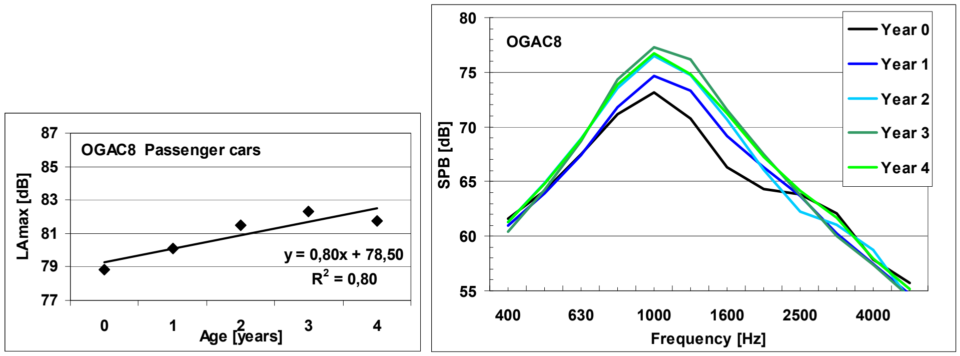


Figure 3.27. Maximum SPB noise level from passenger cars to the left and SPB noise spectra to the right for the OGAC8 pavement (reference speed 110 km/h (69 mph)).

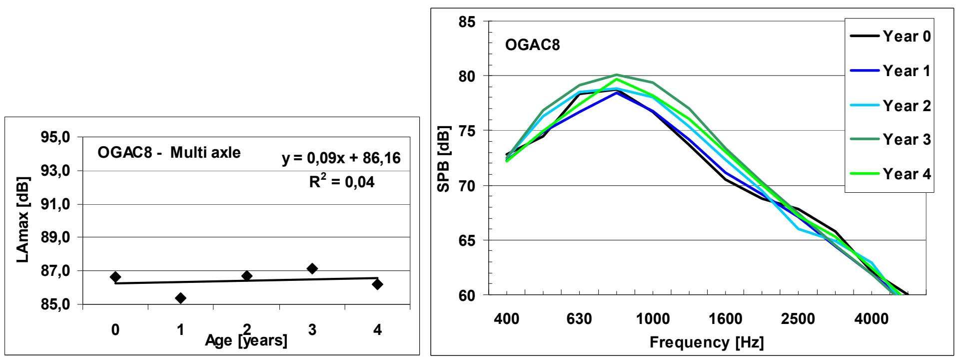


Figure 3.28. Maximum SPB noise level from multi axle vehicles to the left and SPB noise spectra to the right for the OGAC8 pavement (reference speed 85 km/h (53 mph)).

The results for the OGAC8 pavement can be seen in Figures 3.27 and 3.28. The noise level increase fits with a linear regression but with higher Residual Standard Error than the other pavements in the M10 experiment (0.7 and 0.8 dB [see Table 3.5]). The yearly increase for passenger cars is 0.80 dB/year whereas the increase for multi axle trucks is just 0.09 dB/year. Like for the UTLAC8 pavement the noise level for passenger cars increases both in the frequencies above and below 1000 Hz, with the most prominent increase at frequencies above 1000 Hz. This can indicate an increase in the vibration generated lower frequency noise as well as an increase in the high frequency air pumping generated noise caused by the pavement surface becoming denser especially during the first two years.

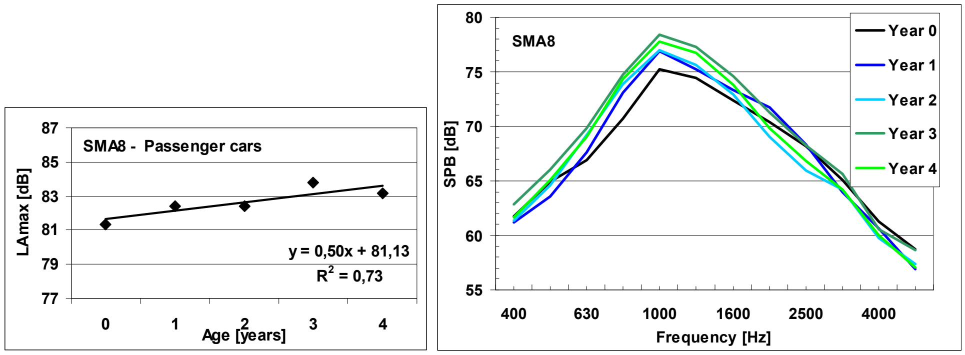


Figure 3.29. Maximum SPB noise level from passenger cars to the left and SPB noise spectra to the right for the SMA8 pavement (reference speed 110 km/h (69 mph)).

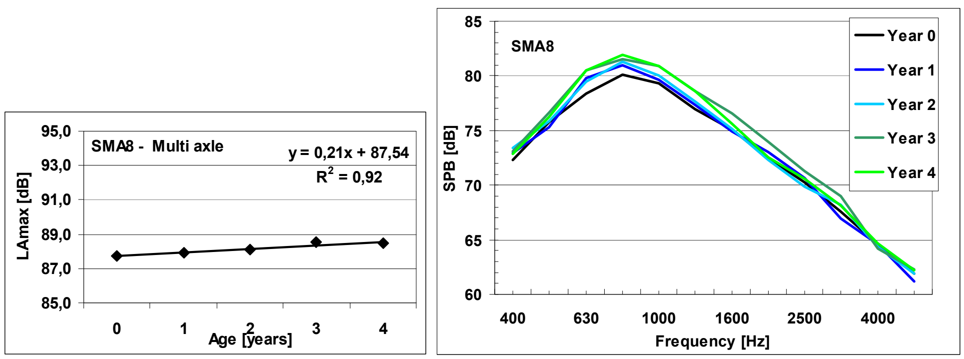


Figure 3.30. Maximum SPB noise level from multi axle vehicles to the left and SPB noise spectra to the right for the SMA8 pavement (reference speed 85 km/h (53 mph)).

The results for the SMA8 pavement can be seen in Figures 3.29 and 3.30 (Residual Standard Error of 0.5 and 0.1 dB [see Table 3.5]). The yearly increase in noise level for passenger cars is 0.50 dB/year and corresponds to the lowest increase of the six pavements on the M10 test section. For multi axle vehicles the increase is 0.21 dB/year. The increase is mainly seen at the lower frequencies (below 1600 Hz) indicating that the pavement surface becomes rougher.

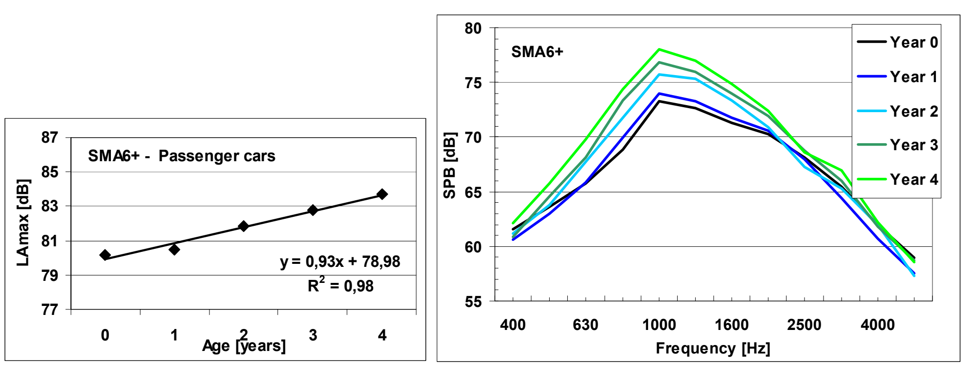


Figure 3.31. Maximum SPB noise level from passenger cars to the left and SPB noise spectra to the right for the SMA6+ pavement (reference speed 110 km/h (69 mph)).

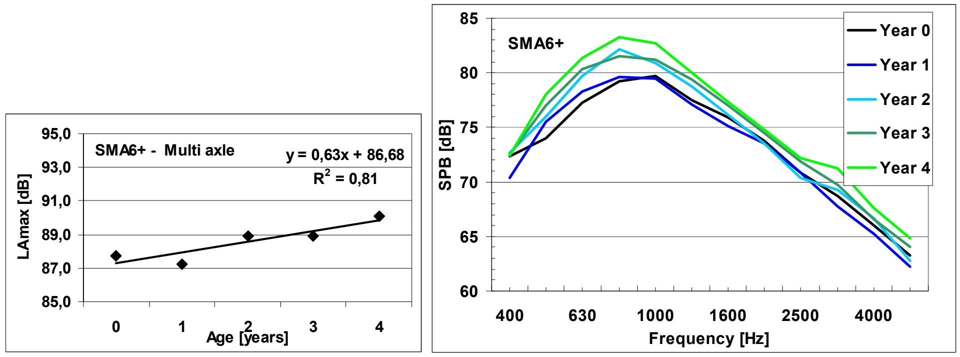


Figure 3.32. Maximum SPB noise level from multi axle vehicles to the left and SPB noise spectra to the right for the SMA6+ pavement (reference speed 85 km/h (53 mph)).

The SMA6+ pavement in Figures 3.31 and 3.32 has a noise level increase for passenger cars and multi axle vehicles of respectively 0.93 and 0.63 dB/year (Residual Standard Error of 0.3 and 0.6 dB [see Table 3.5]). The increase primarily occurs for frequencies below 1600 Hz indicating that the pavement structure becomes rougher over the years.

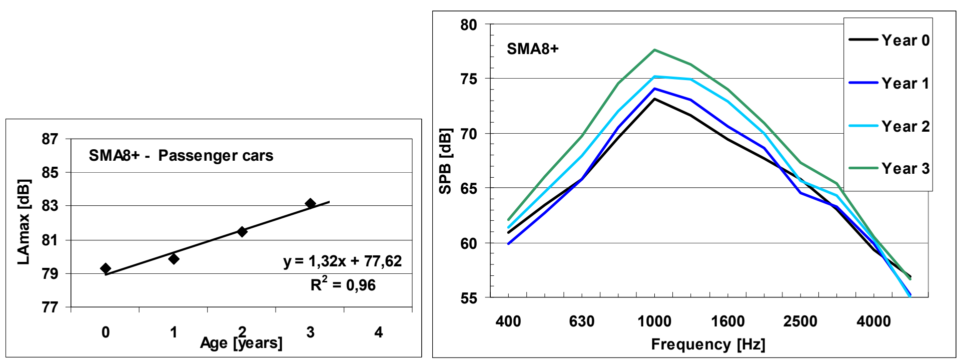


Figure 3.33. Maximum SPB noise level from passenger cars to the left and SPB noise spectra to the right for the SMA8+ pavement (reference speed 110 km/h (69 mph)).

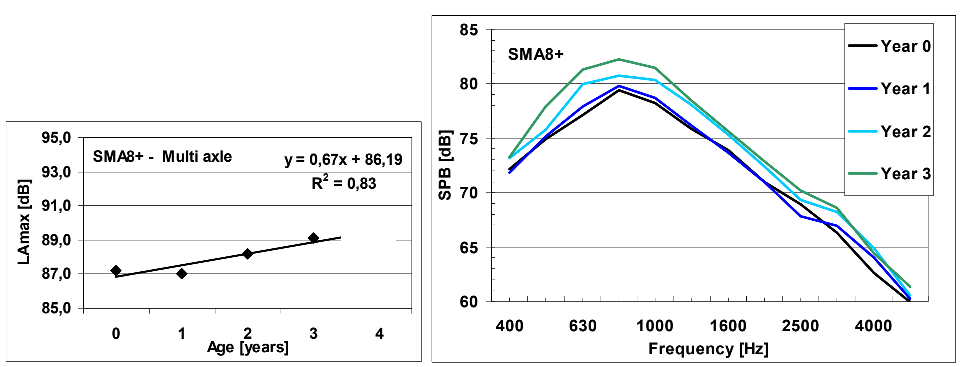


Figure 3.34. Maximum SPB noise level from multi axle vehicles to the left and SPB noise spectra to the right for the SMA8+ pavement (reference speed 85 km/h (53 mph)).

The SMA8+ pavement was constructed one year after the other pavements on M10. Therefore Figures 3.33 and 3.34 only include results from four years. This SMA8+ has the highest noise level increase of the six pavements on M10 with increase for passenger cars and multi axle vehicle of 1.32 and 0.67 dB/year respectively. The spectra show increase over the whole frequency range.

Table 3.5. Average noise level increase per year for passenger cars and multi axle vehicles and Residual Standard Error for the six test pavements on M10 (reference speed 110 km/h (69 mph) for passenger cars and 85 km/h (53 mph) for multi axle vehicles).

Pavement	Passenger cars	Residual Standard Error Passenger	Multi axle vehicles	Residual Standard Error Multi axle
DGAC11	0.72 dB/year	0.2 dB	0.28 dB/year	0.3 dB
UTLAC8	1.06 dB/year	0.3 dB	0.35 dB/year	0.5 dB
OGAC8	0.80 dB/year	0.7 dB	0.09 dB/year	0.8 dB
SMA8	0.50 dB/year	0.5 dB	0.21 dB/year	0.1 dB
SMA6+	0.93 dB/year	0.3 dB	0.63 dB/year	0.6 dB
SMA8+	1.32 dB/year	0.4 dB	0.67 dB/year	0.5 dB

Table 3.5 gives an overview of the slope of the trend lines found at each of the six M10 pavements. For passenger cars the DGAC and the SMA8 pavements have the lowest noise level increase of 0.50 to 0.72 dB/year. For the more open graded pavements, the increase varies between 0.8 and 1.32 dB/year. The increase for multi axle trucks is generally much lower.

3.5 Californian investigation

On the 65 to 76 Californian test pavements the noise was measured by UCPRC using the OBSI measurement method. All the results have been converted, so they represent measurements performed by the SRTT Standard Reference Tire [17] at a reference speed of 96 km/h (60 mph). Temperature corrections are not applied to the results, but according to [27] the SRTT tire is not very sensitive to variations in temperature. The results of noise over the years are grouped for four pavements types (irrespective of maximum aggregate size):

- DGAC
- OGAC
- RAC-O
- RAC-G

The results are presented as the trend of OBSI noise level for each pavement type as well as by an average spectrum for each pavement type in years with data available.

It must be remarked that the layout of this study is much different from the previous four studies where the noise emission from exactly the same pavements has been monitored over the years. In this project a population of pavements (belonging to each pavement type) with different ages are monitored. Each of the pavements has been monitored for three consecutive years (the research continues with the fourth year evaluation in 2009). In addition of tracking each individual section for three years, the study allows for combining sections of nominally the same mix type to obtain a longer time span for pavement of the same type. Combining sections to derive noise trends has some difficulties. Variation in the noise emission can be caused by differences in the design and production of the pavements belonging to the same type for example by the use of different nominal maximum aggregate size (9.5, 12.5 and 19.0 mm) etc. Therefore, a larger spread in the data than in the previous four studies must be expected. Table 3.6 shows Residual Standard Errors in the order of magnitude of 1.3 to 1.5 dB. Due to the spread in the data it will be more difficult to draw firm conclusions on the development of the noise spectra from year to year. The spectra are presented anyway in the following.

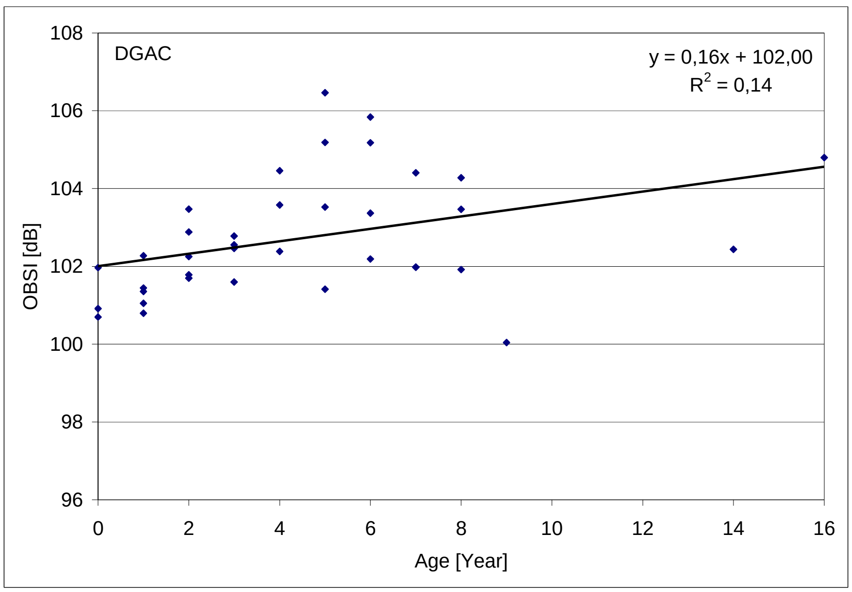


Figure 3.35. OBSI noise level measured for DGAC pavements in the Californian investigation [17].

The yearly increase in noise level for DGAC pavements can be seen in Figure 3.35. The increase is 0.16 dB/year. The frequency spectra in Figure 3.36 shows a “dip” around 1250 Hz when the pavements are 0 to 1 year old. This dip disappears in the second year. This might indicate that the pavements become less open in the surface structure during this period resulting in increased air pumping noise. From the second year, the noise level increases at all frequencies.

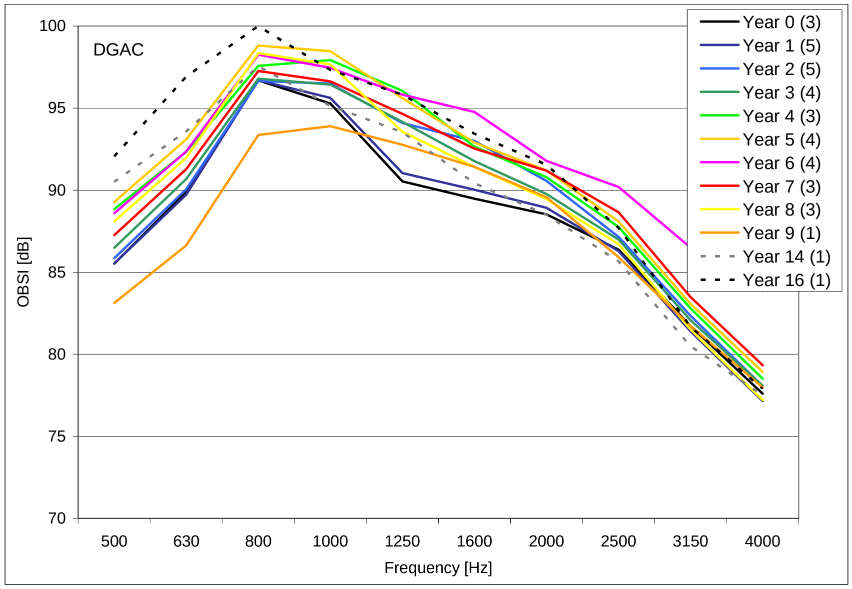


Figure 3.36. Noise spectra for OBSI measurements for DGAC pavements in the Californian investigation. The number in the brackets indicates the number of measurement results that are included in the actual spectrum [17].

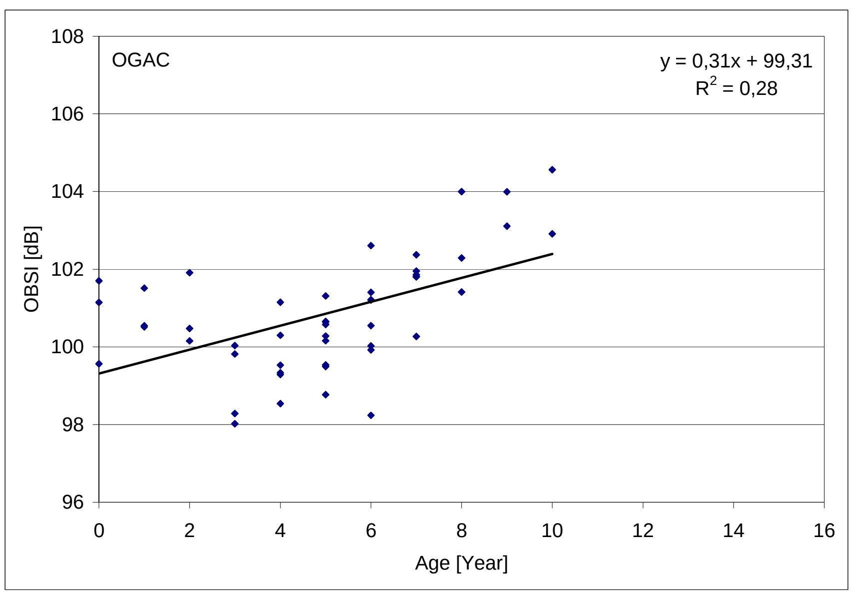


Figure 3.37. OBSI noise level measured for OGAC pavements in the Californian investigation [17].

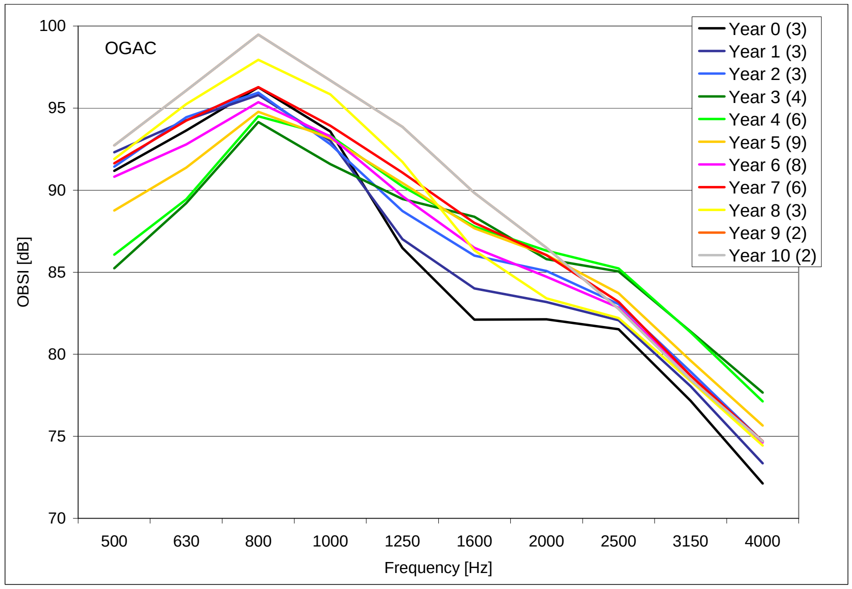


Figure 3.38. Noise spectra for OBSI measurements for OGAC pavements in the Californian investigation. The number in the brackets indicates the number of measurement results that are included in the actual spectrum [17].

The yearly increase in noise level for OGAC pavements can be seen in Figure 3.37. The increase is 0.31 dB/year. The frequency spectra in Figure 3.38 show a "dip" around 1600 Hz when the pavements are 0 to 1 year old, like for the DGAC pavements. This dip disappears in the second year. This might indicate that the pavements become less open in the surface structure during this period, resulting in increased air pumping noise. From the second year, the noise level increases at all frequencies like for the DGAC pavements.

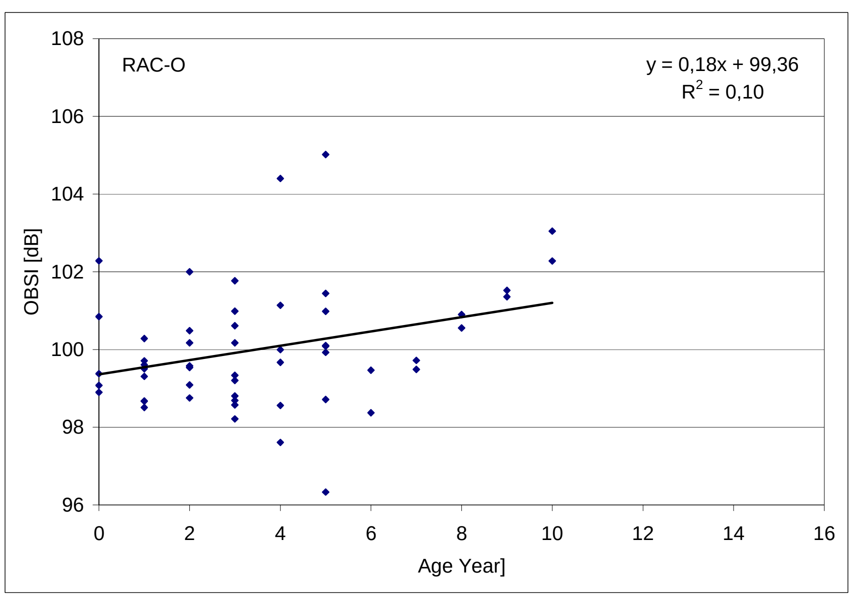


Figure 3.39. OBSI noise level measured for RAC-O pavements in the Californian investigation [17].

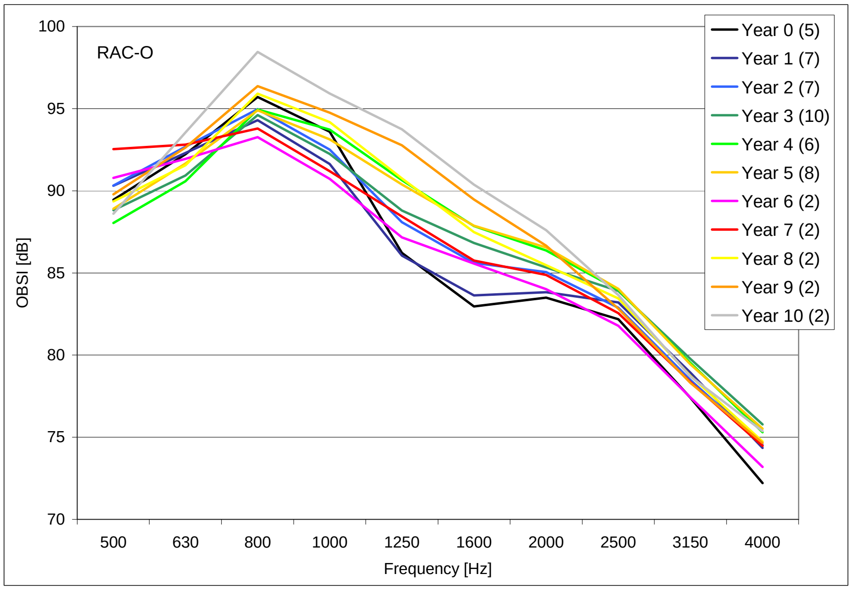


Figure 3.40. Noise spectra for OBSI measurements for RAC-O pavements in the Californian investigation. The number in the brackets indicates the number of measurement results that are included in the actual spectrum [17].

The yearly increase in noise level for the RAC-O pavements can be seen in Figure 3.39. The increase is 0.18 dB/year, similar to that of the DGAC pavements. The frequency spectra in Figure 3.40 also show a “dip” around 1600 Hz when the pavements are new like for the DGAC and OGAC pavements. This might also here indicate that the pavements become less open in the surface structure during this period resulting in increased air pumping noise. From the second year,,the noise level mainly increases in the frequency range between 800 and 2000 Hz.

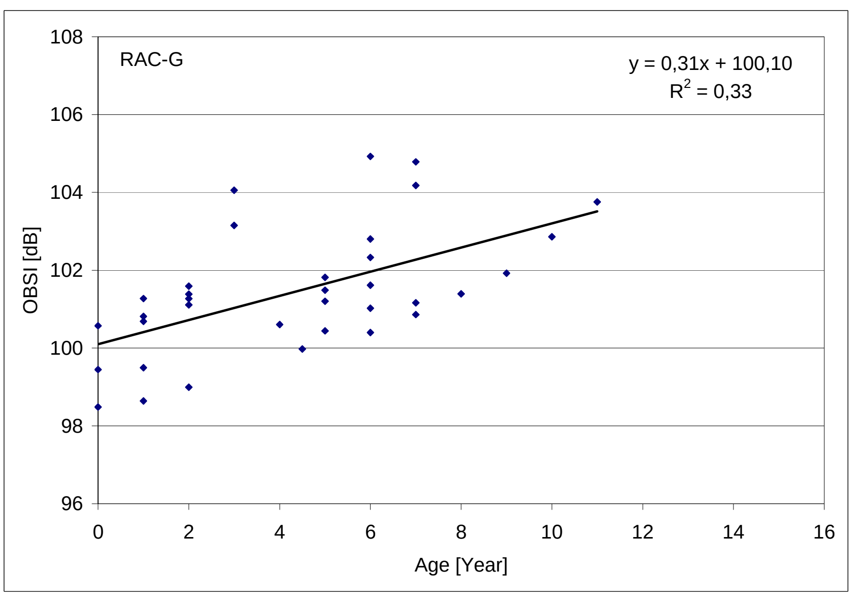


Figure 3.41. OBSI noise level measured for RAC-G pavements in the Californian investigation [17].

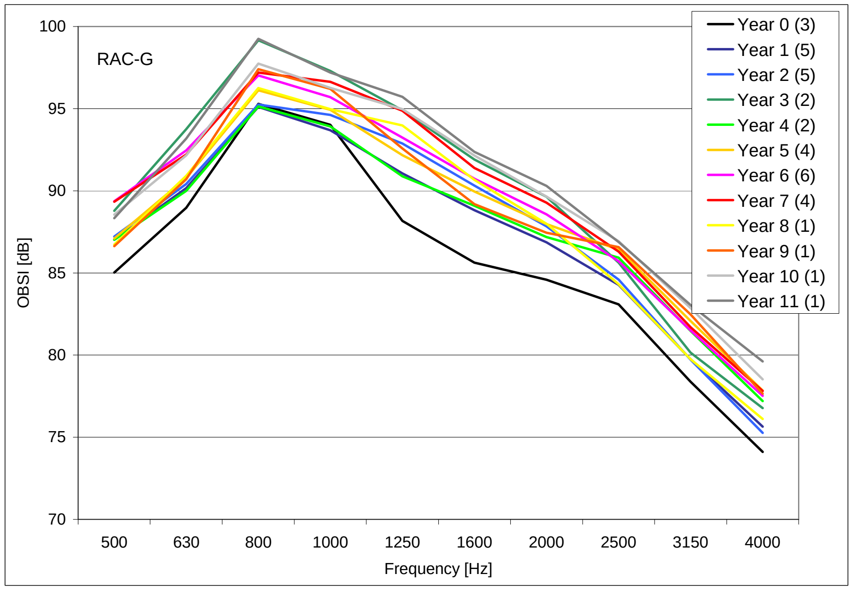


Figure 3.42. Noise spectra for OBSI measurements for RAC-G pavements in the Californian investigation. The number in the brackets indicates the number of measurement results that are included in the actual spectrum [17].

Figure 3.41 shows that the increase in noise level for RAC-G pavements is 0.31 dB/year. The frequency spectra in Figure 3.42 show a "dip" around 1250-1600 Hz when the pavements are new (0 years old) like for the other three pavements types, but this dip disappears in the first year. From the first year, the noise level increases at all frequencies.

Table 3.6. Average noise level increase per year for OBSI noise levels and Residual Standard Error for the four Californian pavement types (reference speed 96 km/h (60 mph).

Pavement	OBSI noise increase	Residual Standard Error
DGAC	0.16 dB/year	1.4 dB
OGAC	0.31 dB/year	1.3 dB
RAC-O	0.18 dB/year	1.5 dB
RAC-G	0.31 dB/year	1.3 dB

Table 3.6 shows a summary of the results for the four pavement types. The noise increase is between 0.16 and 0.31 dB/year.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4. Analysis and comparison

The results from the different test sections in Chapter 3 are compared and evaluated in the following. The comparison is structured in three main parts:

1. The data from all seventeen pavements plus the four pavement types in the Californian investigation are compared (Section 4.1).
2. The data are subdivided into four pavement groups and the results are compared for the pavements in each pavement group (Section 4.2).
3. The average results for each pavement group are compared (Section 4.3).

In Section 4.4, a first attempt to develop a model describing the increase of noise emission for pavements at highways is presented. Such a model could be integrated in a Pavement Management System (PM System) taking noise into consideration.

The results from the I-80 study on OGAC pavements were performed as L_{Aeq} measurements of mixed traffic. Therefore it is not possible to separate the increase of noise from passenger cars and heavy vehicles. As 92.3% of the vehicles at this test site are passenger cars, the results are, as a rough approximation, treated as covering only passenger cars.

4.1 Comparison of all seventeen pavements

The increase in noise level is often expressed as dB per year. But it can be argued that also wear and tear of the traffic (the tires) changes the noise properties of a pavement by changing the surface structure. In order to investigate this, the following five analyses have been performed and the results have been compared for all seventeen pavements:

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 100.000 heavy vehicles passing per lane.
4. $\Delta L_{Mix50/50}$: An artificial indicator defined 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” (see definition in equation 3 below).
5. $\Delta L_{Mix25/75}$: Another artificial indicator defined 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” (see definition in equation 4 below).

Data on the annual average daily traffic per lane and percentage of heavy vehicles can be seen in Table 2.1 in Chapter 2. For multi lane roads, the traffic has for simplicity been distributed evenly on all lanes.

The data from the accelerated Viskinge experiment (Section 3.3) has been modified to an expected lifetime of eleven years (see Table 3.4) in order to make it possible to compare these data directly with the data from the other measurement series.

In the Californian investigation (Section 3.5), the same type of pavements from different roads with different traffic volumes are compared. Therefore it is not possible to analyze these data in relation to traffic volume. This also gives a larger statistical uncertainty on the results (Residual Standard Error 1.3 to 1.5 dB) than the other measurement series where the same pavements have been followed with consecutive yearly measurements (Residual Standard Error 0.1 to 0.8 (1.1) dB). Therefore the results from the Californian investigation are only included in the first comparison of the results in Figure 4.1.

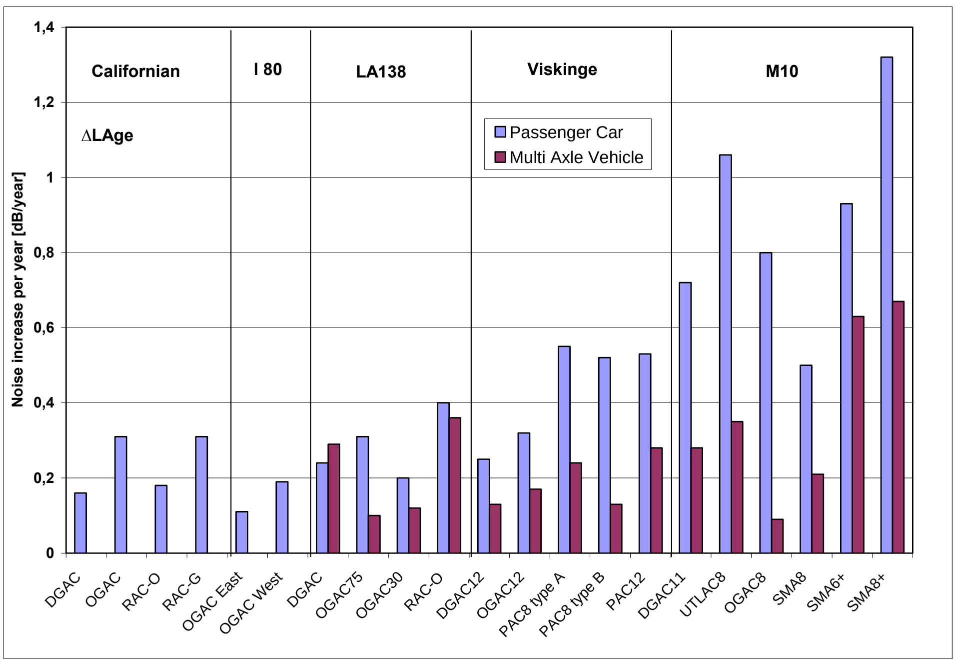

Figure 4.1. ΔL_{Age} noise level increase per year of physical pavement age for all pavements for all test sections for passenger cars and multi axle vehicles.

Figure 4.1 shows an overview of the trends for noise level 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 level increases than the two Californian test roads (I-80 and LA138). For multi axle vehicles the noise increase is not that different.

Figure 4.2 shows the noise level increase per 1 million vehicles (all types of vehicles) passing the test pavement. The noise increase per 1 million vehicles (ΔL_{ADT}) is calculated as follows:

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

Where:

ΔL_{Age} = Increase per year in dB (from Figure 4.1).

ADT = Yearly Average Daily traffic (from Table 2.1).

N = Number of lanes (from Table 2.1).

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 level increase, significantly lower than the LA138 and Viskinge test sites.

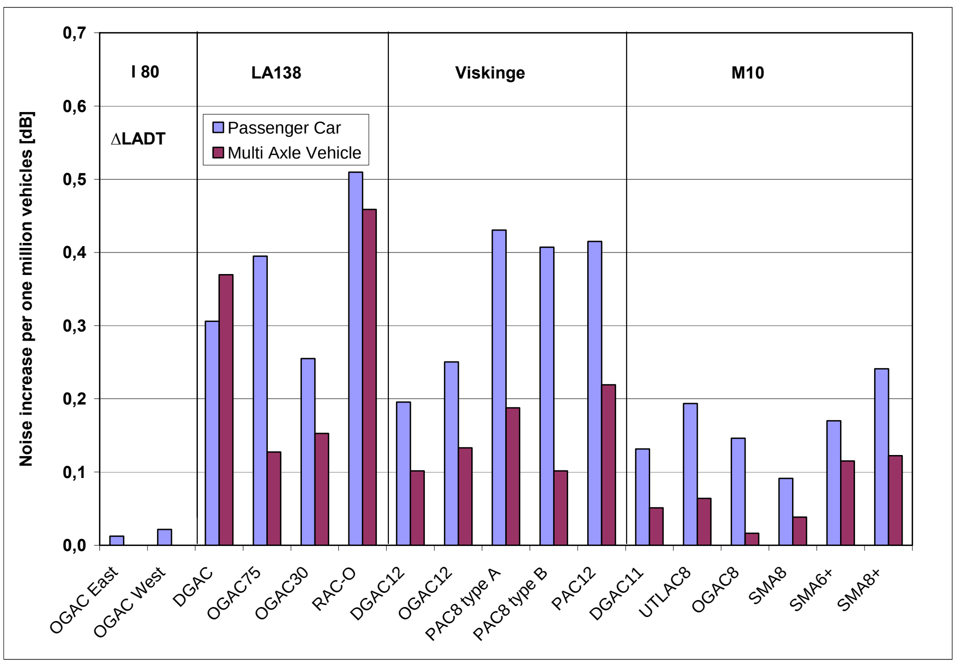

Figure 4.2. ΔL_{ADT} noise increase per 1 million vehicles passing the actual lane for all pavements for all test sections for passenger cars and multi axle vehicles.

Figure 4.3 shows ΔL_{Hvy} the noise increase per 100.000 heavy vehicles passing the actual lane for all pavements. The noise increase per 100.000 heavy vehicles (ΔL_{Hwy}) is calculated as follows:

$$\Delta L_{Hvy} = (\Delta L_{age} \cdot 10^5) / ((ADT \cdot 365/N) \text{ x } HP/100)) \qquad (2)$$

Where:

ΔL_{Age}	=	Increase per year (from Figure 4.1)
ADT	=	Yearly Average Daily traffic (from Table 2.1).
N	=	Number of lanes (from Table 2.1).
HP	=	Percentage of heavy vehicles (from Table 2.1).

Using the noise level increase per 100.000 heavy vehicles does not significantly change the results and ranking of the test sites compared to evaluating the noise increase per one million vehicles passing the test sites because there is not a big variation in the percentage of heavy vehicles on the different test sites varying from 7.6 to 13.2 % with LA138 as an exception with 17 %.

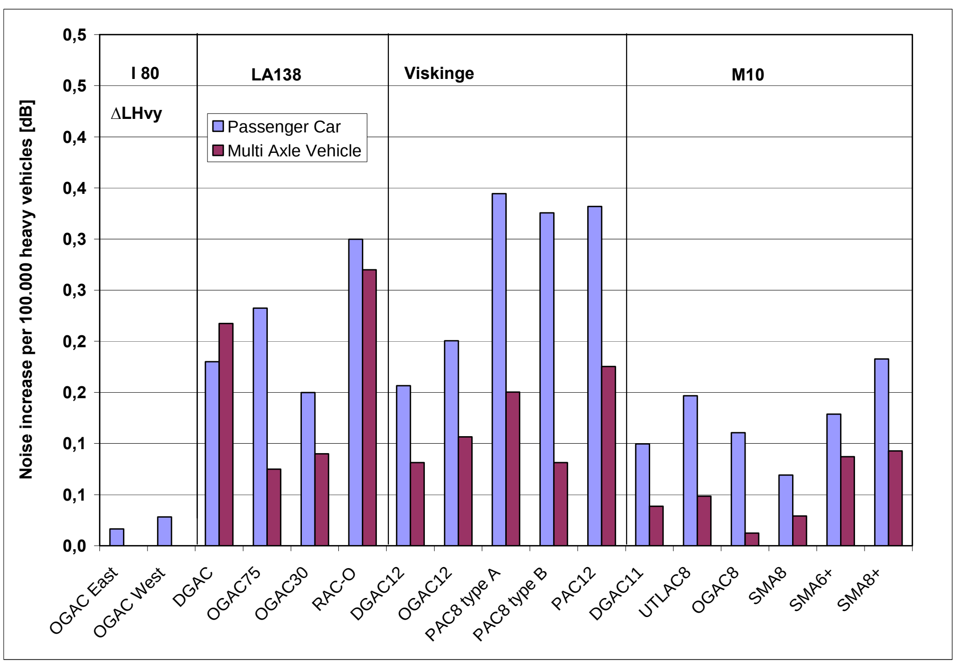

Figure 4.3. ΔL_{Hvy} noise level increase per 100.000 heavy vehicles passing the actual lane for all pavements in four all test sections passenger cars and multi axle vehicles.

It can be argued that the combined effects of both the physical age of a pavement and the wear and tear of the traffic determine 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, a new indicator called "Mixed Indicator" ($\Delta L_{Mix50/50}$) is defined. The indicator $\Delta L_{Mix50/50}$ is calculated as the change of noise as a combination of physical age and traffic load, where age counts for 50 % and traffic load counts for 50 %. This is a 50/50 % combination of ΔL_{Age} and ΔL_{ADT}. $\Delta L_{Mix50/50}$ is calculated as follows:

$$\Delta L_{Mix50/50} = \Delta L_{Age} \cdot 0.5 + \Delta L_{ADT} \cdot 0.5 \qquad (3)$$

Figure 4.4 shows the Mixed Indicator $\Delta L_{Mix50/50}$ for all seventeen pavements. By using $\Delta L_{Mix50/50}$ the difference between the LA138, Viskinge and M10 test sections is reduced remarkably. But the Thin Open layers at M10 still have a higher increase than the porous layers at Viskinge.

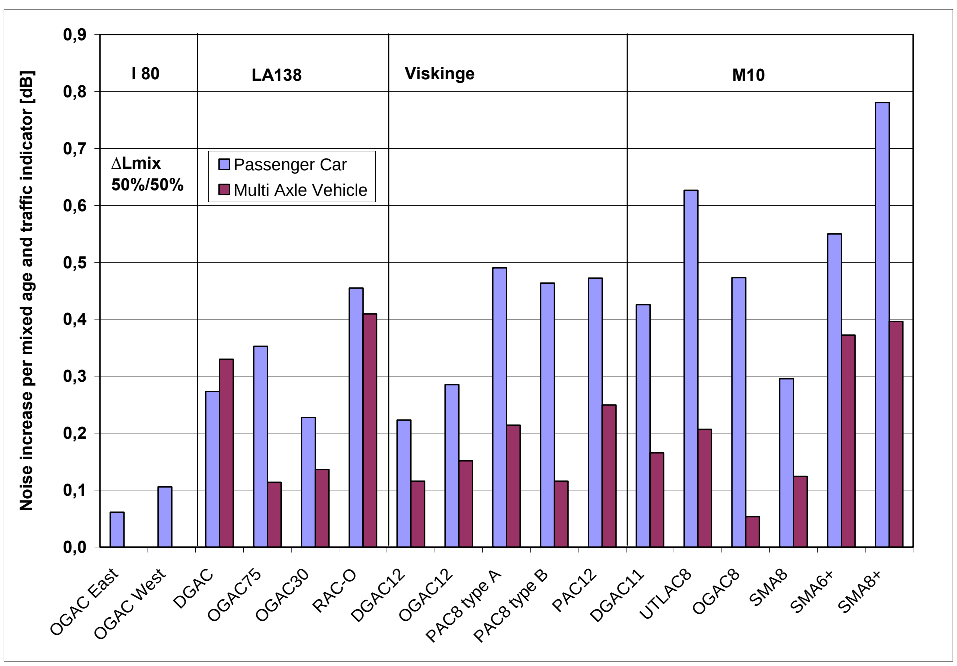

Figure 4.4. $\Delta L_{Mix50/50}$ noise level increase per Mixed Indicator as the change of noise predicted as a combination of physical age and traffic load where the age counts for 50 % and the traffic load counts for 50 %.

It is believed by the authors that the porous pavements at Viskinge should have a higher noise level increase than the Thin Open pavements at the M10 test site because of the tendency of clogging of these porous pavements (see Section 3.3) 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 physical age counts for only 25 % and the traffic volume for 75 % of the noise level increase. This is a 25/75 % combination of ΔL_{Age} and ΔL_{ADT}. The $\Delta L_{Mix25/75}$ indicator is calculated as follows:

$$\Delta L_{Mix25/75} = \Delta L_{Age} \cdot 0.25 + \Delta L_{ADT} \cdot 0.75 \qquad (4)$$

Figure 4.5 shows the Mixed Indicator $\Delta L_{Mix25/75}$ for all seventeen pavements. By using $\Delta L_{Mix25/75}$ the ranking of the LA138, Viskinge and M10 test sections is changed. The porous pavements at Viskinge now generally have a higher noise level increase than the thin layers at M10.

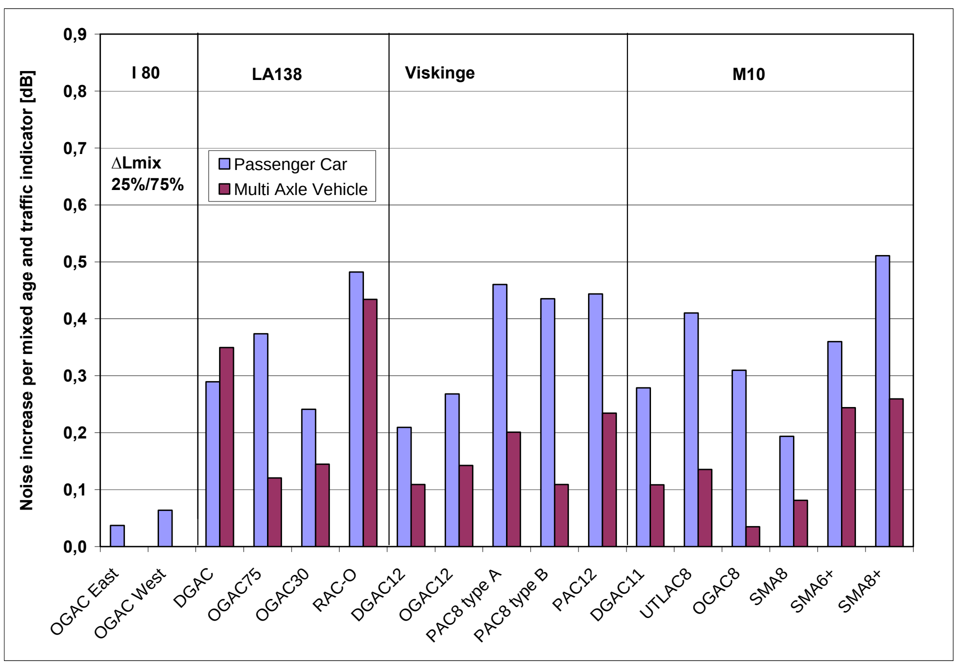

Figure 4.5. ΔLMix25/75 noise level increase per Mixed Indicator as the change of noise predicted as a combination of physical age and traffic load where the age counts for 25 % and the traffic load counts for 75 %.

4.2 Results divided in four pavement groups

In the following figures, pavements belonging to the same type or family are gathered, and the results for three indicators are shown. These are the noise level increase per year and per 1 million vehicles as well as for the “Mixed Indicator” *($\Delta L_{Mix25/75}$)* where the age counts for 25 % and the traffic load counts for 75 %. The increase per 100.000 heavy vehicles is not included as it generally ranks the pavements in the same order as increase per 1 million vehicles (see Section 4.1). The following pavement type groups are included:

- Dense Graded Asphalt Concrete (DGAC) from LA138, Viskinge and M10 (Figure 4.6).
- Open Graded Asphalt Concrete (OGAC) from LA138, Viskinge and M10 (Figure 4.7).
- Porous pavements (PAC) only available at Viskinge (Figure 4.8).
- The Thin Open layers which is mainly different types of noise reducing Open Graded Thin Layers (RAC-O, SMA and UTLAC) from LA138, and M10 (Figure 4.9).

The study at I-80 is based on L_{Aeq} wayside measurements, where it is not possible to separate passenger cars and multi axle vehicles. For this reason, the I-80 results are not included in the analyses of noise level increase per pavement group as it is performed for the two vehicle categories separately. The average increase for the fifteen pavements included is presented for each indicator in the following figures.

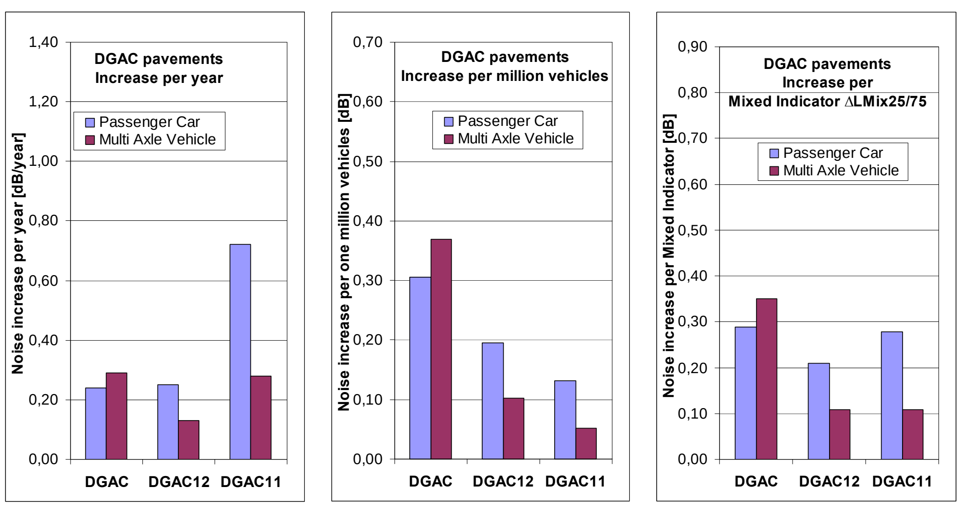

Figure 4.6. Dense graded pavements (DGAC). ΔL_{Age} increase in noise level per year (left), ΔL_{ADT} per 1 million vehicles (middle) and for $\Delta L_{Mix25/75}$ the Mixed Indicator (right).

Figure 4.6 shows the noise level increase for DGAC for the three indicators. When the age is used as parameter the variation for passenger cars is from 0.24 to 0.72 dB/year. For multi axle trucks the variation is smaller (0.13 to 0.29 dB/year).

When using the mixed indicator the variation for passenger cars is significantly reduced (0.21 to 0.29 dB).

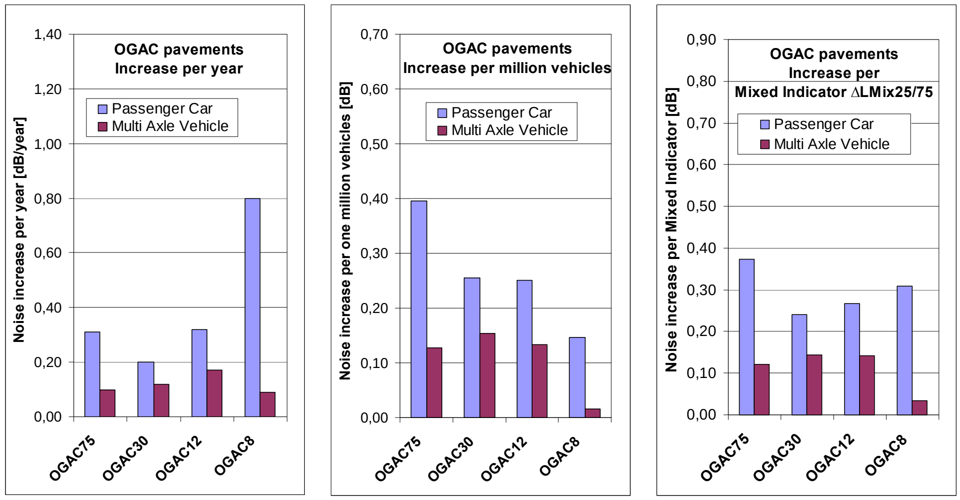

Figure 4.7. Open graded pavements (OGAC). ΔL_{Age} increase in noise level per year (left), ΔL_{ADT} per 1 million vehicles (middle) and for $\Delta L_{Mix25/75}$ the Mixed Indicator (right).

The four OGAC pavements are compared in figure 4.7. When the age is used as parameter, the variation for passenger cars is from 0.20 to 0.80 dB/year. For multi axle trucks the variation is smaller (0.09 to 0.17 dB/year). When using the Mixed Indicator for passenger cars, the variation is reduced to 0.24 to 0.37 dB.

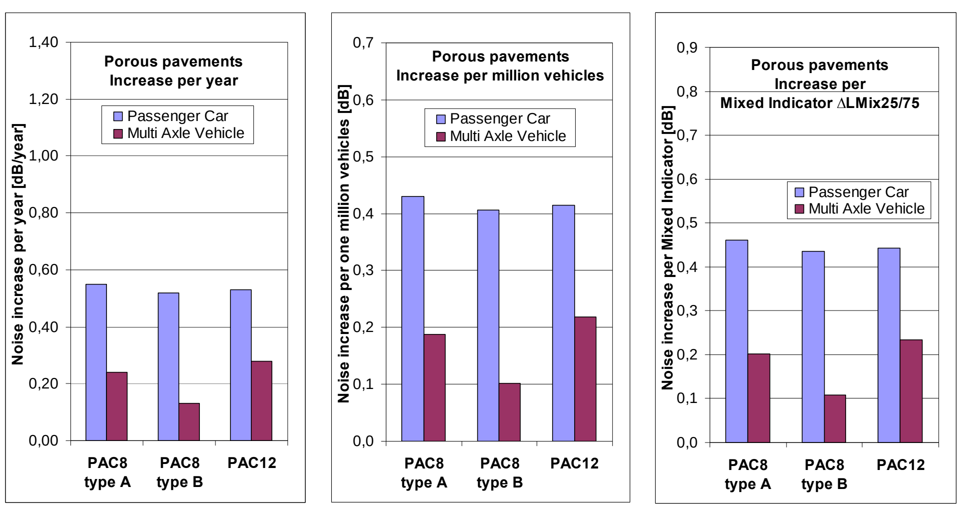

Figure 4.8. Porous pavements (PAC). ΔL_{Age} increase in noise level per year (left), ΔL_{ADT} per 1 million vehicles (middle) and for the $\Delta L_{Mix25/75}$ Mixed Indicator (right).

The three porous pavements are shown in Figure 4.8. The three indicators show the same tendencies. This is because these three pavements are all on the same road so they are all exposed to the same traffic volume. When age is used as parameter, the variation for passenger cars is from 0.52 to 0.55 dB/year. For multi axle trucks the variation is smaller (0.13 to 0.28 dB/year).

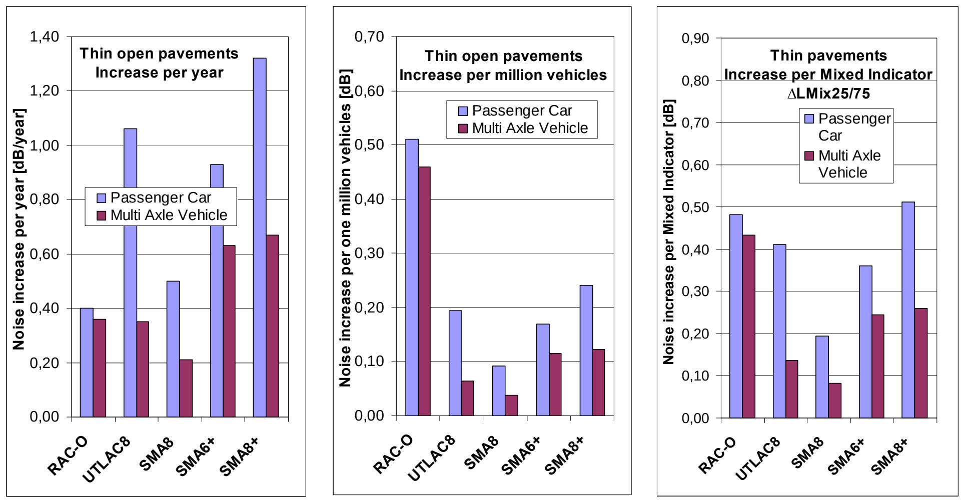

Figure 4.9. The thin layers which are mainly different types of open graded thin layers optimized for noise reduction. ΔL_{Age} increase in noise level per year (left), ΔL_{ADT} per 1 million vehicles (middle) and for $\Delta L_{Mix25/75}$ the Mixed Indicator (right).

Finally the Thin Open layers which are mainly different types of open graded thin layers optimized for noise reduction are shown in Figure 4.9. Also for these pavements, the use of the Mixed Indicator reduces the variation. For age the variation for passenger cars is between 0.40 and 1.32 dB/year. For the mixed indicator the variation is reduced to 0.19 to 0.51 dB.

4.3 Average results for each pavement group

In this section the average results for each pavement group is predicted and compared. This is done for four of the indicators previously described leaving out the $\Delta L_{Mix50/50}$ Mixed Indicator.

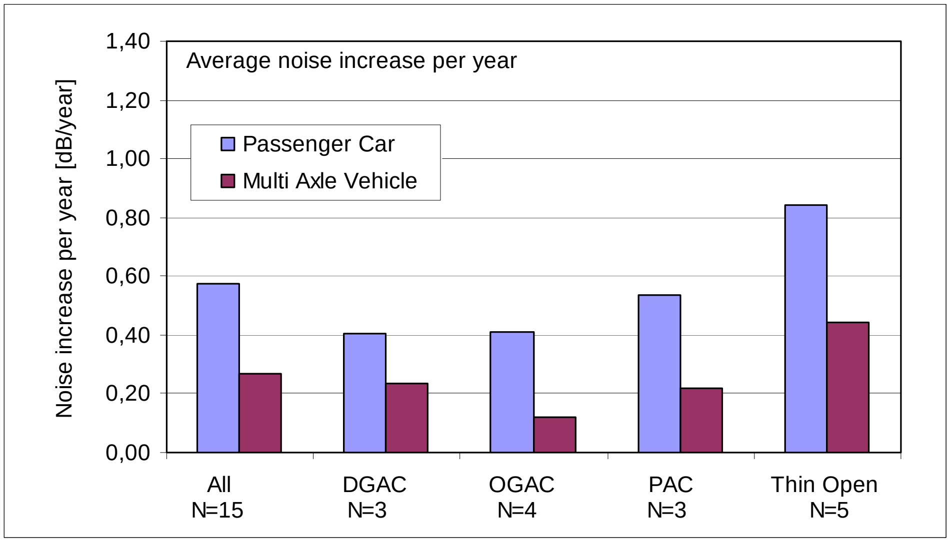

Figure 4.10. ΔL_{Age} average noise level increase per year for all pavements and for each pavement group.

Figure 4.10 shows $\Delta L_{Age,}$ the average noise level increase per year for passenger cars and for multi axle vehicles. For passenger cars, the average increase for all fifteen pavements 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. The increase per year for multi axle vehicles is around 50 % of the increase for passenger cars, and the pavement types are nearly ranked in the same way.

In the SILENCE study [5] an increase of 0.1 dB/year for passenger cars was reported for DGAC pavements (see Section 1.3.1). This is significantly lower (25%) than the result of the current study. For porous and open graded pavements 0.4 dB/year was reported and that is much closer to the results of the current study.

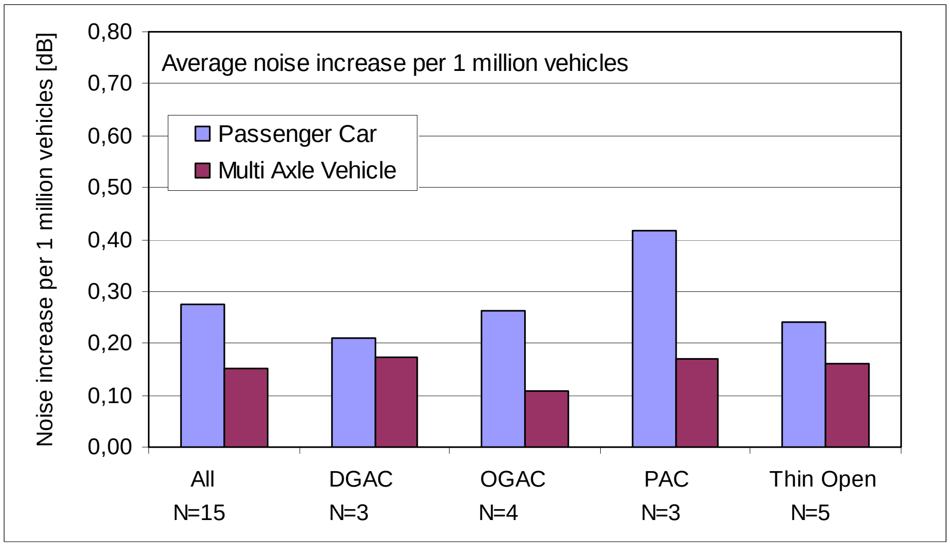

Figure 4.11. ΔL_{ADT} average noise increase per 1 million vehicles for all pavements and for each pavement group.

Figure 4.11 shows ΔL_{ADT} the average noise level increases if the traffic load is expressed in the unit of dB noise level increase per one million vehicles passing the driving lane (assuming even distribution of the traffic across all lanes). Expressed as this indicator, the average for passenger cars for all fifteen pavements is 0.28 dB per 1 million vehicles. For DGAC and OGAC, the increase is respectively 0.21 and 0.26 dB per 1 million vehicles. This is almost the same as for Thin Open pavements (0.24 dB per 1 million vehicles). For porous pavements, the increase is higher (0.42 dB per 1 million vehicles).

Figure 4.12 shows ΔL_{Hvy} the noise increase per 100.000 heavy vehicles passing the driving lane (assuming even distribution of the heavy traffic across all lanes). The same tendencies that were seen using the one million vehicles indicator can be observed.

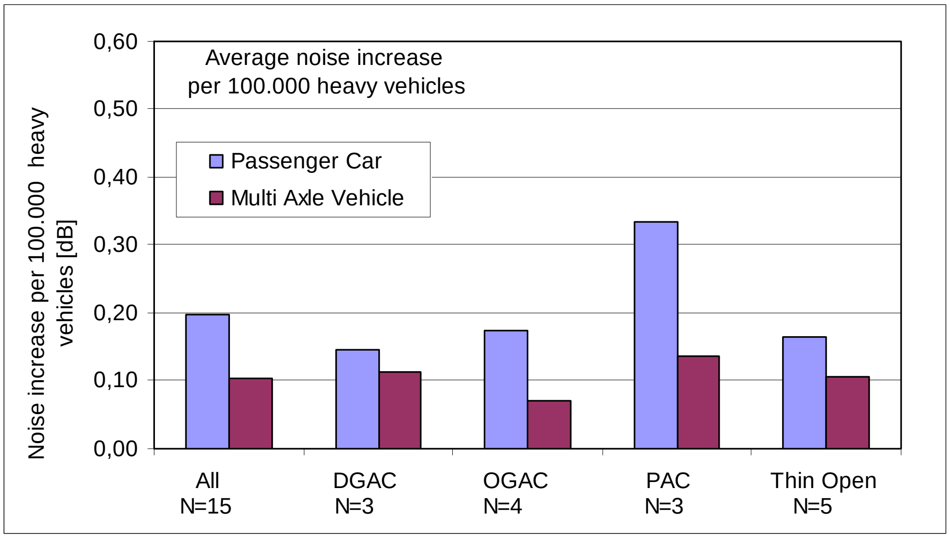

Figure 4.12. ΔL_{Hvy} average noise level increase per 100.000 heavy vehicles for all pavements and for each pavement group.

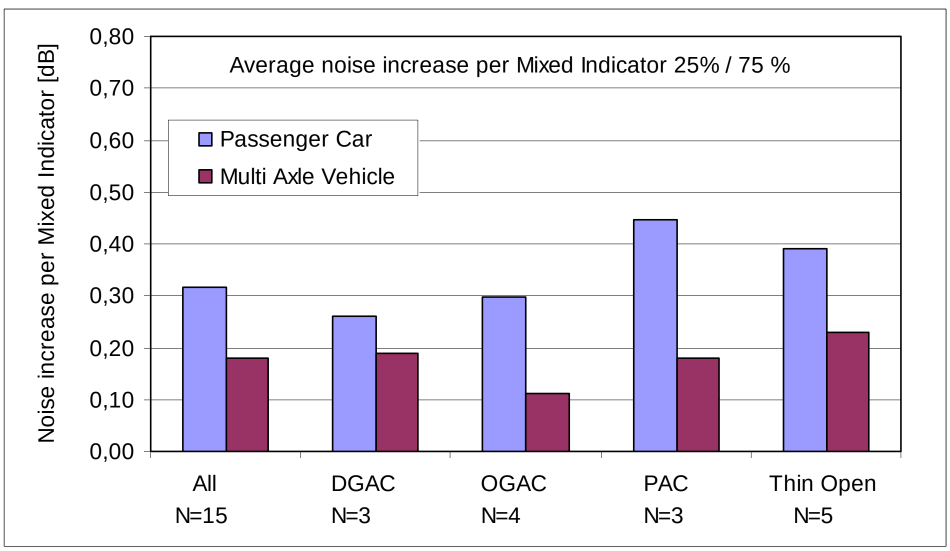

Figure 4.13. $\Delta L_{Mi25/75x}$ average noise level increase for the Mixed Indicator for all pavements and for each pavement group.

Finally, Figure 4.13 shows the results using $\Delta L_{Mix25/75}$ the Mixed Indicator which is an attempt to combine the physical age of a pavement with the exposure to traffic load (see Section 4.1). The average $\Delta L_{Mix25/75}$ for passenger cars is 0.32 dB. The ΔL_{Mix} 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. The Thin Open pavements follow with an increase of 0.39 dB. The porous pavements have the highest increase of 0.45 dB using the ΔL_{Mix} indicator.

Table 4.1 and Table 4.2 summarize the results of noise level increase expressed by the four indicators respectively for passenger cars and multi axle heavy vehicles.

Table 4.1. The average noise level increase for passenger cars for the four pavement groups expressed as the four indicators ΔL_{Age}, ΔL_{ADT}, ΔL_{Hvy} and $\Delta L_{Mix25/75}$.

Pavement type	**ΔL_{Age} [dB/year]**	**ΔL_{ADT} [dB/1 mil vehicles]**	**ΔL_{Hvv} [dB/100.000 heavy vehicles]**	**$\Delta L_{Mix25/75}$ [dB/mix]**
All average	0,58	0.28	0.20	0.32
DGAC	0.40	0.21	0.15	0.26
OGAC	0.41	0.26	0.17	0.30
Thin Open	0.84	0.24	0.17	0.39
PAC	0.53	0.42	0.33	0.45

Table 4.2. The average noise level increase for multi axle heavy vehicles for the four pavement groups expressed as the four indicators ΔL_{Age}, ΔL_{ADT}, ΔL_{Hvy} and $\Delta L_{Mix25/75}$.

Pavement type	**ΔL_{Age} [dB/year]**	**ΔL_{ADT} [dB/1 mil vehicles]**	**ΔL_{Hvv} [dB/100.000 heavy vehicles]**	**$\Delta L_{Mix25/75}$ [dB/mix]**
All average	0.27	0.15	0.10	0.18
DGAC	0.23	0.17	0.11	0.19
OGAC	0.12	0.11	0.07	0.11
Thin Open	0.44	0.16	0.11	0.23
PAC	0.22	0.17	0.14	0.18

4.4 Model for noise increase

If noise is to be integrated in a Pavement Management System one of the necessary building stones is a model that can describe the increase of noise emission as time and traffic go by on different pavement types. The results of the present analyses can be used as a first attempt to develop such a model. From the analyses performed in the previous sections of this chapter it seems most relevant to develop such an aging model taking both the physical age of a pavement and the traffic load into consideration. Therefore the model will be set up using the $\Delta L_{mix25/75}$ indicator.

The model predicts the increase in noise ΔL_{aging}(A) that has to be added to the noise emission of pavements when they are new - no more than one year old - as a function of the traffic volume on a given road. These initial noise levels have to be measured or defined as a starting point. The results of this current project can be used as a first input to the establishment of noise level changes for PM Systems.

$$\Delta L_{Aging}(A) = (0.25 \cdot \Delta L_{Age} \cdot A) + ((0.75 \cdot \Delta L_{ADT} \cdot ADT \cdot 365 \cdot A) / (10^6 \cdot N)) \qquad (5)$$

Where:

ΔL_{Age} defined in Table 4.3 [dB] as age component of noise level increase.

ΔL_{ADT} defined in Table 4.3 [dB] as traffic load component of noise level increase (noise increase per 1 mil vehicles).

A is the physical age of the pavement in years.

ADT = Average Daily Traffic (total of both directions).

N = Number of lanes (total of both directions).

Table 4.3. Factors for noise level increase for the noise increase model based on the analyses in Section 4.3 (Table 4.1).

Pavement type	**DGAC**	**OGAC**	**Thin Open**	**PAC**
ΔL_{Age}	0.40 dB/year	0.41 dB/year	0.84 dB/year	0.53 dB/year
ΔL_{ADT}	0.21 dB/1 mil vehicles	0.26 dB/1 mil vehicles	0.24 dB/1 mil vehicles	0.42 dB/1 mil vehicles

This aging model and specially the aging factors included in Table 4.3 are developed on the background of long-time measurement series at different highways with speed limits ranging from 80 to 110 km/h (50 to 69 mph). Therefore this model is primarily valid for highways with speeds over 80 km/h (50 mph).

The model could be improved and refined by:

- Refine the ΔL_{mix} indicator by testing different ways of constructing the indicator like other weighting of age and traffic volume.
- Refine the ΔL_{Age} and ΔL_{ADT} indicators for different environmental conditions or climate regions.
- Integrate the noise level increase of heavy vehicles that is normally lower than for passenger cars. This can be done by including the percentage of heavy vehicles and the average increase for multi axle trucks in the model.
- Improve factors for increase per year. In order to do so more data on measured noise level increase on roads with different pavements has to be retrieved.
- Make one version for high speed roads and highways and another for urban lower speed roads. According to the SILENCE aging study [5], there is a difference in the noise increase for porous and open pavements on low and high speed roads.

5. Conclusions and recommendations

The development of traffic noise emission on different pavement types used on highways has been analyzed on the background of long-time measurement series carried out in California and in Denmark. In this project the main focus has been on the development of noise over time. 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. The pavements included in this project were grouped in the following main types:

- DGAC Dense Graded Asphalt Concrete
- OGAC Open Graded Asphalt Concrete
- PAC Porous Asphalt Concrete
- Thin Open Asphalt Layers

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

- The noise level on asphalt pavements normally increases with time.
- The increase occurs continuously and before significant pavement deterioration with raveling and cracks etc. begins.
- There are exceptions where the noise level is reduced over the first year for porous pavements.
- A linear regression gives a good fit of the relation between pavement age and noise level both for passenger cars and multi axle heavy vehicles. This was also seen in the European SILENCE study.
- The yearly noise level increase is generally around double as high for passenger cars than for heavy vehicles.

In this project different parameters have been used to describe the increase of noise with time. The increase in noise is often expressed as dB per year, but wear and tear of the traffic also has an influence on the changes of the noise properties of a pavement. It can be argued that the combined effects of both the physical age of a pavement and the wear and tear due to the traffic load determine the increase of noise levels. 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 new indicators called “Mixed Indicator” ($\Delta L_{Mix50/50}$ and $\Delta L_{Mix25/75}$) have been defined. The noise increase has been analyzed for five different indicators:

1. ΔL_{Age}: The change of noise level per year (actual physical age of the pavement).

2. ΔL_{ADT}: The change of noise level per 1 million vehicles (all types) passing per lane.
3. ΔL_{Hvy}: The change in noise level per 100.000 heavy vehicles passing per lane.
4. $\Delta L_{Mix50/50}$: A new indicator as the change of noise level 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. $\Delta L_{Mix25/75}$: A new indicator as the change of noise level 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 showed that the ΔL_{ADT} and the ΔL_{Hvy} resulted in the same ranking of the pavements presumably because there was no big variation in the percentage of heavy vehicles in the road data included. By using $\Delta L_{Mix25/75}$ instead of $\Delta L_{Mix50/50}$, the porous pavements generally have a higher noise level increase than the thin layers, which is believed to be correct as the porous pavements has a tendency of clogging which is not seen on non-porous thin layers. Therefore the following three indicators ΔL_{Age}, ΔL_{ADT} and $\Delta L_{Mix25/75}$ have been found to be the most relevant for the description of the development of noise emission. The results for these three indicators for the four pavement types can be seen in table 5.1 for passenger cars.

Table 5.1. The average noise level increase for passenger cars for the four pavement groups expressed as the four 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	0.58	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

The average noise level 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 load (ΔL_{ADT}) is taken into consideration as an indicator for noise level increase, the ranking of the pavement types changes significantly. The increase for the porous pavements is almost twice the increase for the dense, thin, or open graded asphalt concrete pavements.

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. The Thin Open pavements follow next 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.

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 ("post compaction", increased air pumping noise). After some years there is also an increase in frequencies below 1600 Hz indicating that the pavement surface becomes rougher with an increase in the tire vibration 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 ("post compaction") and after some years there is also an increase in frequencies below 1600 Hz indicating that the pavement surface becomes rougher with an increase in the tire vibration noise. But for some of the pavements 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 tire vibration 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 noise over 1000 Hz presumably because of increased generation of air pumping noise. As the porous pavements get older there is an increase in the low frequency noise (below 1600 Hz) indicating increased tire vibration noise caused by a rougher pavement surface structure.
- When heavy raveling occurs, the tire vibration generated low frequency noise (below 1600 Hz) increases for all pavement types.

A first attempt to develop a noise emission performance model for pavements on highways has been made. Such a model can be used as a building stone if noise is to be integrated in a Pavement Management System. The results from this project indicate that it seems most relevant to develop such an aging model taking both the physical age of a pavement as well as the traffic load into consideration. The model has been developed using the $\Delta L_{mix25/75}$ indicator.

The model predicts the increase in noise $\Delta L_{aging}(A)$ that has to be added to the noise emission of highway pavements when they are new (not more than one year old) as a function of the age of the pavement, the traffic load , and the pavement type. The proposed model is the following:

$$\Delta L_{Aging}(A) = (0.25 \cdot \Delta L_{Age} \cdot A) + ((0.75 \cdot \Delta L_{ADT} \cdot ADT \cdot 365 \cdot A) / (10^6 \cdot N))$$

Where:

ΔL_{Age} defined in Table 4.5 [dB/year] as age component of noise level increase.

ΔL_{ADT} defined in Table 4.5 [dB/1 mil vehicles]] as traffic load component of noise level increase.

A is the physical age of the pavement in years.

ADT = Average Daily Traffic (total of both directions).

N = Number of lanes (total of both directions).

This model is primarily developed for highways with speeds over 80 km/h (50 mph). This is a first version of a pavement noise performance model that can be improved and refined as more knowledge is gained.

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

- The first version of a noise emission performance model for highway pavements has been developed and can be used in Pavement Management Systems as a building stone to integrate noise as an important parameter in such systems.
- The noise emission performance model can be improved and refined like for example by including analyses of pavements on urban roads with lower speed.
- There is a need for further research in order to give a better understanding which changes in the pavement surface structure cause the noise increase. Detailed analyses of pavement structure and noise spectra etc. might be a way to follow.
- More long-time measurement series are needed to get an even better understanding of the noise level increase as a function of pavement age.
- It is important, whenever possible, to follow the development of noise at existing experimental road pavement tests sections from the time they are new until they are replaced.
- 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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