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Temperature Influence on Road Traffic Noise: Californian OBSI Measurement Study

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Abstract: The work described in this report is adjunct to a five-year study of tire/pavement noise undertaken by the University of California Pavement Research Center for the California Department of Transportation under the Partnered Pavement Research Center program (PPRC). This part of the study was performed in cooperation with the Danish Road Institute/Road Directorate, and it examined the influence of air temperature on tire/pavement noise measurements performed on two types of tires (Aquatred and Standard Reference Test Tire [SRTT]) on different asphalt pavement surfaces using the On-board Sound Intensity (OBSI) method.

Field noise measurement testing was carried out in two series: one in the Southern California desert on State Route 138 using the SRTT, and the other with data collected on a statewide selection of pavements tested with the Goodyear Aquatred tire in an earlier part of the PPRC noise study. The field measurements yielded data for deriving air temperature coefficients for the two types of tires, and a comparison of them is made.

A worldwide survey of the available literature accompanies the field work and analysis, and a summary of it is used to compare the air temperature coefficients of the SRTT with a combination of tire types used in European testing. In addition, findings in the literature serve as the basis for a series of predicted temperature coefficients for passenger cars on various cement concrete and asphalt pavements.

Finally, the report presents ten general conclusions drawn regarding the relationship between air temperature correction and tire/road noise on asphalt and concrete pavements.

Keywords: Tire/pavement noise, On-board sound intensity, Temperature influence, Temperature coefficient

Proposals for implementation: It is recommended that Caltrans begin using the temperature corrections noted in this report in its measurements.

Related documents:

- 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
- H. Bendtsen, H., Q. Lu, and E. Kohler. 2009. *Acoustic Aging of Asphalt Pavements: A Californian/Danish Comparison.* Reprint report. UCPRC-RP-2010-01
- 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
- E. Kohler. 2010. *Quieter Pavement Research: Concrete Pavement Tire Noise.* Research report: UCPRC-RR-2010-03

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DISCLAIMER

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Temperature influence on road traffic noise

Californian OBSI measurement study

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Executive summary

International experience indicates that temperature is a factor which has some influence on the results of measurements of road traffic noise. The objective of this report is to analyze how temperature affects the On-Board Sound Intensity (OBSI) measurements of tire/pavement noise. The results are also relevant for the Close Proximity method (CPX) if a Standard Reference Test Tire (SRTT) is utilized. It can be discussed whether the temperature coefficient shall be given in relation to the air, pavement or tire temperature. There has so far been some international tendency to use air temperature as an independent variable so this will be done in the following.

The work presented in this document was done by analyzing two sets of measurement data. A series of detailed OBSI noise measurements with the SRTT were performed on the Caltrans test sections at highway LA138 in the Mojave Desert in Southern California. The measurements were carried out in the desert in wintertime where the variation of the air temperature over the day was from to 2 to 22°C. The noise has been measured on the same day or within a few consecutive days with the same equipment, by the same operator, and on the same pavements, at low (morning), medium (midday), and high (afternoon) temperatures. This ensures that the only main variable parameter during these measurements was the temperature. In the second measurement series, a Goodyear Aquatred tire was used, which was the former standard test tire for OBSI. The variation of the pavement temperature over the day was from to 11 to 35°C.

The objective was to perform measurements where the only variable was the temperature and where the following factors were constant:

- Same measurement tire.
- Same inflation and rubber hardness of the measurement tire.
- No changes in age, tear and wear of the measurement tire.
- Same acoustical measurement equipment.
- Measurement tire mounted on the same car.
- Same measurement operator.
- No changes in pavement conditions other than the temperature.

The coefficients of noise vs. temperature measured with the SRTT and the Aquatred tire are significantly different. The average air temperature coefficient for the Aquatred tire is three times higher than for the SRTT depending on the pavement type. This means that the Aquatred tire is much more sensitive to temperature than the SRTT. The tire hardness was a little lower for the SRTT than for the Aquatred tire (67 versus 69 Shore A). This might partly explain this difference in temperature coefficients but other tire properties like the chemical composition of the rubber, the tread pattern and the tread depth differences etc. might also play a role.

The results from different international measurement series are also summarized in the report. SRTT have significantly lower temperature correction factors than the other tires and tire populations included in the comparison. This shows that the SRTT is not very sensitive to temperature variations. The average air temperature coefficient for the SRTT on asphalt concrete pavements is -0.027 dB/°C. There is no big difference between dense and open graded pavements: -0.029 dB/°C versus - 0.026 dB/°C. Therefore it is suggested that -0.027 dB/°C be used as the air temperature correction factor for the SRTT used on asphalt pavements. Third octave band correction factors have also been determined. There has not been any data available to evaluate the temperature correction coefficient for the SRTT used on cement concrete pavements.

A series of rough general average air temperature coefficients for passenger cars at the different pavement types are predicted and shown in the table below. These coefficients are predicted on the background of the results from the different international measurement series summarized in the report and the measurements carried out in this project. There is no big difference between temperature corrections for dense (-0.061 dB/°C) and open graded asphalt pavements (-0.052 dB/°C). The correction factor for cement concrete pavements is -0.043 dB/°C and lower than for asphalt concrete pavements.

Dense asphalt pavements (DGAC)	Open graded asphalt pavements (OGAC)	Average all asphalt pavement types	Cement concrete pavements
-0.061 dB/°C	-0.052 dB/°C	-0.057 dB/°C	-0.043 dB/°C

These general correction factors are relevant in relation to measurement methods where a large amount of different light vehicles and tires are included like the Statistical Pass-By method or L_{Aeq} measurements. Generally these results are quite close to the coefficient of -0.05 dB/°C for passenger cars commonly used in Denmark and the Netherlands, and to the coefficient used in the EU tire noise directive of -0.06 dB/°C up to 20 °C. These factors are approximately double of those for the SRTT on asphalt tested in California.

The following general conclusions can be drawn regarding temperature corrections to tire/road noise measurements:

- The air temperature has an important influence on the tire/road noise measurements results.
- The dependence of tire/road noise on temperature can be approximated by a linear relation.
- The temperature coefficient varies significantly for different tire types.
- The temperature coefficient is generally smaller for truck tires than for passenger car tires.

- At low frequencies, the temperature coefficient is low. At frequencies above 1000 Hz the temperature coefficient is higher.
- The temperature coefficient is different for different pavement types.
- The temperature coefficient seems to be higher for dense asphalt concrete than for open/porous asphalt pavement.
- The temperature coefficient seems to be lower for cement concrete pavements than for asphalt concrete pavements.
- The difference in temperature coefficients for different asphalt pavement types almost vanishes when many different tires are included.
- Temperature coefficients have to be determined specifically for each measurement method taking into consideration the specific test tire(s) or the tire population included in the measurements.

Sammenfatning

Internationale erfaringer viser, at temperaturen er en faktor som har en vis indflydelse på resultaterne af målinger af vejtrafikstøj. Formålet med denne rapport er at analysere, hvorledes temperatur influerer på On-Board Sound Intensity (OBSI) målinger af dæk/vejstøj. Resultaterne er også vigtige for Close Proximity metoden (CPX), såfremt et Standard Reference Test Tire (SRTT dæk) anvendes.

Arbejdet, der præsenteres i denne rapport blev udført ved at analysere to sæt måledata. En række detaljerede OBSI støjmålinger med SRTT dæk blev udført på Caltrans' (vejdirektoratet i Californien) prøvestrækninger på LA138 i Mojave ørkenen i det sydlige Californien. Målingerne blev foretaget i vintermånederne, hvor variation af lufttemperaturen om dagen var fra 2 til 22 °C. Støjen blev målt den samme dag eller inden for et par efterfølgende dage med det samme udstyr, den samme operatør, og på de samme belægninger, ved lav formiddagstemperatur, mellem middagstemperatur og høje eftermiddagstemperaturer. Dette sikrer, at den eneste vigtigste variabel i løbet af disse målinger er temperaturen. I den anden måleserie anvendtes et Goodyear Aquatred dæk, som var det tidligere standard testdæk for OBSI metoden. Variationen i belægningens temperatur i løbet af dagen var fra 11 til 35 °C.

Formålet var at udføre målinger, hvor den eneste variabel var temperaturen, og hvor følgende faktorer var ens:

- Samme måledæk
- Samme tryk og gummihårdhed af måledækket
- Ingen ændringer i alder og slitage af måledækket
- Samme akustisk måleudstyr
- Måledækket monteret på den samme bil
- Samme måleoperatør
- Ingen ændringer i slitagen af vejbelægningerne.

Målingerne med SRTT dæk og Aquatred dæk viser en markant forskel i temperaturkoefficienterne for disse to dæk. Den gennemsnitlige lufttemperaturkoefficient for Aquatred dæk var 3 gange højere end for SRTT afhængig af belægningstype. Dette betyder, at Aquatred dækket er langt mere følsomt over for temperatur end et SRTT. Dækkets hårdhed var lidt lavere for SRTT end for Aquatred dækket (67 mod 69 Shore A). Dette kan delvis forklare forskellen i temperaturkoefficienterne, men andre dækegenskaber, så som den kemiske sammensætning af gummiet, slidbanemønsteret og mønsterdybden osv. kan spille en rolle.

Resultaterne fra forskellige internationale måleserier er sammenfattet i rapporten. SRTT har markant lavere temperaturkoefficienter end de andre dæk og dækgrupper, som indgår i sammenligningen. Dette viser, at SRTT dæk ikke er særlig følsomme over for temperaturvariationer. Den gennemsnitlige lufttemperaturkoefficient for SRTT på asfaltbetonbelægninger var -0,027 dB/°C. Der var ingen stor forskel mellem tætte og åbne belægninger: -0,029 dB/°C mod -0,026 dB/°C. Derfor er det foreslået at anvende -0,027 dB/°C som den lufttemperaturkoefficient for SRTT dæk som bruges på asfaltbelægninger. Tredjedel oktavbånd korrektionsfaktorer er også blevet fastlagt. Der findes ingen data til at vurdere lufttemperaturkoefficienten for SRTT dæk brugt på betonbelægninger.

På baggrund af resultaterne fra de forskellige internationale måleserier, som er sammenfattet i rapporten, og de målinger, der er gennemført, er en række gennemsnitlige lufttemperaturkoefficienter for personbiler på de forskellige belægningstyper beregnet (se tabellen nedenfor). Der er ingen stor forskel mellem lufttemperaturkoefficienten for tætte (-0,061 dB/°C) og åbne asfaltbelægninger (-0,052 dB/°C). Lufttemperaturkoefficienten for betonbelægninger er -0,043 dB/°C og lavere end for asfaltbetonbelægninger.

Tætte asfaltbelægninger	**Åbne asfaltbelægninger**	**Gennemsnit alle asfaltbelægninger**	**Betonbelægninger**
-0,061 dB/°C	-0,052 dB/°C	-0,057 dB/°C	-0,043 dB/°C

Disse generelle lufttemperaturkoefficienter er relevante i forhold til målemetoder, hvor en stor mængde forskellige lette køretøjer og dæk er medtaget, som ved Statistical Pass-By-metoden (SPB) eller L_{Aeq} målinger. Generelt er disse resultater ganske tæt på koefficienten -0,05 dB/°C for personbiler, der almindeligvis anvendes i Danmark og Holland, og koefficienten, der anvendes i EU dækstøjdirektivet af -0,06 dB/°C op til 20 °C.

På baggrund af dette projekt kan følgende generelle konklusioner drages angående lufttemperaturkoefficienter ved dæk/vejstøjmålinger:

- Temperaturen har en vigtig indflydelse på dæk/vejstøjmåleresultater.
- Der er en lineær afhængighed mellem temperatur og dæk/vejstøj.
- Temperaturkoefficienten varierer betydeligt for forskellige dækmodeller.
- Temperaturkoefficienten er generelt mindre for lastbildæk end for dæk til personbiler.
- Ved lave frekvenser er temperaturkorrektionskoefficienten lav. Ved frekvenser over 1000 Hz er temperaturkorrektionskoefficienterne højere.
- Temperaturkoefficienten varierer efter belægningstyperne.
- Temperaturkoefficienten synes at være højere for tæt asfaltbeton end åbne/drænasfaltbelægninger.

- Forskellen i temperaturkoefficienten for forskellige typer asfalt forsvinder næsten, når mange forskellige dæk er inkluderet.
- Temperaturkoefficienten synes at være lavere for betonbelægninger end asfaltbetonbelægninger.
- Temperaturkoefficienten skal fastsættes specifikt for de enkelte målemetoder under hensyntagen til de specifikke testdæk eller dækgrupper, som indgår i målingerne.

Preface

International experiences indicate that temperature is a factor which has some influence on the results of measurements of road traffic noise. The On Board Sound Intensity (OBSI) method is used by University of California Pavement Research Center (UCPRC) as well as by other researchers and consultants in USA to perform detailed measurements of tire noise emission from road pavements. The OBSI method is frequently used in noise projects performed for the California Department of Transportation (Caltrans). An Expert Task Group organized by the U.S. Federal Highway Administration is currently working on a standard for the OBSI method, which is expected to be adopted by the American Association of State Highway and Transportation Officials (AASHTO) as standard AASHTO TP-76. In Europe the Close Proximity method (CPX) is currently used to perform detailed measurements of tire noise emission from road pavements.

Reliable and accurate noise data is an important factor for efficient implementation and use of noise reducing pavements by road administrations. The objective of this current report is to analyze how the temperature affects the results of noise measurements performed according to the OBSI method as it is currently applied by the UCPRC, through the use of an SRTT test tire. The results are also relevant for the CPX method with an SRTT applied. The report can also be seen as a contribution to the ongoing international work on development of standardization of noise measurement methods like the CPX and wayside measurements like the Statistical Pass-by method (SPB) etc. An overview of international results is presented as an introduction.

The analysis is based on a unique series of detailed noise measurements performed on the Caltrans test sections for noise reducing pavement at State Route 138 in the Mojave Desert in Southern California. The measurements were carried out in the desert within three consecutive days in the wintertime where the variation of the air temperature over the day was from to 2 to 22°C. This secures that the main variable parameter during these measurements is the temperature. A series of other similar measurement results performed by the UCPRC in the Davis Sacramento area is also included.

The project has been carried out under the framework of the research technical agreement titled “Supplementary Studies for the Caltrans Quieter Pavement Research Program” between Caltrans and UCPRC as a part of the task: “Policy documents: guidelines for Caltrans policy”. The Danish Road Institute (DRI-DK) was subcontracted by UCPRC to work on the project. The work was 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.
- Qing Lu, University of California Pavement Research Center.
- Erwin Kohler, Dynatest Consulting Inc.

Erwin Kohler was responsible for the OBSI measurements, collected in the field by Mark Hannum, of the UCPRC, as part of a Caltrans project “Third Year Monitoring of Asphalt Pavement Sections” Partnered Pavement Research Center Strategic Plan Element 4.19. The data analysis was performed by Qing Lu, UCPRC and the report has been written by Hans Bendtsen, DRI-DK. Bent Andersen (DRI-DK) has taken part in the evaluation and discussion of the results and he has performed a Quality Assessment of the report.

Forord

Internationale erfaringer viser, at temperaturen er en faktor som har en vis indflydelse på resultaterne af målinger af vejtrafikstøj. On Board Sound Intensity (OBSI) metoden anvendes ved University of California Pavement Research Center (UCPRC) såvel som af andre forskere og konsulenter i USA til at foretage detaljerede målinger af dækstøjemission fra vejbelægninger. OBSI metoden anvendes tit i støjprojekter udført for California Department of Transport (Caltrans). En ekspertgruppe nedsat af USA's Federal Highway Administration arbejder i øjeblikket på en standard for OBSI metoden, som forventes at blive vedtaget af American Association of State Highway and Transportation Officials (AASHTO) som standard AASHTO TP-76. I Europa anvendes Close Proximity metoden (CPX) til at udføre detaljerede målinger af dæk/støjemission fra vejbelægninger.

Pålidelige og præcise støjdata er en vigtig faktor for en effektiv implementering og anvendelse af støjreducerende belægninger i vejforvaltninger. Formålet med denne rapport er at analysere, hvordan temperaturen påvirker resultaterne af støjmålinger udført efter OBSI metoden, som i øjeblikket anvendes i UCPRC, med anvendelse af et SRTT testdæk. Resultaterne er også relevant for CPX-metoden, hvor der anvendes et SRTT dæk. Rapporten kan også ses som et bidrag til det igangværende internationale arbejde med udvikling af standardisering af støjmålemetoder som CPX og den Statistiske Pass By-metode (SPB) osv. En oversigt over hidtidige internationale resultater præsenteres som en introduktion.

Analysen er baseret på en unik serie af detaljerede støjmålinger udført på Caltrans test sektioner med støjreducerende belægninger på vej LA138 i Mojave ørkenen i det sydlige Californien. Målingerne blev foretaget i ørkenen inden for tre dage i vintermånederne, hvor variationen af lufttemperaturen hen over dagen var fra 2 til 22 °C. Dette sikrer, at den vigtigste variabel i løbet af disse målinger er temperaturen. En række andre resultater af lignende målinger udført af UCPRC i Davis Sacramento området er også medtaget.

Projektet er gennemført inden for rammerne af en aftale med titlen ”Supplerende Undersøgelser for Caltrans ”Quieter Pavement Research Program”” mellem Caltrans og UCPRC som en del af opgaven: ”Policy documents: guidelines for Caltrans policy”. Vejdirektoratet/Vejteknisk Institut har været kontraheret af UCPRC til at udføre en del af arbejdet. Arbejdet er udført af en projektgruppe med deltagelse af følgende personer:

- Hans Bendtsen, Vejdirektoratet/Vejteknisk Institut (DRI-DK) der arbejdede som gæsteforsker på UCPRC fra august 2008 til august 2009.
- Qing Lu, University of California Pavement Research Center.
- Erwin Kohler, Dynatest Consulting Inc.

Erwin Kohler var ansvarlig for OBSI målingerne udført af Mark Hannum fra UCPRC, som en del af en Caltrans projektet "Third Year Monitoring of Asphalt Pavement Sections". Dataanalysen blev udført af Qing Lu, UCPRC og rapporten er skrevet af Hans Bendtsen, DRI-DK. Bent Andersen DRI-DK har deltaget i evaluering og diskussion af resultaterne, og han har kvalitetssikret rapporten.

1. Introduction and existing knowledge

Different methods are used to measure noise emission caused by road traffic passing over a specific pavement. Noise measurements are often carried out with the objective of measuring the noise properties of a specific road surface. High levels of accuracy are needed in such measurements as the difference in noise emission between different pavements is often quite small. From international experience it is known that temperature influences the noise generated by road traffic. There is therefore a need for knowledge on the influence of temperature in relation to the different measurement methods used. In this report the main focus is on the On Board Sound Intensity (OBSI) method used in California and in other U.S. states. The results will also have relevance for other noise measurement methods (see Section 1.2) like the Close Proximity method (CPX) with an SRTT applied.

In this project, the temperature will generally be given in degrees Celsius (°C) and when relevant also the temperature in Fahrenheit (°F) will be given. The box below states the transformations between these two units of temperature.

Temperature correction:	$(T_{Fahrenheit} - 32) * 5/9 = T_{Celsius}$
Temperature coefficient correction:	$c_{Fahrenheit} * 1.8 = c_{Celsius}$ (see Section 1.2)

All the noise levels presented in this report are A-weighted. The unit "dB" is used in this report and it is equal to what is often denoted "dB(A)" and "dBA".

1.1 The "Tyre/Road Noise Reference Book"

The Tyre/Road Noise Reference Book by Sandberg and Ejsmont from 2002 [6] includes a summary of international status of the current knowledge at that time on the influence of temperature on tire/road noise generation. The general knowledge was that the tire/road noise from automobile tires is influenced by about -1 dB per 10 °C temperature increase. It is stated that the current problems were:

- that the mechanisms by which the noise generation are influenced by temperature were not properly understood,
- that the measured effects of temperature have varied greatly,
- that it had been difficult to see any general rule that could be practically applied.

There are two major friction/adhesion related tire pavement noise generating mechanisms described as hypotheses by Sandberg and Ejsmont in [6] (see Figure 1.1):

- *"The first mechanism is the "stick-slip" mechanism in which tangential stresses in the rubber-road interface are built up and released. This causes a tangential vibration that might be called "scrubbing". When the surface is not perfectly flat, the vibrations affected by this process may have both radial and tangential components."*

- *"The "stick-slip" mechanism will give increased noise emission when friction is increased, in particular at high frequencies, and in particular for tires with small tread pattern depth."*
- *"The second one is a "stick-snap" mechanism due to adhesive bonds between rubber and road which are broken at a certain level when rubber is "pulled away" from the road contact. This may cause a combination of radial and tangential vibrations, but the sudden release of a rubber block from the surface may also cause a transient air-flow through the opening slit."*
- *"The stick-snap mechanism will give increased noise when the attraction force between rubber and the road surface is increased. This is not necessarily closely related to the tangential friction characteristics important for the stick-slip, but more related to having a very close and unbroken rubber-surface contact. An extremely smooth surface might provide such conditions. However, it depends largely also on material properties; i.e., whether and to what extent the materials are hydrophobic (have high attraction to each other) or hydrophilic (have low attraction)."*
- *"An increased microstructure will normally give increased friction, and thus increased stick-slip motion amplitudes, but it may give decreased adhesion bond strengths, which will reduce stick-snap effects."*

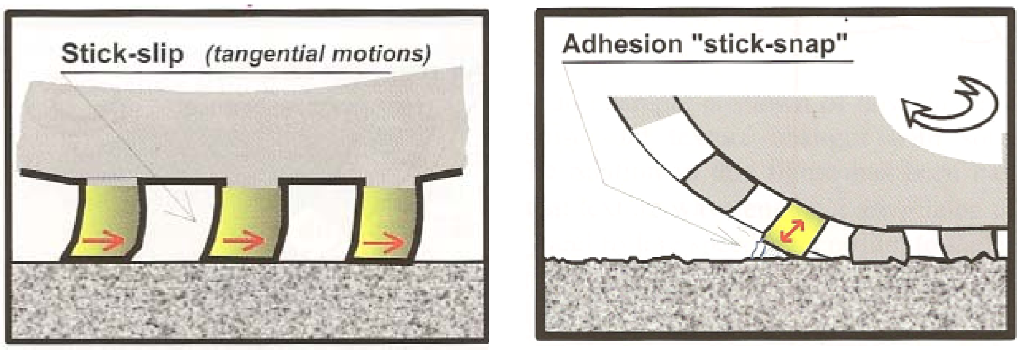

Figure 1.1. Illustration of the "stick-slip" and the adhesion "stick-snap" tire-road noise generating mechanisms [6] (used with permission from Ulf Sandberg, VTI).

It could be anticipated that the adhesion "stick-snap" tire-road noise generating mechanisms will mainly lead to increased noise levels at the "back" end of the tire where the rubber blocks "leave" the pavement surface. For "stick-slip", the scrubbing of the rubber on the pavement will occur at both the back and the front of the tire. In the OBSI method, noise is measured both in front and behind the tire. It could be analyzed if there is a systematic difference of these two noise levels and if such a difference varies with temperature.

On the background of available data the following general trends are presented in [6]:

1. Tire temperature is not very useful for considering a correlation between noise and temperature.

2. There seems to be no clear benefit in using road temperature instead of air temperature or vice versa as a temperature descriptor.
3. The effect of speed on the noise temperature relation is inconsistent.
4. There is a big range in temperature coefficients from -0.03 to -0.20 dB/°C for different passenger car tires.
5. For truck tires the temperature coefficient is much lower.
6. There is a big range in temperature coefficients from -0.03 to -0.20 dB/°C for different pavement types.
7. The temperature coefficients are clearly frequency dependent.
8. The tangential stiffness of an asphalt surface may be influenced by temperature which could potentially influence the noise generation from the "stick-slip" process (see Figure 1.1) where the rubber tread blocks motions relative to the road surface causing tangential tire vibrations presumably over 1000-2000 Hz.
9. It has been suggested to develop a model for the noise-temperature relation as a function of the elastic modulus of the tire tread compound or the tread hardness.

Work on the subject is under way within the International Organization for Standardization (ISO), but is currently not finalized as of the end of 2008.

1.2 Temperature and different noise measurement methods

Two different types of noise measurement methods are commonly used:

1. The "close to source" methods where the noise is measured near the tire/pavement interface:

    a. The On Board Sound Intensity method [1] where the sound intensity is measured by microphone probes placed very close to the contact point between the tire and the road surface (see Chapter 3). The measurement equipment is mounted on a passenger car. Here the temperatures of the actual test tire as well as the pavement temperature are relevant parameters. This method is currently used in California and other U.S. states. Development of a standard for the OBSI method is ongoing in the U.S.
    b. In the Close Proximity method (CPX) [2], sound pressure levels are measured by microphones placed very close to the contact point between the tire and the road surface. The measurement equipment is mounted either on a trailer or a passenger car. Here the temperatures of the actual test tire/tires as well as of the pavement are relevant parameters. This method is commonly used in Europe. Work is ongoing on finalizing an ISO standard for the CPX method.

2. The “roadside methods” where noise is measured at the road side:

   a. In the Statistical Pass-by method (SPB) [3], noise is measured from randomly chosen single vehicles driving at constant speed at a distance of 7.5 m between the microphone and the center line of the lane and at a height of 1.2 m. Here the average temperatures of the tires of all the selected vehicles as well as of the pavement are relevant parameters.
   b. In the Controlled Pass-by method (CPB), noise is measured from one or a few selected vehicles at the same microphone position as the SPB method. Here the temperatures of the tires of the one or few selected vehicles as well as of the pavement are relevant parameters.
   c. L_{Aeq} measurements where the noise from the vehicles passing by is measured over a longer period.

From the above it can be seen that depending on the method used either the average tire temperature of the vehicles included in the measurements or the temperature of the test tire/tires used are important together with the pavement temperature.

None of general specifications for these methods today include procedures for temperature correction. But some of the organizations in Europe using these noise measurement methods have developed their own practice for making temperature corrections. The Danish Road Institute (DRI-DK) uses for example the air temperature and applies the following corrections to SPB measurements with a reference air temperature of 20 °C (68 °F) [5]:

$$T_{corr;P} = 0.05 \cdot (T_{measured} - 20) \quad ; \textit{Passenger cars}$$

$$T_{corr;H} = 0.03 \cdot (T_{measured} - 20) \quad ; \textit{Heavy vehicles}$$

The air temperature is recorded approximately every 20 minutes. These temperature corrections are based on recommendations in a publication from the Dutch organization CROW [4]. For CPX measurements, DRI-DK uses the same temperature correction as for passenger cars in the SPB method.

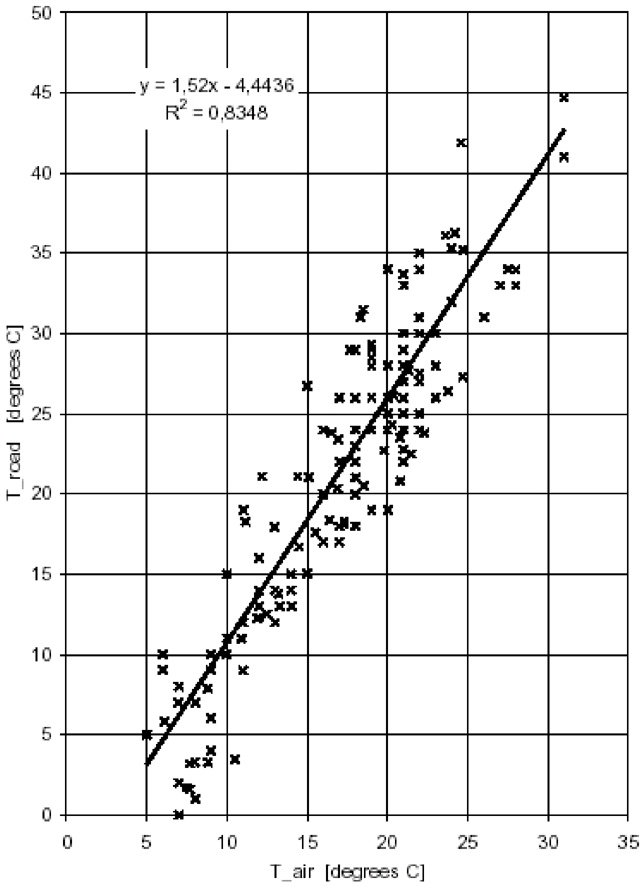

Figure 1.2. The pavement temperature as a function of the air temperature (data from the SPB measurement series carried out in different European countries), [8].

It can be discussed which temperature is the one that is important for the noise generation. There are three main possibilities:

1. The air temperature.
2. The temperature of the pavement surface.
3. The temperature of the tire/tires.

The pavement is heated up by the ambient air and radiation from the sun. Figure 1.2 and 1.3 shows different series of simultaneous measurements of air and pavement surface temperature performed in Europe and in California.

Figure 1.2 shows the relation between the pavement surface temperature and the air temperature based on data from the SPB measurement series carried out in different European countries [8]. There is a rather good linear correlation (R^2 = 0.83) between pavement and air temperature. The pavement surface temperature was on average 10 °C higher than the air temperature when the air temperature was 30 °C and the pavement temperature was on the average a little lower (3 °C) than the air temperature when the air temperature was 5 °C. In general, for a given air temperature there was a ±5 °C variation in pavement temperature.

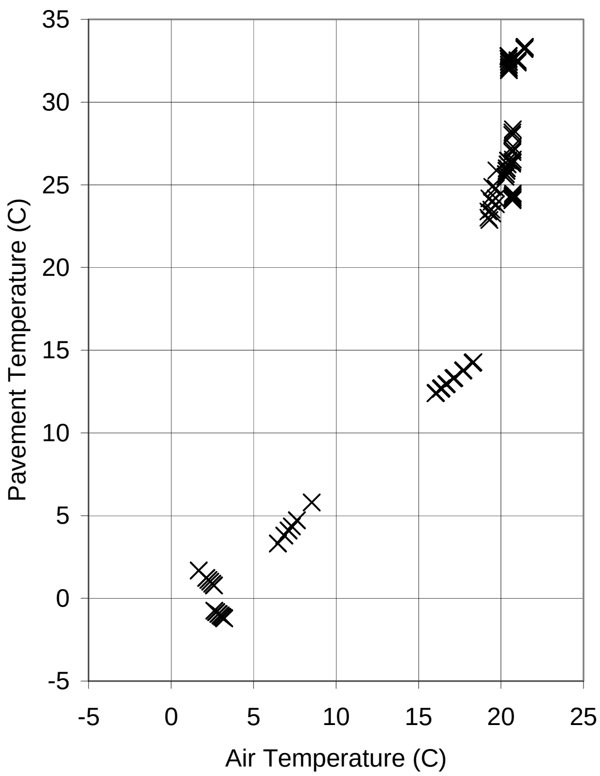

Figure 1.3. Simultaneously measured pavement and air temperature at some Caltrans test sections on highway LA138 in Mojave desert in Southern California. The measurements were carried out in the wintertime.

Figure 1.3 shows the results of simultaneously measured pavement and air temperature at some Caltrans test sections on highway LA138 in Mojave Desert in the winter period. Until the air reaches around 20 °C the pavements are colder than the air then the pavements starts to heat up faster than the air.

The tire road noise is generated by vibrations in the tires caused by the roughness of the pavement surface as well as by air pumping and other mechanisms (see section 1.1). If the contact between the rubber blocks of the tread pattern of the tire becomes soft or elastic, the noise will be reduced. The temperature might influence this in two different ways:

1. By a more elastic pavement surface caused by higher temperatures.
2. By a softer rubber in the tread pattern of the tire caused by a higher temperature.

In the European SILVIA project [9] the influence of pavement elasticity on noise generation was analyzed [10]. It was concluded that the stiffness of present pavements is much larger than the tire stiffness and that a reduction of the noise is only possible if the pavement stiffness is in the same order of magnitude as the tire stiffness (pavement stiffness/tire stiffness <10).

This is not at all the case with normal asphalt and concrete pavements, and an increase in temperature cannot reduce the pavement stiffness to a stiffness which is in the same order of magnitude as the stiffness of a rubber tire. This will only be possible if alternative materials like rubber are used for pavement construction instead of rock aggregate.

On this background it can be concluded that it is not a change in the pavement temperature that affects the noise properties in relation to elasticity of a “normal” pavement. This means the temperature affects the noise properties of the tires. It can be anticipated that when the tire gets warmer, the rubber becomes softer and this influences/reduces the vibration generated noise and possibly the “stick-slip” process. Therefore the tire temperature is a relevant parameter for estimating the temperature effect on the tire-pavement rolling noise generation.

The temperature of a tire must be defined by the ambient air temperature as well as by the heat generated in the tire when the tire is deformed while rolling over the pavement. The air presumably heats/cools the tire until an equilibrium tire temperature is reached. The tires only touch the pavement at a small contact area during a short time, and therefore the pavement temperature cannot be the most significant factor for the tire temperature.

If tire temperature measurements are not available, the air temperature might be regarded a better indicator of the tire temperature than the pavement temperature even though this can be discussed. In this project, noise will be analyzed both in relation to air as well as to pavement temperature. Tire temperatures have not been available.

In the following, a series of international results for the last ten years will be presented.

1.3 Results from the German-Dutch Sperenberg project

A closed military airport (Sperenberg) near Berlin in Germany has been turned into a test facility for different pavement types. A total of 46 different pavements have been constructed. Noise and other pavement properties have been measured intensively [7]. A survey of the influence of temperature has also been performed at Sperenberg by application of the Controlled Pass-by noise measurement method for two passenger cars with eight different tires and one truck with four different tires. Six different pavements were included in the measurement series. The coast-by noise without the engine running has been measured using a roadside microphone position placed at a height of 1.2 m above the pavement and 7.5 meters from the centre line of the vehicle passing by. The measurements were carried out in an air temperature range between 0 and 35 °C. Some main results are presented in the following.

Figure 1.4. A Mercedes passenger car on the Sperenberg pavement test site with 46 different pavements on a closed military airport near Berlin in Germany.

Noise measurements have been performed for two passenger cars. A Mercedes with eight different tires (called M1 to M8, typical dimension 195/65 R15) and a VW Polo also with eight different tires (called W1 to W8, typically 175/70 R13). A truck with four different tires was also included (called T1 to T4, 315/80 R22.5). For each category tire No. 1 is not a normal tire, but a slick tire. The following linear regression model has been used to describe the noise level ($L_{A,max}$):

$$L_{A,max} = a + b\,(10\log(v/v_o)) + c\,(T_{air}\text{-}20)$$

Where v is the vehicle speed and v_o is a reference speed of 80 km/h for passenger cars and 70 km/h for trucks. c is the regression coefficient for the air temperature in dB/°C. A c-value of -0.05 dB/°C means that the noise decreases 0.5 dB when the air temperature increases 10 °C.

Some main results from measurements on a dense asphalt concrete with a maximum aggregate size of about 8 mm and a porous pavement also with a maximum aggregate size of 8 mm are shown in Figure 1.5. It can be seen that there is quite a big variation of c for the different tires on the same car. For example, c varies for dense asphalt pavements between -0.037 and -0.129 dB/°C for the different tires on the Mercedes passenger car. The picture is the same for the different tires on the VW-Polo (-0.062 to -0.131 dB/°C). The air temperature coefficient c is smaller for the truck tires (-0.039 to -0.055 dB/°C). These measurements indicate that for noise measurement methods like OBSI and CPX as well as the CPB that uses specific tires it is necessary to apply special temperature corrections that are related to the specific tires used, whereas for the Statistical Pass-By method an average temperature correction seems relevant for each vehicle category.

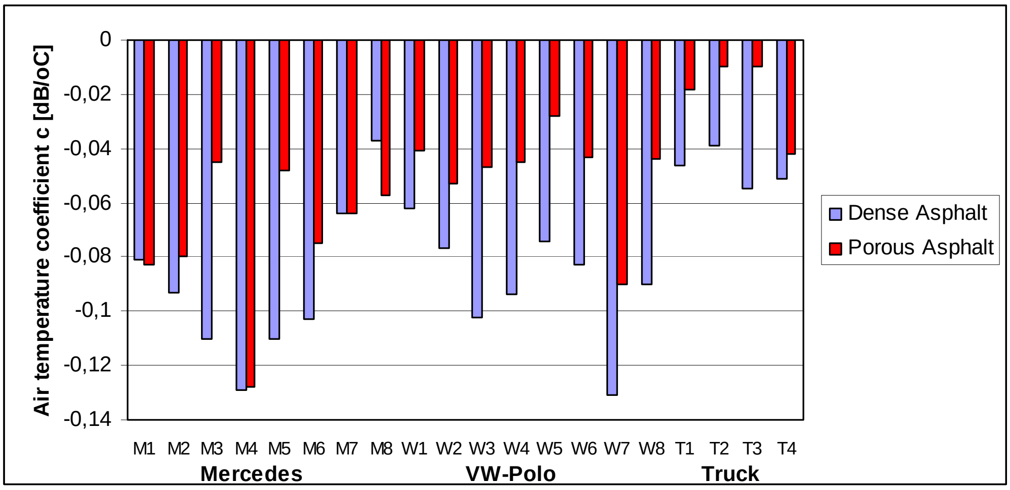

Figure 1.5. Air temperature coefficients in dB/°C for pass-by noise measurements of two passenger cars with 8 different tires and a truck with 4 different tires on dense asphalts and porous pavements [7].

Figure 1.6 shows the same type of data for a cement concrete pavement again compared to the dense asphalt concrete also presented in Figure 1.5. The temperature coefficients *c* are smaller on the cement concrete pavement than on the asphalt pavement.

Table 1.1. The temperature coefficient c in dB/°C for the 3 vehicles averaged over all the tires used on these vehicles for the three pavement types [7].

Pavement type	Dense asphalt	Porous asphalt	Cement concrete
Mercedes car (8 different tires)	-0,091	-0,073	-0,044
VW-Polo car (8 different tires)	-0,089	-0,049	-0,042
Truck (4 different tires)	-0,048	-0,020	0,001

Table 1.1 shows the air temperature coefficient *c* for the three vehicles averaged over all the tires used on these vehicles for the three pavement types. From these data it seems that the temperature effect on tire-road noise is around twice as high for passenger cars than for trucks. It also seems that the temperature coefficient depends on the pavement type. The tires at the dense asphalt have the highest temperature coefficient, around twice the coefficient for the porous asphalt pavement. The cement concrete pavement has the lowest coefficient but the variation for the concrete pavement is high.

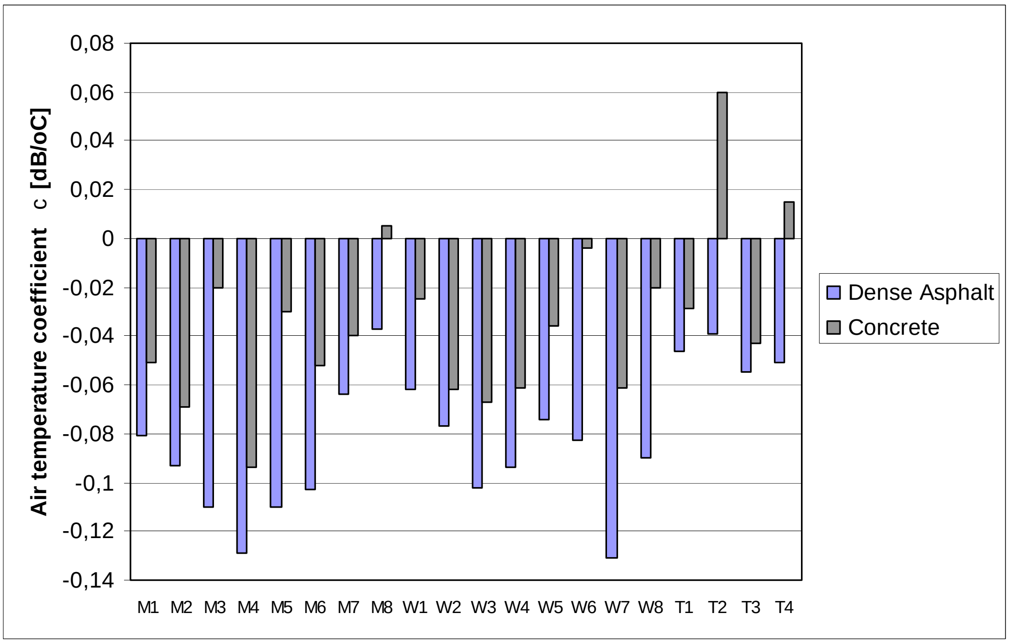

Figure 1.6. Air temperature coefficients in dB/°C for pass-by noise measurements of two passenger cars with eight different tires and a truck with four different tires on dense asphalt and cement concrete pavements [7].

The frequency dependency of the air temperature coefficient is shown for dense asphalt and cement concrete pavements in Figure 1.7 averaged for the normal passenger car tires included in the measurements at Sperenberg. At low frequencies, the temperature coefficient is quite low. At frequencies over 630 to 1000 Hz, the temperature coefficient is around -0.12 dB/°C for asphalt pavement and -0.10 dB/°C for cement concrete pavement.

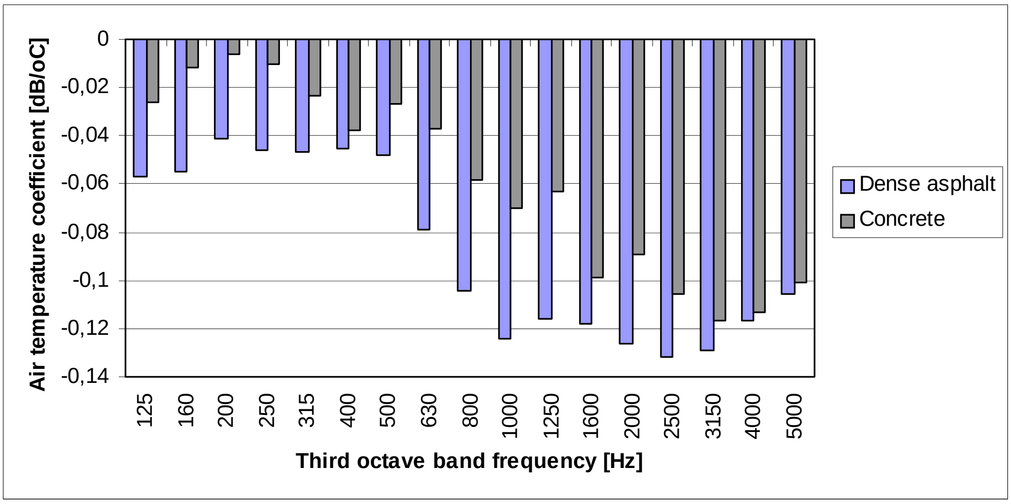

Figure 1.7. Average spectral temperature coefficient in dB/°C at different frequencies for selected passenger car tires at dense asphalt and cement concrete pavements [7].

Some general conclusions from the Sperenberg temperature study [7] are:

- With increasing temperature, the noise is decreased.
- This temperature effect is not significantly dependent on the vehicle speed (measured in the range from 50 to 110 km/h.
- The temperature is most dominant in the frequency range from 630/1000 to 5000 Hz.
- The temperature effect varies a lot for different tires.
- The temperature effect varies for the three different asphalt pavement types but the trend is not very consistent.
- The temperature effect varies for the three different pavement types but the trend is not very consistent.
- The temperature effect is higher on asphalt pavements than on cement concrete surfaces.
- The temperature effect for passenger car tires is approximately twice the effect for truck tires.

1.4 Semi-generic temperature correction method

At the Inter.Noise conference in 2004 in Prague, Ulf Sandberg suggested a method for temperature corrections [18]. A "semi-generic" correction method has been developed, where a correction factor is specified separately for each major group of tires and each major group of road surfaces. The method is developed on the background of the empirical data measured in the Sperenberg experiment [7] (see Section 1.3) as well a by expert judgments. The air temperature is used as the temperature indicator. The input for the method are pavement characteristics like texture expressed as MPD and air voids. The selected air temperature correction coefficients are predicted as average values for a series of different tires (basically the 20 tires included in the Sperenberg experiment). Therefore this method is developed to be used for correction of noise measurements including a large series of different vehicles with different tires on the same road surface like typically the SPB method as well as L_{Aeq} measurements over longer periods (see Section 1.2). The method is not suitable to be used directly for OBSI or CPX measurements where only one or a few specific tires are used.

The suggested air temperature coefficients for passenger cars can be seen in Table 1.2. For trucks the values have to be divided by 2 [18]. Due to lack of data, frequency-dependent temperature coefficients were not suggested [18].

Table 1.2. Proposed air temperature coefficients in dB/°C for passenger cars for various types of road surfaces [18]. Values in parenthesis are for uncommon surfaces for which there were no available measurement data.

Pavement type	Texture	Dense Air void 0-8 %	Open graded Air void 8-15 %	Porous Air void >16 %
Asphalt Concrete	**Smooth MPD < 0.7 mm**	-0.10	-0.08	(-0.06)
	Medium 0.7 < MPD < 1.4 mm	-0.06	-0.06	-0.05
	Rough MPD > 1.4 mm	-0.12	-0.06	-0.04
Cement Concrete	**Smooth MPD < 0.7 mm**	-0.05	(-0.04)	(-0.04)
	Medium to rough MPD > 0.7 mm	-0.09	(-0.04)	-0.03
All other surfaces	**Any**	(- 0.06)	(-0.05)	(-0.04)

1.5 Previous American investigations

At the TRB ADC40 noise and vibration meeting in Key West in July 2008, three different series of measurement data on the effect of temperature on OBSI measurements were reported.

Paul R. Donavan and Dana M. Lodico presented measurements on a Dense Asphalt Concrete (DGAC) and a Portland Cement Concrete (PCC) pavement performed with a SRTT (see Figure 1.8) as well as a Dunlop SP Winter Sports tire [15 and 22]. Noise measurements were performed at different air temperatures ranging from 30 to 40 °C (86 to 104°F).

Figure 1.8. A Standard Reference Test Tire (SRTT) to the left (photo Bruce Rymer, Caltrans) and the Dunlop SP Winter Sports tire to the right (photo Paul A. Donavan, Illingworth & Rodkin, Inc).

The pavement temperatures were ranging from 35 to 61 °C (95 to 142 °F). For the Dunlop tire, the air temperature coefficient *c* was nearly the same for the DGAC pavement and for the PCC pavement, respectively -0.100 and -0.086 dB/°C. No clear correlations were found for the SRTT at this temperature range, but the data indicate that the air temperature coefficient *c* is around -0.024 dB/°C for DGAC pavement and -0.027 for the PCC pavement.

Judith Rochat and Aron Hastings [16] presented two series of measurements. The first was performed in Arizona on a transversely tined Portland Cement Concrete (PCC) pavement, and the second on two Asphalt Rubber Friction Courses (ARFC) which were new and one year old respectively. The noise measurement method used was roadside L_{Aeq} measurements over 5 minute periods on the actual traffic passing the measurement position. This means that these measurements included different vehicles and different vehicle categories with many different tires contrary to OBSI measurements. Noise measurements were performed at different air temperatures ranging from 29 to 39 °C (85 to 102 °F). The pavement temperatures were ranging from 29 to 51 °C (84 to 124 °F). The results can be seen in Figure 1.10. The pavement temperature coefficient *c* varied between -0.018 and -0.072dB/°C. For the air temperature coefficient *c* the variation was between -0.043 and -0.160 dB/°C. The average air temperature coefficient for ARFC was -0.064 dB/°C and for the PCC it was -0.130 dB/°C.

Figure 1.9. Road with Asphalt Rubber Friction Course (ARFC) in Phoenix Arizona.

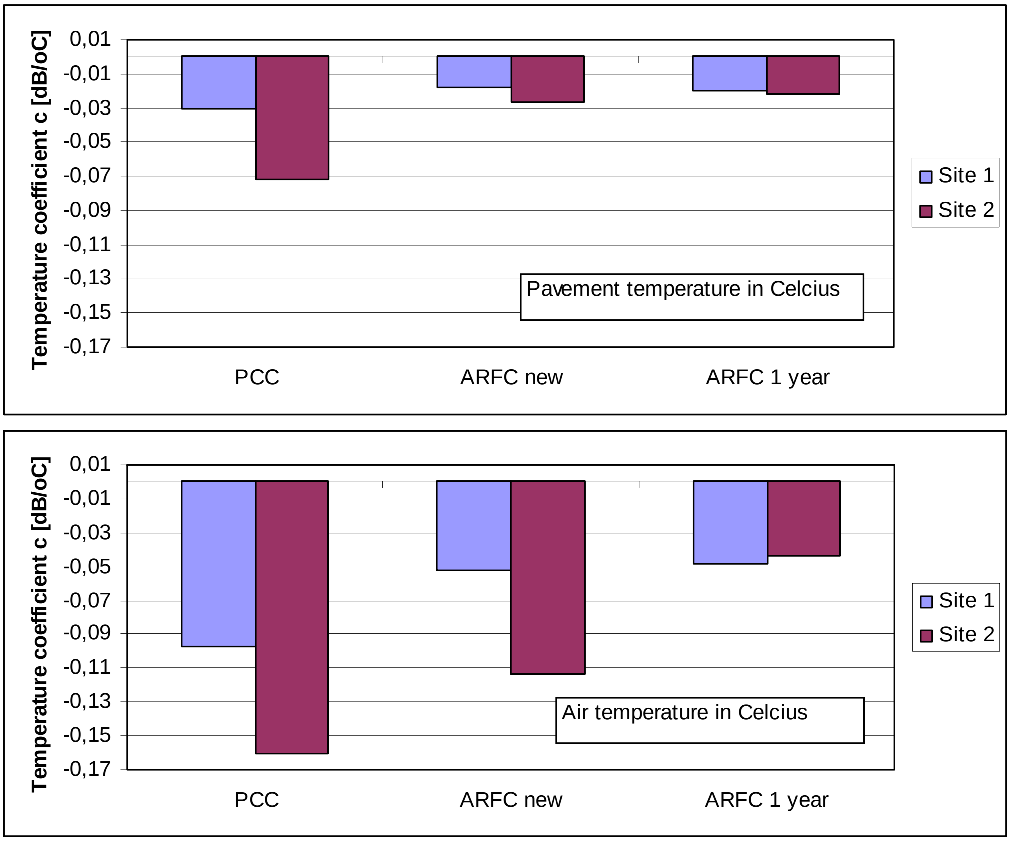

Figure 1.10. Temperature coefficients in dB/°C for pavement temperature respectively air temperature measured in Arizona using roadside L_{Aeq} measurements over 5 minute periods on the actual traffic [16].

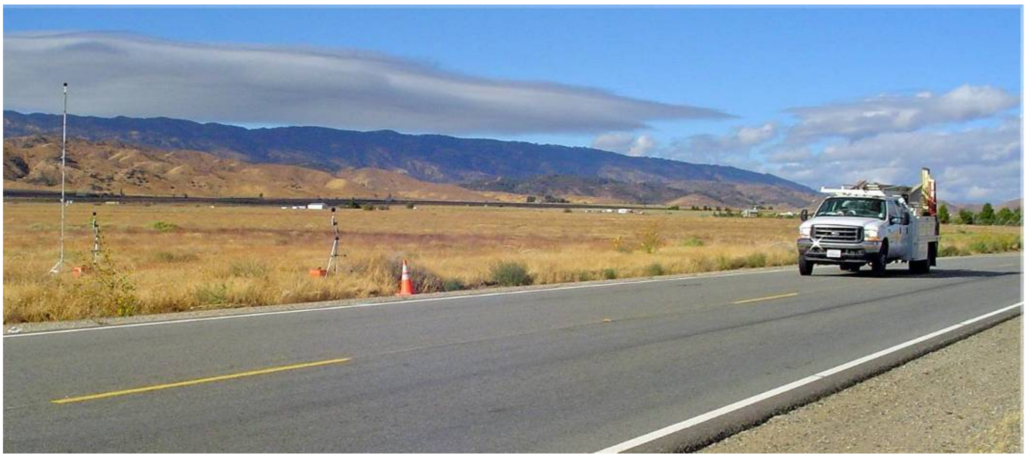

Figure 1.11. The roadside SPB noise measurement setup at LA138 test road in the Mojave Desert (Photo Judith Rochat, VOLPE).

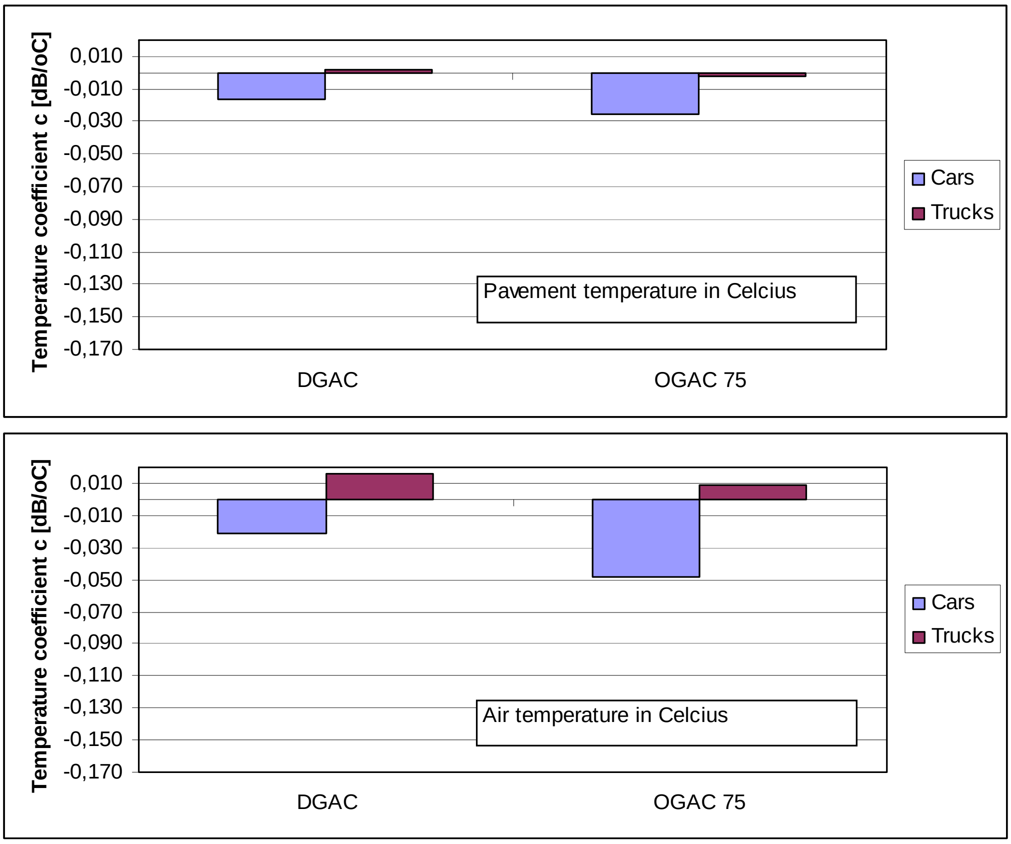

Figure 1.12. Temperature coefficients in dB/°C for pavement temperature respectively air temperature measured on LA138 using the roadside SPB method [16].

Results from a series of roadside SPB noise measurements are also presented in [16]. The measurements were performed on a Dense Graded (DGAC) and an Open Graded (OGAC 75) asphalt concrete pavement on the LA138 test road in the Mojave Desert (see Chapter 2). These measurements include different vehicles with many different tires contrary to OBSI measurements. New OBSI measurements on these pavements at different temperatures will be presented in Chapter 4. Noise measurements were performed at different air temperatures ranging from 8 to 32 °C (47 to 90 °F). The pavement temperatures were ranging from 7 to 49 °C (45 to 121 °F). The results can be seen in Figure 1.12. For the air temperature coefficient *c,* the variation was between -0.022 and -0.049 dB/°C for passenger cars, whereas it was slightly positive for trucks (0,009 to 0,016 dB/°C). The temperature coefficients in dB/°C measured at LA138 were generally significantly lower than the coefficients measured in Arizona.

1.6 Results from a French experiment

In an article in Applied Acoustics from 2007, Fabienne Anfosso-Lédée and Yves Pichaud present results from a French experiment [19] carried out on the test tracks of the National French Road Laboratory (LCPC) in Nantes (see Figure 1.13). Two different Michelin summer tires were used (a more "noisy" Tire A and a "low noise" Tire B (see Figure 1.14)). The rubber hardness of the A tire was 76.3 shore A and of the B tire 79.5 shore A [21]. The noise measurements have been performed on seven different dense and open graded pavements (see Table 1.3) including asphalt and cement concrete as well as surface dressings.

Figure 1.13. The LCPC test tracks in Nantes.

One test vehicle driving at constant speed was used. The noise measurements were performed by the roadside Controlled Pass-By (CPB) method with a microphone placed at a height of 1.2 m and a distance of 7.5 m from the centre line of the test vehicle. The results are presented for a speed of 90 km/h (56 mph). To cover a large temperature range, the measurements were performed at different seasons over the year 2000 to 2001 covering a range in air temperatures from 0 to 30 °C. Pavement, air and tire temperatures were measured.

The following temperature relations in degrees Celsius were found:

$T_{road} = 1.7T_{air} - 4.5$ [°C]
$T_{tire} = 1.05T_{air} + 15.8$ [°C]

Table 1.3. The seven pavements included in the French experiment [19].

Name	Type	Maximum aggregate size in mm	Mean Profile Depth (MPD) in mm
DGAC	Dense asphalt concrete	10	0.86
PAC	Porous asphalt concrete	10	1.67
OGAC	Very thin open graded asphalt concrete	10	1.49
SD rough	Rough epoxy bound surface dressing	10	4.3
SD fine	Thin and smooth epoxy bound surface dressing	1.5	0.70
PCC burlap	Burlap textured cement concrete	-	0.80
PPCC	Porous cement concrete	-	1.14

Figure 1.14. The two Michelin summer tires used in the French experiment. The "noisy" Tire A to the left and "low noise" Tire B to the right (photo Fabienne Anfosso-Lédée, LCPC).

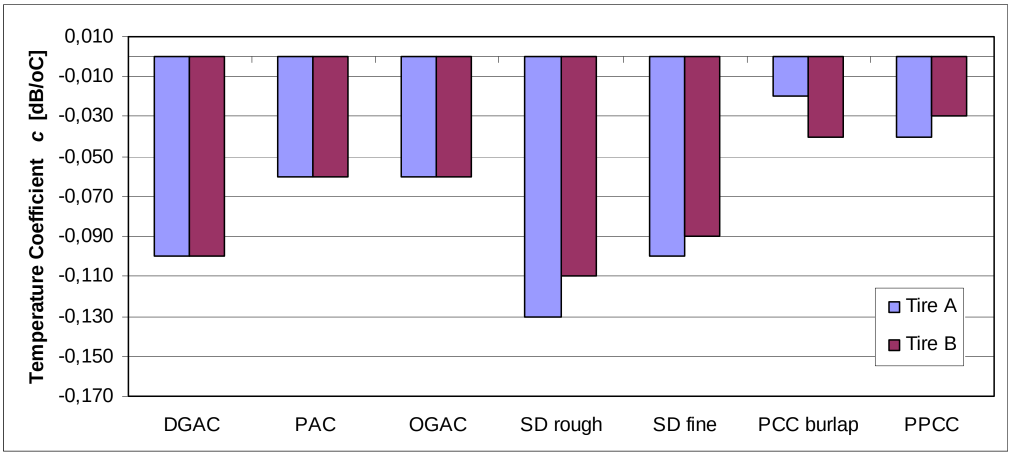

Figure 1.15. Air temperature coefficients in dB/°C measured at the LCPC test tracks using the road-side CPB method [19].

Air temperature coefficients can be seen in Figure 1.15. The results from the two tires are practically the same and the coefficients vary between -0.02 and -0.13 dB/°C. The results are grouped for three pavement types: dense and open asphalt concrete as well as cement concrete (see Table 1.4). The air temperature coefficient is -0.10 dB/°C for the dense pavements and -0.06 dB/°C for the open graded (and porous) pavements. For both the porous and dense cement concrete the coefficient is -0.03 dB/°C.

Table 1.4. Average temperature coefficients from the French study grouped for three pavement types [19].

Pavement type	**Average Air temperature coefficients**	**Average Pavement temperature coefficients**	**Average Tire temperature coefficients**	**Range in MPD**
Dense asphalt concrete	-0.10 dB/°C	-0.06 dB/°C	-0.09 dB/°C	0.70 – 0.86 mm
Open asphalt concrete	-0.06 dB/°C	-0.04 dB/°C	- 0.05 dB/°C	1.49 – 4.3 mm
Cement concrete	-0.03 dB/°C	-0.02 dB/°C	-0.03 dB/°C	0.80 – 1.14 mm

Spectral analysis [19] showed that in general the noise in the low frequencies (below 500 Hz) and in the high frequencies (from 1600 to 5000 Hz) seems to be affected by temperature. For higher frequencies, the noise levels are 2-3 dB lower for higher temperatures than for lower temperatures.

1.7 The European Union Tire Noise Directive

The European Union has a directive that regulates the noise emission from new tires sold in the Union [20]. In Annex 5 of this directive there is a description of the test procedures for measuring tire noise emission. The measurement method is a coast by method where the noise is measured at the roadside (distance 7.5 m and height 1.2 m) while test vehicles equipped with the tires to be tested are driving on a specified dense asphalt concrete surface with a maximum aggregate size of 8 mm.

A reference speed of 80 km/h is used for tires for passenger cars and vans/small trucks where as the reference speed for tires for heavy vehicles is 70 km/h. Measurements of air as well as test pavement temperature are mandatory. Measurements shall not be made when the air temperature is below 5 °C or above 40 °C or when the test pavement temperature is below 5 °C or above 50 °C. A reference speed of 80 km/h is used for tires for passenger cars and vans/small trucks where as the reference speed for tires for heavy vehicles is 70 km/h. Prior to testing, tires shall be warmed up by running under test conditions.

The final results are normalised to a test pavement reference temperature of 20 °C using the following pavement temperature correction factors:

- Passenger cars (called type C1) – 0.03 dB/°C when the pavement temperature is over 20°C and – 0.06 dB/°C when the pavement temperature is under 20 °C.
- Vans/small trucks (called type C2) – 0.02 dB/°C.
- Heavy vehicles (called type C3) no temperature correction.

1.8 The challenge

A hypothesis could be that the "stick-snap" and the adhesion "stick-slip" mechanisms might be influenced by temperature (see Section 1.1.). These mechanisms are thought to lead to increased noise levels at higher frequencies above 1000 to 2000 Hz.
The measurement series both from Sperenberg (see Section 1.3) and France (see Section 1.6) showed that high frequency noise is reduced with increasing temperatures. These two tire-road noise generating mechanisms might mainly lead to increased noise levels at the "back" end of the tire where the rubber blocks "leaves" the pavement surface. In OBSI and the CPX methods, noise is measured both in front and behind the tire. It could be analyzed if there is a systematic difference between these two noise levels and if such a difference varies with temperature. Such analyses have not been carried out in this current project.

The Sperenberg and the French results also indicate that both the properties of the tire as well as the pavement type have an influence on the temperature coefficient. As regards the tire influence, a hypothesis can be that increased temperature makes the rubber compound softer and this reduces the vibration generated noise from the tires. If this was the case, the temperature influence should occur in the lower frequencies, but as already mentioned the Sperenberg results show increased noise levels at higher frequencies above 1000 to 2000 Hz.

As regards pavement influence one of the conclusions from the SILVIA project was that (see Section 1.1) the stiffness of present pavements is much larger than the tire stiffness, and that a reduction of the noise is only possible if the pavement stiffness is in the same order of magnitude as the tire stiffness. Pavements are normally not as stiff in the same order of magnitude as tire rubber even under very warm weather conditions, which indicates that other noise-related properties than the pavement stiffness might be influenced by increased temperature. These could be the "stick-snap" and the "stick-slip" mechanisms.

In this report the main objective is to investigate the influence of temperature on the On Board Sound Intensity method currently applied in California through the use of an SRTT test tire. The results are also relevant for the CPX method with an SRTT applied. This is done by analyzing two sets of measurement data:

1. A series of detailed OBSI noise measurements performed by UCPRC on the Caltrans test sections for noise reducing pavements at highway LA138 in the Mojave Desert in Southern California [11]. The measurements are carried out in the desert in the wintertime where the variation of the air temperature over the day was from to 2 to 22 °C and pavement temperatures from to -1 to 33 °C. Here the noise has been measured on the same day or within a few consecutive days with the same equipment, by the same operator, and on the same pavements, at low morning, medium midday and high afternoon temperatures. This ensures that the only main variable parameter during these measurements is the temperature. For these measurements, a Standard Reference Test Tire (SRTT) was used.
2. Another measurement series was performed by UCPRC in California as part of a large project on pavement noise [12]. For these measurements, a Goodyear Aquatred tire was used, which was the old former standard test tire for OBSI. The objective was to measure the noise at three different temperatures on three different types of pavements. The variation of the pavement temperature over the day was from to 11 to 35 °C. Here the noise was measured on the same day with the same equipment, by the same operator, and at the same measurement positions at three different temperatures.

The objective of the two measurement series was to perform measurements where the only variable was the temperature and where the following factors were constant:

- Same measurement tire.
- Same inflation and rubber hardness (at a reference temperature) of the measurement tire.
- No changes in age, tear, and wear of the measurement tire.
- Same acoustical measurement equipment.
- Measurement tire mounted on the same car.
- Same measurement operator.
- No changes in wear and tear of pavements.

2. The test sections

The pavements for the two sets of test sections included in this project are presented in the following.

2.1 The LA138 pavements

The LA138 test sections were constructed on State Highway 138 in the Mojave Desert west of Lancaster in 2001. The purpose was to develop and test different types of noise reducing pavements [11]. A total of 5 different pavements were constructed including a Dense Graded Asphalt Concrete (DGAC) used as a reference. The OBSI measurements were performed both in the eastbound and the westbound directions in February 2008 when the pavements were 8 years old. The DGAC was for practical reasons only measured in one direction. Therefore a total of 9 datasets are included in this survey.

Figure 2.1. The LA138 test road on Highway 138 in the Mojave Desert.

The following pavements were constructed on the test road (see Table 2.1):

- A Dense Graded Asphalt Concrete (DGAC) with a specified thickness of 30 mm used as a noise reference pavement.
- An Open Graded Asphalt Concrete (OGAC 30) with a specified thickness of 30 mm.
- An Open Graded Asphalt Concrete (OGAC 75) with a specified thickness of 75 mm.
- An Open Graded Asphalt Concrete with rubber powder added to the bitumen (RAC-O) and a specified thickness of 30 mm.
- A Bonded Wearing Course (BWC). A propriety product used in California.

Table 2.1. Close up pictures of the LA138 test pavements and results of a visual inspection performed in October 2008. The size of the black and white squares at the photos is 10 mm times 10 mm.

Photo October 2008	Visual inspection October 2008
	**S1 DGAC** The pavement is generally in a good condition. Very small signs of a little raveling are not considered to affect the noise generation. There are transversal cracks at a width of 2-5 mm at the whole width of the lane at approximately each 5 m. Not possible to hear increased noise at the roadside when tires were passing the cracks.
	**S2 OGAC 75** The pavement has an open “negative” surface structure. When water was poured on the pavement it did not significantly penetrate down into the surface structure (not porous). The pavement is generally in a good condition. Very small signs of a little raveling are not considered to affect the noise generation. Transversal cracks at a width of 2-5 mm at the whole width of the lane at approximately each 5 m. Not possible to hear increased noise when tires were passing the cracks.
	**S3 OGAC 30** The pavement has an open “negative” surface structure. When water was poured on the pavement it did not penetrate down into the surface structure (not porous). The pavement is generally in a good condition. Small signs of a little raveling are not considered to affect the noise generation. Transversal cracks at a width of 2-5 mm at the whole width of the lane at approximately each 5 m. Not possible to hear increased noise when tires were passing the cracks.
	**S4 RAC-O** The pavement has an open “negative” surface structure. When water was poured on the pavement it did not penetrate down into the surface structure (not porous). Small signs of raveling are not considered to affect the noise generation. Some longitudinal cracking. Transversal cracks at a width of 2-5 mm at the whole width of the lane at approximately each 5 m. Not possible to hear increased noise when tires were passing the cracks.
	**S5 BWC** This pavement seems to have the roughest surface structure of the five pavements. The pavement is generally in a good condition. Practically no raveling. Transversal cracks at a width of up to 10 mm at the whole width of the lane at approximately each 5 m. Possible to hear slightly increased noise when tires were passing the cracks.

The five pavements all had a maximum aggregate size of 12.5 mm. The three open graded pavements had a built-in air void content of around 10 % (measured on drill cores when they were six years old).

Table 2.2. Data on the LA138 test pavements. The air void is measured on drill cores in 2007.

Site No.	Pavement type	Maximum aggregate size	Specified thickness	Air void
S1	DGAC	12.5 mm	30 mm	7.0 %
S2	OGAC 75	12.5 mm	75 mm	10.6 %
S3	OGAC 30	12.5 mm	30 mm	10.3 %
S4	RAC-O	12.5 mm	30 mm	10.7 %
S5	BWC	12.5 mm	30 mm	5.0 %

To describe the pavements in relation to noise, the result of road side Statistical Pass-By measurements for passenger cars when the pavements were 16 month old were carried out and the results are shown in Table 2.3. The open graded pavements have a noise reduction of 2 to 3½ dB in relation to the dense graded pavement. SPB measurements have also been carried out when the pavements were 52 month old in 2006 showing noise reductions quite similar to the results in month 16 [14].

Table 2.3. Noise measured by the Statistical Pass-By method for mixed traffic (SPBI for passenger cars at 96 km/h (60 mph) and trucks at 88 km/h (55 mph)) when the pavements were 16 month old at a microphone height of 1.5 m and a distance of 7.5 m [11].

Pavement type	SPBI Month 16	Noise reduction relative to DGAC month 16
DGAC	82.5 dB	-
OGAC 75	79.0 dB	3.5 dB
OGAC 30	80.7 dB	1.7 dB
RAC-O	80.2 dB	2.3 dB
BWC	80.7 dB	1.8 dB

One of the authors has performed a visual inspection of the pavements in October 2008. The outcome of this inspection can be seen in Table 2.1. Generally the pavements were found to be in a reasonable condition with no remarkable signs of wear and tear that can have a significant influence of the noise emission except for cracks in the BWC pavement.

2.2 Californian pavements

Another set of test pavements are included in this temperature project. These pavements are part of a UCPRC project on noise emission from typical pavements used in California [12] that is carried out for Caltrans as a part of the Caltrans Quieter Pavements Research Work Plan. Two other pavements on roads in Davis are also included, Old Davis Road (ODR) and Road 105 (RD 105).

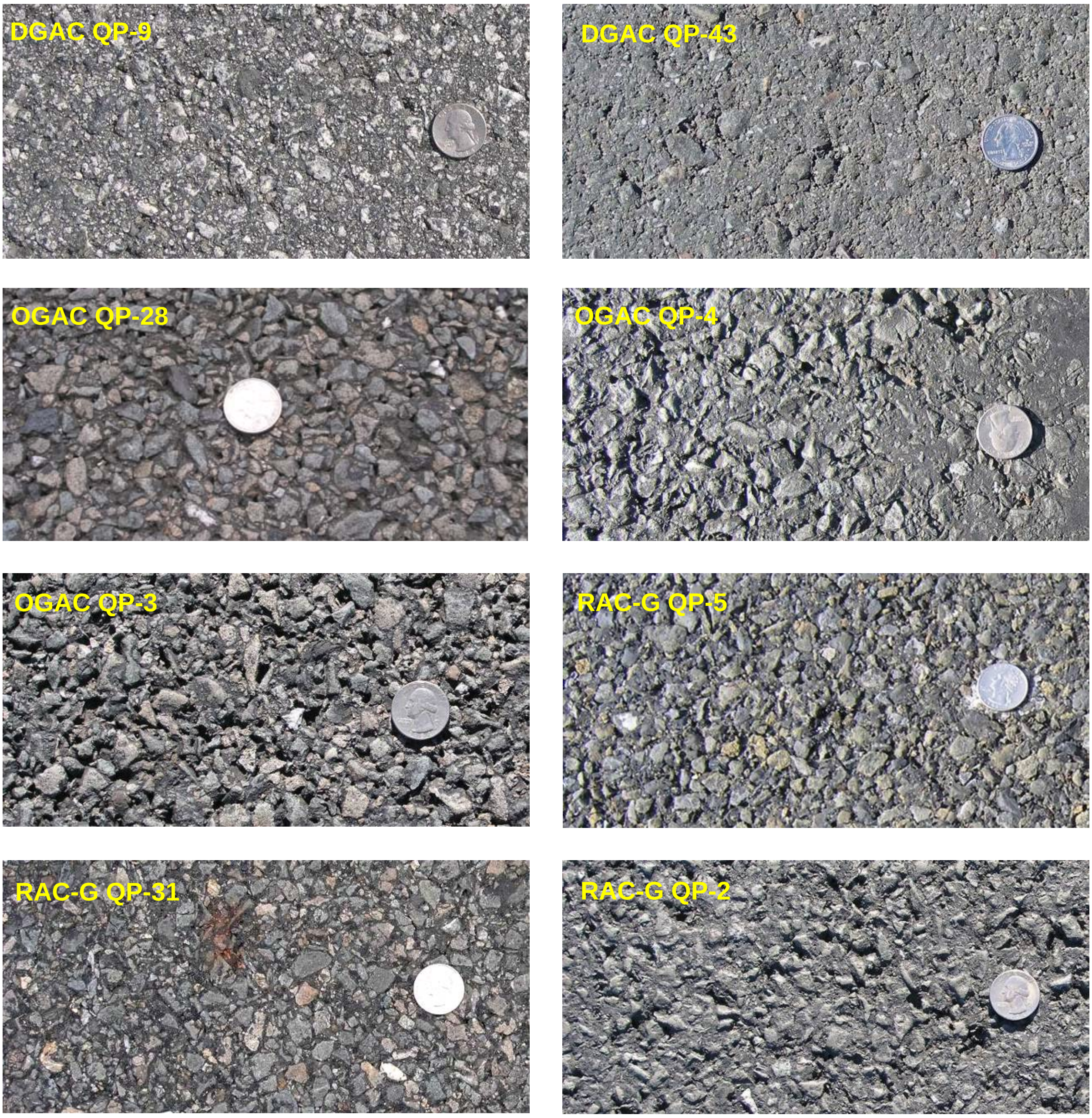

Figure 2.2. Close up photos of eight of the Californian pavements included in this temperature project. The diameter of the US quarter dollar coin is 24 mm.

Three types of pavements were included:

- Dense Graded Asphalt Concrete (DGAC). Four different pavements.
- Open Graded Asphalt Concrete (OGAC). Three different pavements.
- Gap-graded rubberized asphalt concrete (RAC-G). Three different pavements.

An overview of characteristics for the ten pavements can be seen in Table 2.4. Photos of eight of the pavements can be seen in Figure 2.2. Further information is available in [12].

Table 2.4. Data on the Californian pavements included in this temperature project [12].

Type	Name	Age in years	Nominal Maximum Aggregate Size	Air void
DGAC	ODR	-	-	-
DGAC	QP-9	7	12.5 mm	2.9 %
DGAC	RD 105	-	-	-
DGAC	QP-43	2	12.5 mm	4.9 %
OGAC	QP-28	5	12.5 mm	12.8 %
OGAC	QP-4	5	12.5 mm	17.4 %
OGAC	QP-3	7	12.5 mm	19.2 %
RAC-G	QP-5	10	12.5 mm	8.0 %
RAC-G	QP-31	6	12.5 mm	7.3 %
RAC-G	QP-2	6	12.5 mm	9.3 %

3. The OBSI measurement method

The noise measurements have been performed using the On Board Sound Intensity method (OBSI) [1] as it is set up in the UCPRC Dodge Stratus sedan OBSI measurement vehicle (see Figure 3.1). The steel box behind the vehicle is an inertial laser profilometer that measures the pavement elevation profile on both wheel tracks. The surface texture expressed as the Mean Profile Depth (MPD) is also measured in the right wheel track. The OBSI measurement equipment has been developed by Paul Donavan from the company Illingworth & Rodkin, Inc. in California.

Figure 3.1. The UCPRC OBSI measurement vehicle.

In the OBSI method, the sound intensity is measured. Sound intensity is a vector quantity as it has both magnitude and direction. The sound intensity in a specified direction is the amount of sound energy flowing through a unit area normal to that direction [13]. It is a measure commonly used to measure the sound power of a given noise source because the method can be used to focus on one noise source without interference of noise from other sources.

Two sets (probes) of two microphones are in the OBSI method placed at the leading and the trailing edge of the right back tire (passenger side). The microphones (see Figure 3.2) are placed 3 inches (76.2 mm) over the pavement surface and 4 inches (101. 6 mm) from the side of the tire. The distance between the two sets of microphones is 8.25 inches (209.6 mm). The sound intensity is measured in dB and the results are A-weighted.

The OBSI measurements are performed at a speed of 60 mph (96 km/h) on a pavement section at a length of 134 m (5 seconds at 60 mph). The measurement is repeated three times on the same pavement section.

The starting of a pavement section is marked on the road surface with reflective tape or at the roadside by reflecting material mounted on a marking post. When a light ray from the vehicle is reflected by the reflecting material a photo cell triggers the noise measurement. The result is the average value of the three rounds of measurements on the same pavement section.

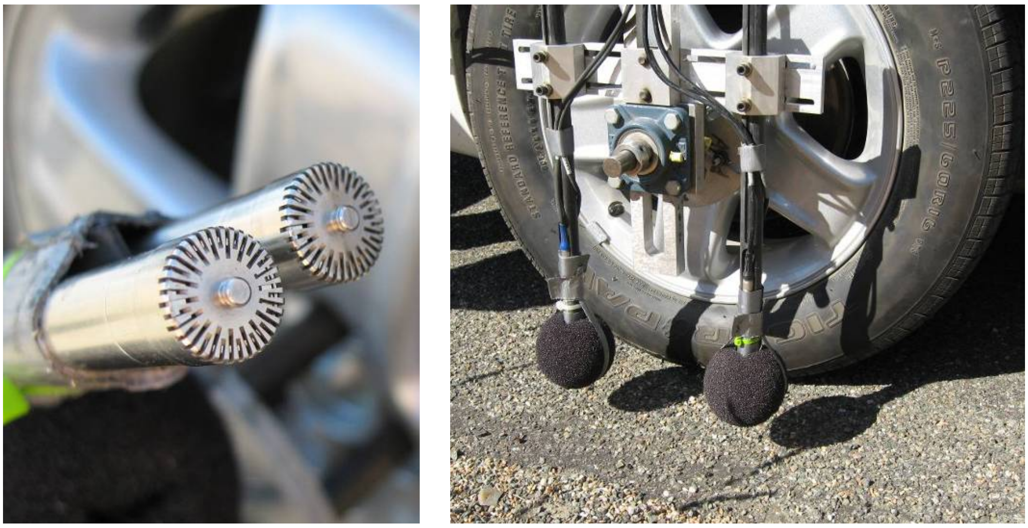

Figure 3.2. The microphones for the intensity probe and the probe positions of the OBSI method.

In the CPX method currently used in Europe [2], the sound pressure level is measured at fixed positions. The sound pressure level is measured in dB and the results are A-weighted and averaged for the front and rear position. The position of the two microphones in the CPX method are 100 mm (3.94 inches) over the pavement surface and 200 mm (7.87 inches) from the side of the tire. The distance between the two sets of microphones is 400 mm (15.75 inches). The distance between the tires and the microphones is twice as long in the CPX method as in the OBSI method. In the CPX method, it is recommended to perform measurements of pavement sections with a length of at least 100 m and at least 200 m in total shall be measured. The DRI-DK application of the CPX method in an open trailer (deciBellA) can be seen in [5].

Table 3.1. Microphone positions in the OBSI and CPX methods [2].

Method	Distance to tire	Height over pavement	Distance between microphones
OBSI	101.6 mm	76.2 mm	209.6 mm
CPX	200 mm	100 mm	400 mm

In different measurements, it has been found that OBSI levels normally are 2 to 4 dB higher than CPX levels measured on the same pavement depending on which test tires are used [17 and 22]. The higher OBSI levels can partly be explained by the microphone positions where the OBSI microphones are placed much closer to the noise source (tire and pavement) than the CPX microphones. The different types of tires used for CPX and the OBSI also explain the difference. It must be expected that the two methods will rank pavements in the same way in relation to noise.

The following instruments and procedures were used for the temperature measurements. A pocket weather station is used to measure air temperature. The measurements are taken on the tested traffic lane at 1.2 to 1.5 meters over the pavement (measurements out of the car's window). A piece of paper/cardboard was held over the weather station in order to provide shielding from direct sun rays. The pavement temperature is measured using a thermal infra-red gun, and is the average of three to five readings taken on the right wheel path. Air and pavement temperature are measured immediately before and immediately after the OBSI testing. The devices for air and pavement temperature are shown in Figure 3.3. The pocket weather station provides, in addition to air temperature, the air relative humidity and the barometric pressure.

Figure 3.3. Pocket weather station and Fluke thermal infrared gun used to measure respectively air and pavement temperature.

In the expression for calculating sound intensity from sound pressures measured at two closely spaced points, the actual air density is required. In most commercial analyzers, this is accounted for by entering the ambient air temperature and barometric pressure at the time the data is acquired. If air density is not accounted for at the time of the measurement, it can be accounted for afterwards by applying a correction factor using the following formulas [23, 24]:

$$M_{skg} = 3.884266 \times 10 \wedge ((7.5 \times T_c)/(237.7 + T_c))$$

$$M_{kg} = M_{skg} \times \text{Humidity\%}/100$$

$$T_{vc} = ((1 + 1.609 \times M_{kg})/(1 + M_{kg})) \times T_c$$

$$\text{AirDensity} = (\text{Baro} \times 100)/((T_{vc} + 273) \times 287))$$

$$\text{OBSI}_{\text{Correction}} = 10 \times (\text{Log10(ReferenceAirDensity)} - \text{Log10(AirDensity)})$$

M_{skg}	=	factor to use in humidity correction
T_c	=	temperature (°C)
M_{kg}	=	adjustment for humidity
Baro	=	pressure in mbars
T_{vc}	=	application of correction to temperature using the humidity adjustment
ReferenceAirDensity	=	1.21 kg/m^3

If not corrected by the noise analyzer used, the correction factor ($OBSI_{Correction}$) has to be added to the measured sound intensity levels at each frequency. It can be seen in the above formulas that the air temperature is included in the correction formulas. Figure 3.4 shows the correction factor predicted for different temperatures and with all other factors kept constant at the average levels measured when OBSI measurements were performed at the LA138 test sections (see Section 4) in February 2008 (pressure 27.20 and relative humidity 40.5 %). It can be seen that the correction factor is 0 dB at 17 °C (63°F) and that it increases with higher temperatures. At 30 °C (86°F) it is +0.29 dB.

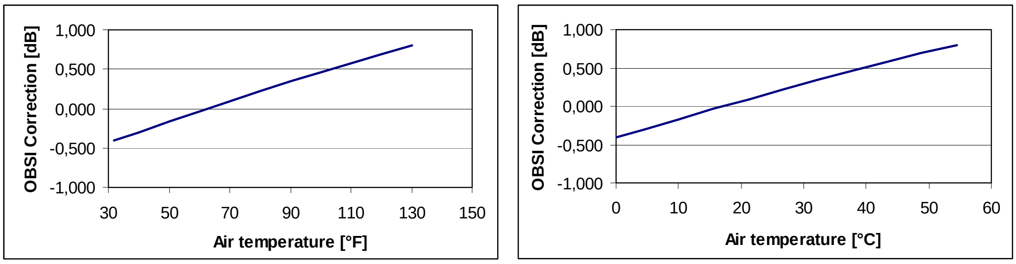

Figure 3.4. The correction factor ($OBSI_{Correction}$) in dB for air density applied to OBSI sound intensity measurements as a function of temperature (in degrees Celsius to the right and Fahrenheit to the left).

It will be noted that temperature is an issue for OBSI measurements of tire/pavement noise for two unrelated reasons.

1. Air density is a fundamental parameter in the determination of sound intensity. If temperature and barometric pressure are not accounted for in the analyzer used for the measurement, a correction can be applied if needed afterward. Temperature is not a parameter for measurements of sound pressure (like the CPX and SPB/CPB methods).
2. The temperature's influence on results of noise measurements is related to the mechanisms generating the noise when the tire rolls on the pavement. As discussed in Chapter 1, temperature can have an effect on the properties of the tire and maybe also of the pavement.

4. The LA138 measurements

OBSI measurements were performed by UC Davis at the LA138 test sections (see Section 2.1) using the SRTT. The rubber hardness of the tire was measured to 67 Shore A some months before and after the time of the measurements at 24 °C. The noise measurements were carried out on February 26 to 28, 2008 in the daytime between 5 am and 4 pm. Measurements were performed five times during the day at each pavement in order to cover respectively low, medium, and high temperature. The measurements were performed in both the westbound and eastbound direction on each pavement except the DGAC, where the measurements for practical reasons were only performed in one direction. The air and the pavement temperature were measured immediately before and immediately after the noise testing. Each measurement was repeated three times one after another (at practically the same temperature). The results for one of the nine pavement sections are presented in the following – normalized by application of the air density corrections (see Chapter 3). The actual air density correction was between + 0.7 and +1.1 dB.

Table 4.1. Normalized results of individual OBSI runs on the OGAC 75 pavement at different air temperatures in the eastbound direction. The Standard Deviation for the three runs at the same temperature is shown.

Temperature in °C	Run 1 OBSI in dB	Run 2 OBSI in dB	Run 3 OBSI in dB	Average OBSI in dB	Standard Deviation in dB
1.7 – 2.5	100.5	100.5	100.8	100.7	0.15
6.5 – 7.6	100.7	100.9	101.0	100.9	0.15
19.2 – 19.7	100.1	100.3	100.0	100.1	0.17
20.3 – 20.4	100.4	99.1	100.4	100.1	0.72
21.4 – 21.4	100.3	100.7	100.7	100.6	0.25

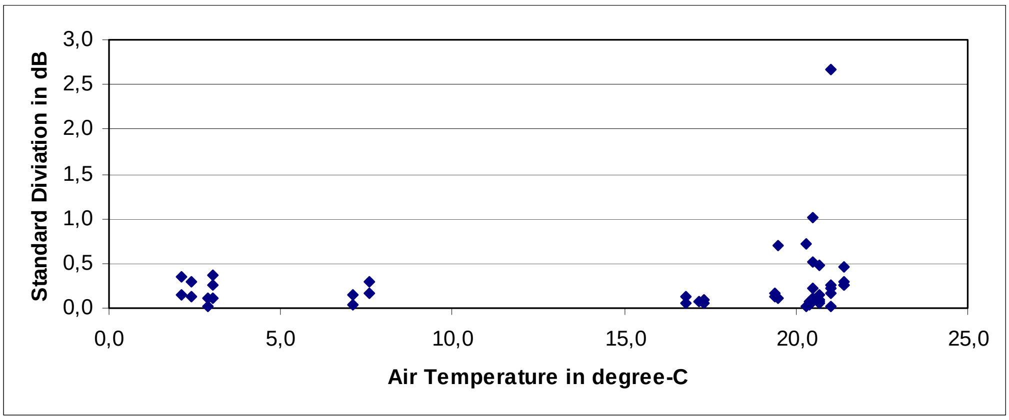

Figure 4.1. Standard Deviation for all the sets of three repeated OBSI runs on the same pavement at the same temperature.

As an illustration, the variations of the OBSI results for the three repeated measurements carried out at the same pavement at the same temperature just after one another are shown in Table 4.1 for the OGAC 75 pavement in the eastbound direction together with the Standard Deviation.

In Figure 4.1, the Standard Deviation for all the sets of three OBSI runs on the same pavement at the same temperature is presented for the temperature range of the measurements. The Standard Deviation for the three repeated measurements at the same temperature is generally below 0.5 dB with a few exceptions. There are two outliers at 1.0 and 2.7 dB. These outlying data have not been included in the further analyses. The Standard Deviation below 0.5 dB must be considered a reasonably good repeatability of the OBSI measurements, but it is in the same order of magnitude as the temperature influence on the noise (see the following results). This highlights the general problem of conducting noise measurements in order to investigate very small differences of noise levels. The current experiment contains a large series of OBSI measurements which ensures reasonable reliability in the results.

One of the reasons for the variation in measured noise level at the three repeated runs can be that the driver of the measurement car does not always hit exactly the same wheel track or the same part of the wheel track with the right rear tire where the microphones are situated. Another reason can be minor uncertainty in the measurement system used specially with regard to small speed variations as speed corrections were not applied to the results.

The results are presented first in relation to the air temperature and afterwards in relation to the pavement temperature. The general relation between the air and pavement temperature at these measurements can be seen in Figure1.2 and 1.3 in Section 1.1.

4.1 Air temperature and noise

The results of the measurements of noise and air temperature are shown in the following figures for each of the pavements included in the project for both directions (eastbound and westbound). The air temperature was in the range from 2 to 22 °C. The figures to the left show the normalized results of each of all the OBSI runs (three per pavement per temperature). A linear regression analysis is included. The figure to the right shows the 1/3 octave band spectra at different temperatures as average spectra for the three OBSI runs per pavement at approximately the same temperature.

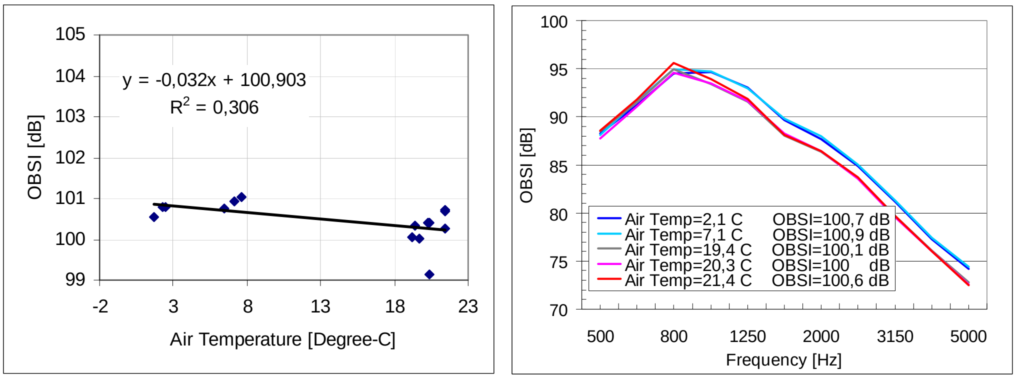

Figure 4.2. OGAC 75 pavement eastbound. Normalized OBSI noise measurement results with SRTT versus air temperature to the left and average spectra at the different temperatures to the right.

The results from the OGAC 75 pavement in east and westbound directions can be seen in Figure 4.2 and 4.3. The air temperature coefficients are -0.032 dB/°C in both directions. Below 800 Hz, the frequency spectra are quite alike - independent of the temperature. At the frequencies above 1000 Hz, the level is around 1 dB higher at 2 °C than at 20 °C. The same tendencies were seen for different tires at the Sperenberg experiment (see Figure 1.7 in Section 1.3).

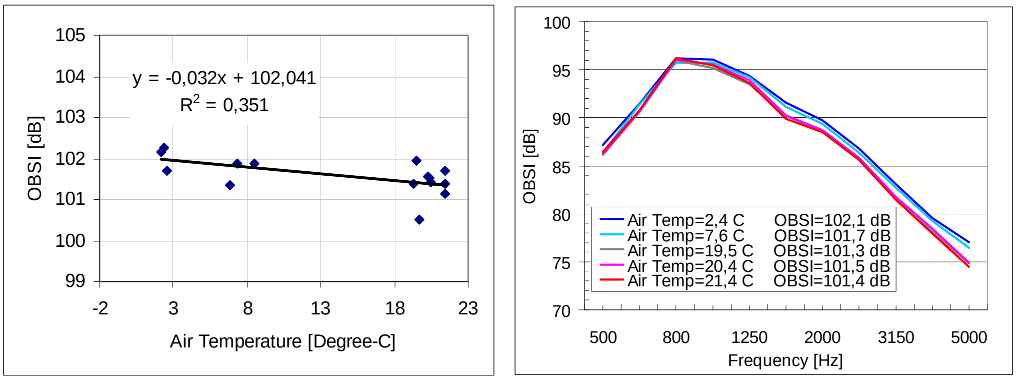

Figure 4.3. OGAC 75 pavement westbound. Normalized OBSI noise measurement results with SRTT versus air temperature to the left and average spectra at the different temperatures to the right.

The noise levels in the westbound direction are around 1 dB higher than in the eastbound direction on the same pavement. This general tendency is seen for all the four pavements for which measurements have been carried out in both directions. In Table 4.2 it can be seen that the Medium Profile Depth (MPD) is lower in the west direction than in the east direction indication that the pavements are denser in the surface structure in the west direction and this can effect the noise generation. The asphalt pavements were seven years old when the OBSI measurements were carried out. Differences in construction conditions and/or tear and wear by traffic might be an explanation for the difference on the same pavement between the east and westbound directions. This east/west phenomenon has no influence on the temperature dependency of the measurement results.

Table 4.2. Medium Profile Depth (MPD) in Microns of the LA138 pavements in east-/ westbound direction.

Direction	OGAC 75	OGAC 30	RAC-O	BWC	DGAC
East	1054	997	815	726	-
West	967	887	686	714	745

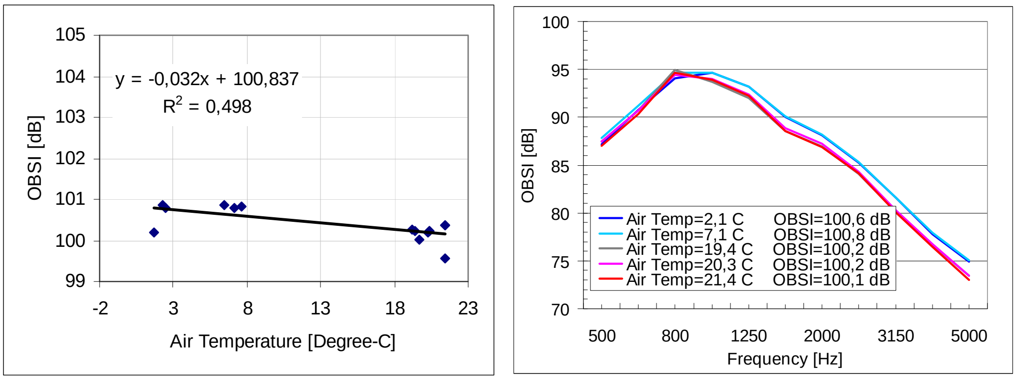

Figure 4.4. OGAC 30 pavement eastbound. Normalized OBSI noise measurement results with SRTT versus air temperature to the left and average spectra at the different temperatures to the right.

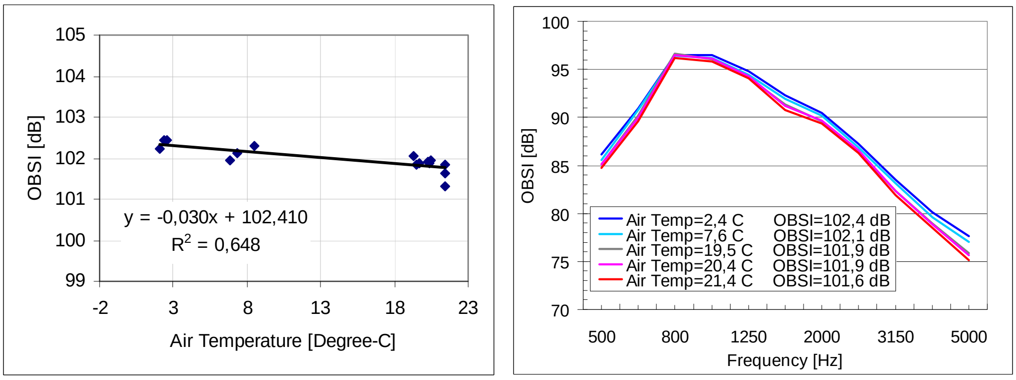

Figure 4.5. OGAC 30 pavement westbound. Normalized OBSI noise measurement results with SRTT versus air temperature to the left and average spectra at the different temperatures to the right.

The results for the OGAC 30 pavement in the two directions are shown in Figure 4.4 and 4.5. The results of the temperature influence on the noise are quite similar to what was seen for the OGAC 75 pavement. The air temperature coefficients for the two directions are -0.032 dB/°C and -0.030 dB/°C respectively.

The results for the RAC-O pavement can be seen in Figure 4.6 and 4.7. The temperature coefficients are -0.009 dB/°C and -0.020 dB/°C respectively for the two directions and less pronounced than for the two OGAC pavements.

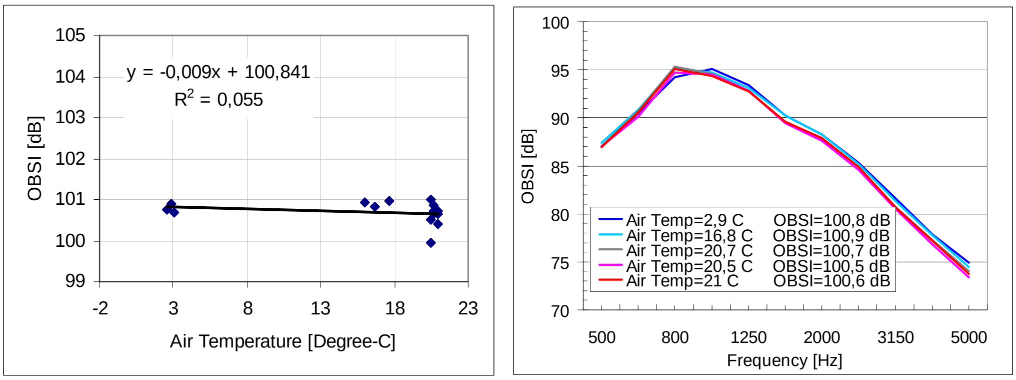

Figure 4.6. RAC-O pavement eastbound. Normalized OBSI noise measurement results with SRTT versus air temperature to the left and average spectra at the different temperatures to the right.

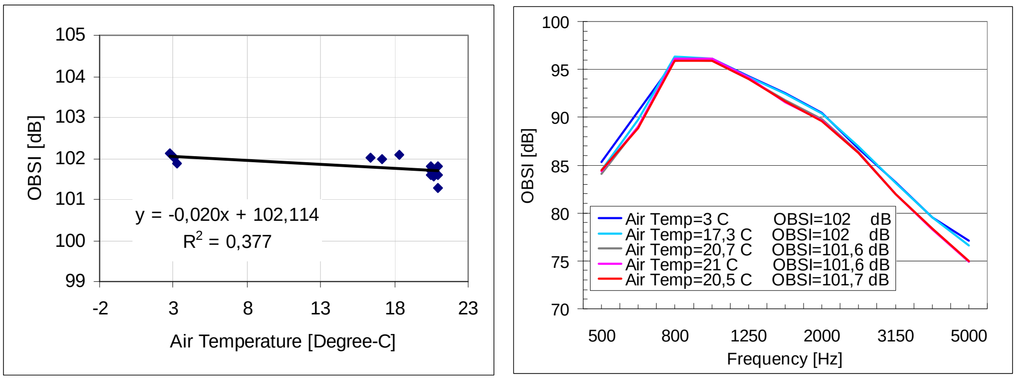

Figure 4.7. RAC-O pavement westbound. Normalized OBSI noise measurement results with SRTT versus air temperature to the left and average spectra at the different temperatures to the right.

For the BWC pavement, the results can be seen in Figure 4.8 and 4.9. The temperature coefficients for the two directions are -0.013 dB/°C and -0.029 dB/°C respectively. This temperature coefficient is somewhat between the coefficients for the OGAC and the RAC-O pavements.

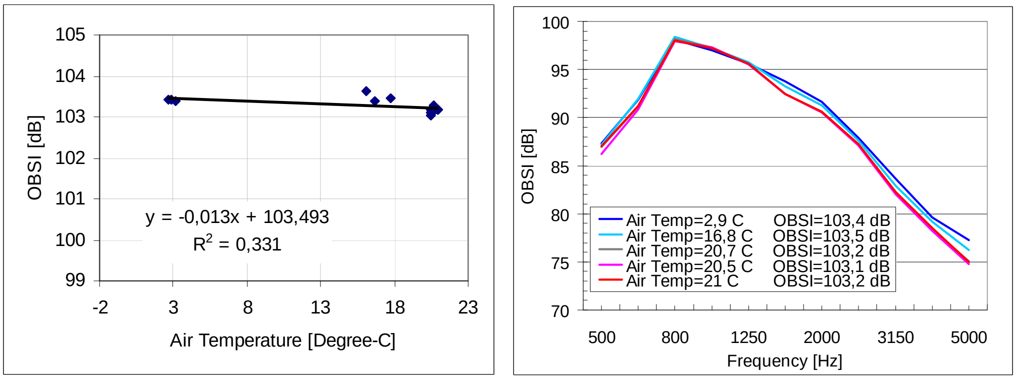

Figure 4.8. BWC pavement eastbound. Normalized OBSI noise measurement results with SRTT versus air temperature to the left and average spectra at the different temperatures to the right.

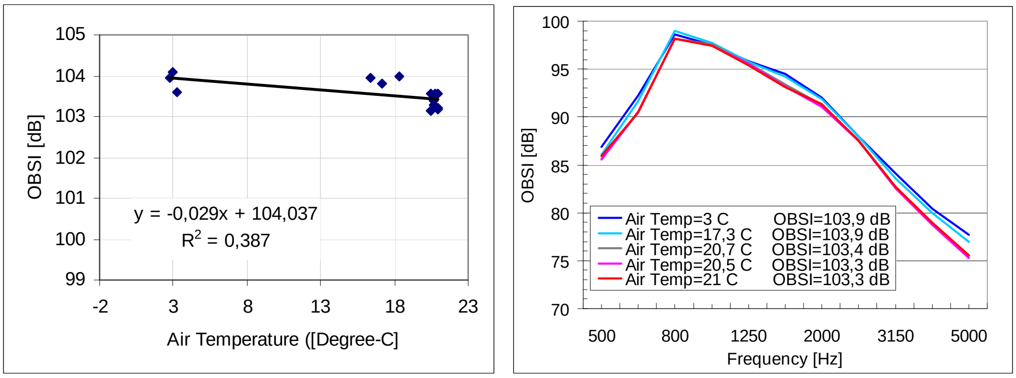

Figure 4.9. BWC pavement westbound. Normalized OBSI noise measurement results with SRTT versus air temperature to the left and average spectra at the different temperatures to the right.

The DGAC pavement was only measured in the westbound direction. The air temperature coefficient is -0.046 dB/°C and higher than for the other pavements.

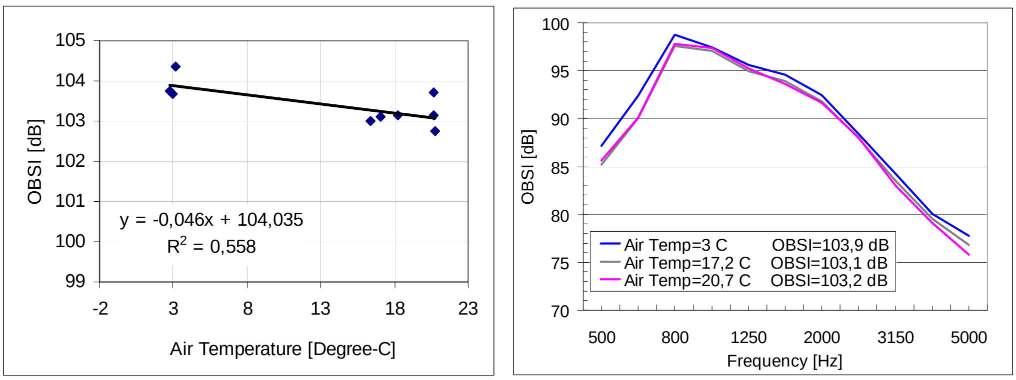

Figure 4.10. DGAC pavement westbound. Normalized OBSI noise measurement results with SRTT versus air temperature to the left and average spectra at the different temperatures to the right.

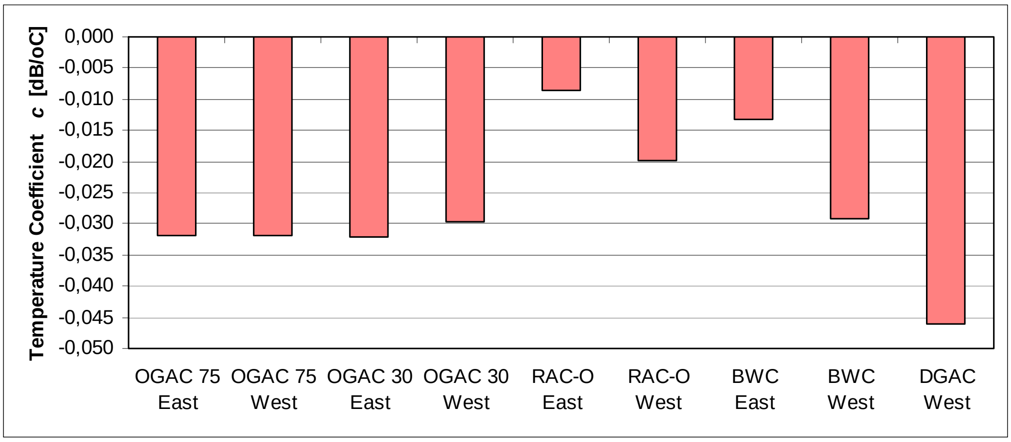

Figure 4.11. Air temperature coefficients in dB/°C measured in the range 2 – 22 °C at LA138 using the OBSI method and the SRTT.

The air temperature coefficients for all the nine measurements ranges between -0.009 dB/°C and -0.046 dB/°C (see Figure 4.11). For the different pavement types the results are the following:

- The average air temperature coefficient *c* is -0.027 dB/°C (or -0.015 dB/°F) for all nine measurements.
- For the dense pavements (DGAC and BWC with air void respectively 7 and 5 %) the average is -0.029 dB/°C (-0.016 dB/°F)
- For the open graded pavements (OGAC 30, OGAC 75 and RAC-O all with an air void of 10 to 11 %) the average is -0.026 dB/°C (-0.014 dB/°F).

All the data collected with the OBSI method on the LA138 test sections using an SRTT in the air temperature range from 2 to 22 °C.

4.2 Pavement temperature and noise

The following figures show the results of the OBSI noise measurements versus the pavement temperature. The spectra are not shown since they are the same as shown in Figures 4.2 to 4.10 just related to the pavement temperatures.

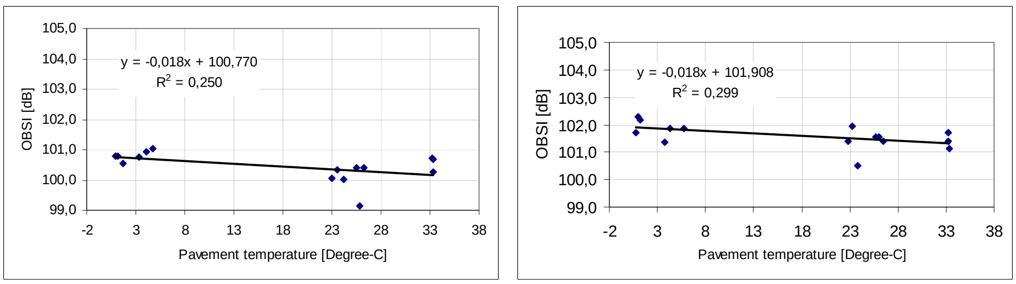

Figure 4.12. OGAC 75 pavement eastbound to the left and westbound to the right. Normalized OBSI noise measurement results with SRTT versus pavement temperature.

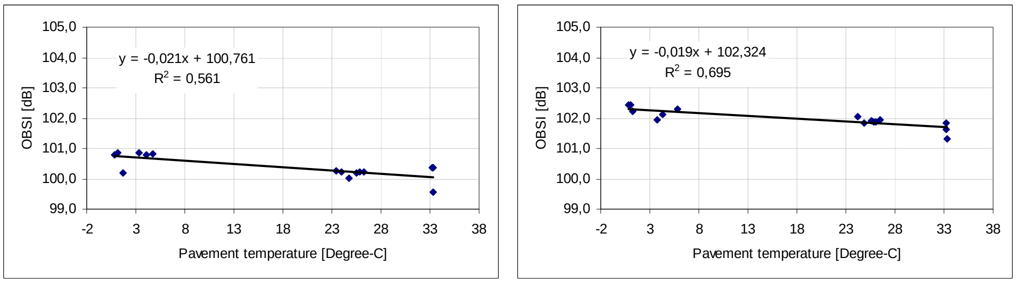

Figure 4.13. OGAC 30 pavement eastbound to the left and westbound to the right. Normalized OBSI noise measurement results with SRTT versus pavement temperature.

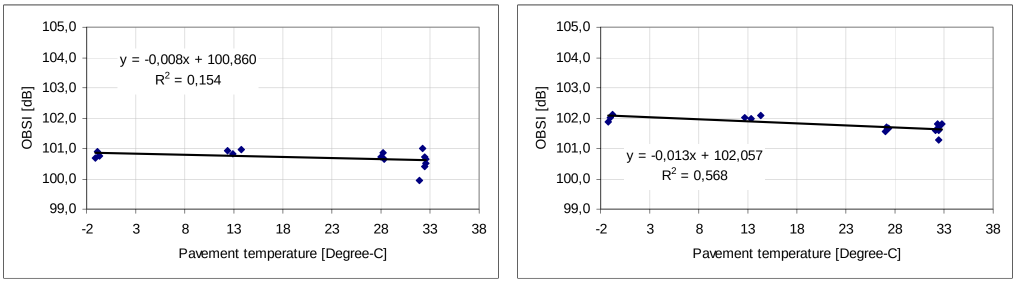

Figure 4.14. RAC-O pavement eastbound to the left and westbound to the right. Normalized OBSI noise measurement results with SRTT versus pavement temperature.

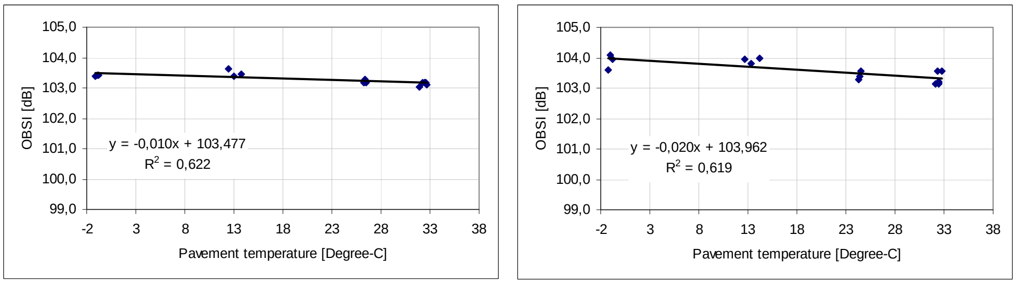

Figure 4.15. BWC pavement eastbound to the left and westbound to the right. Normalized OBSI noise measurement results with SRTT versus pavement temperature.

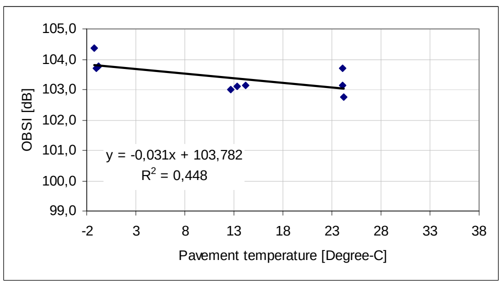

Figure 4.16. DGAC pavement westbound. Normalized OBSI noise measurement results with SRTT versus pavement temperature.

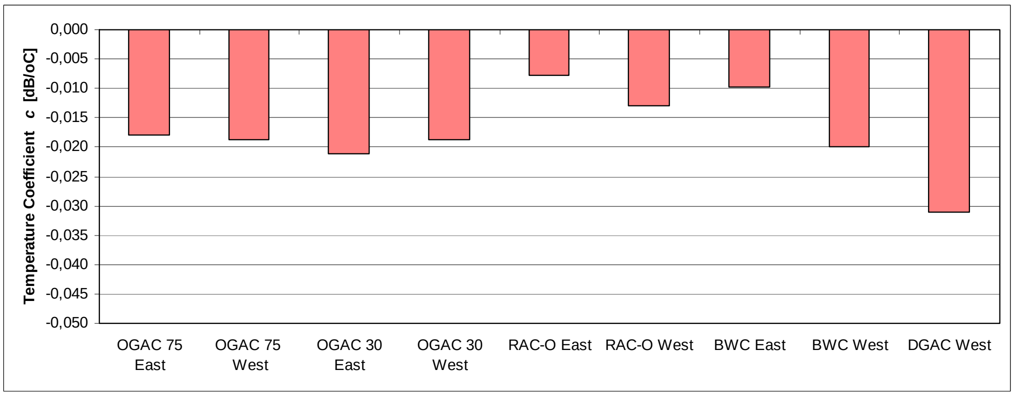

Figure 4.17. Pavement temperature coefficients in dB/°C measured in the range -2 – 33 °C at LA138 using the OBSI method and the SRTT.

The pavement temperature coefficients for all the nine measurements range between -0.008 dB/°C and -0.031 dB/°C (see Figure 4.17). For the different pavement types the results are the following:

- The average pavement temperature coefficient *c* for all nine pavements is -0.018 dB/°C (or -0.010 dB/°F).
- For the dense pavements (DGAC and BWC) the average is -0.020 dB/°C (-0.011 dB/°F).
- For the open graded pavements (OGAC 30, DGAC 75 and RAC-O) it is -0.016 dB/°C (-0.009 dB/°F).

Again, all data were collected with the OBSI method on the LA138 test sections using an SRTT.

5. The California measurements

The results of the noise measurements performed on ten different Californian pavements (see Section 2.2) at different temperatures can be seen in the following graphs. The OBSI measurements were performed using a Goodyear Aquatred tire (see Figure 5.1) which was the previous standard for OBSI before the SRTT was adopted.
The rubber hardness of the Aquatred tire was measured to 69 Shore A at the period of the measurements and at 24 °C.

The measurements were performed June-July 2007, and the purpose was to determine at that time the feasibility of using pavement temperature correction. Due to practical reasons, only the pavement temperature data are available for reporting. No spectral data are available for this measurement series. In order to investigate the influence of temperature, noise measurements were carried out on the same pavement on the same day at 3 different temperatures (targeted air temperatures 15, 25, and 35°C).

The pavement sections included in this study correspond to a small subset of the total of asphalt pavement sections monitored by the UCPRC [12]. The QP number of each section can be tracked down to the database of material properties and pavement performance data [12]. Air density corrections have been performed on these results (see Chapter 3).

Figure 5.1. A Goodyear Aquatred tire.

The results for the ten pavements grouped according to pavement types can be seen in Figure 5.2 to 5.4.

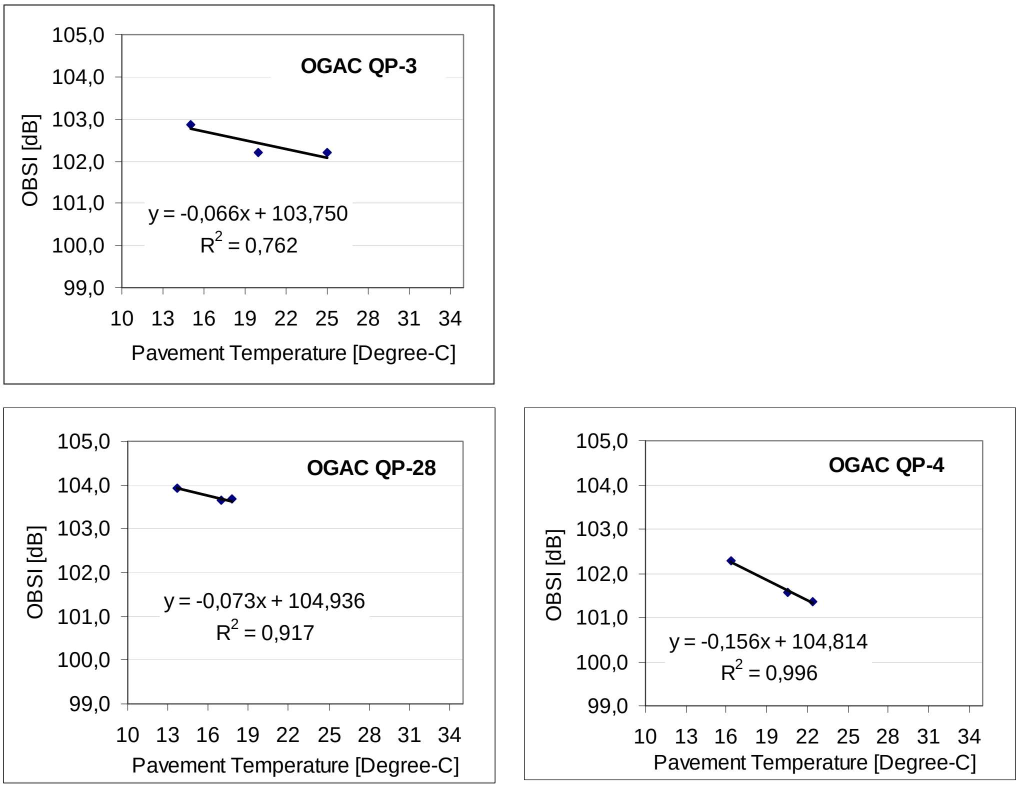

Figure 5.2. Three OGAC pavements. Normalized OBSI noise measurement results with Aquatred tire versus pavement temperature.

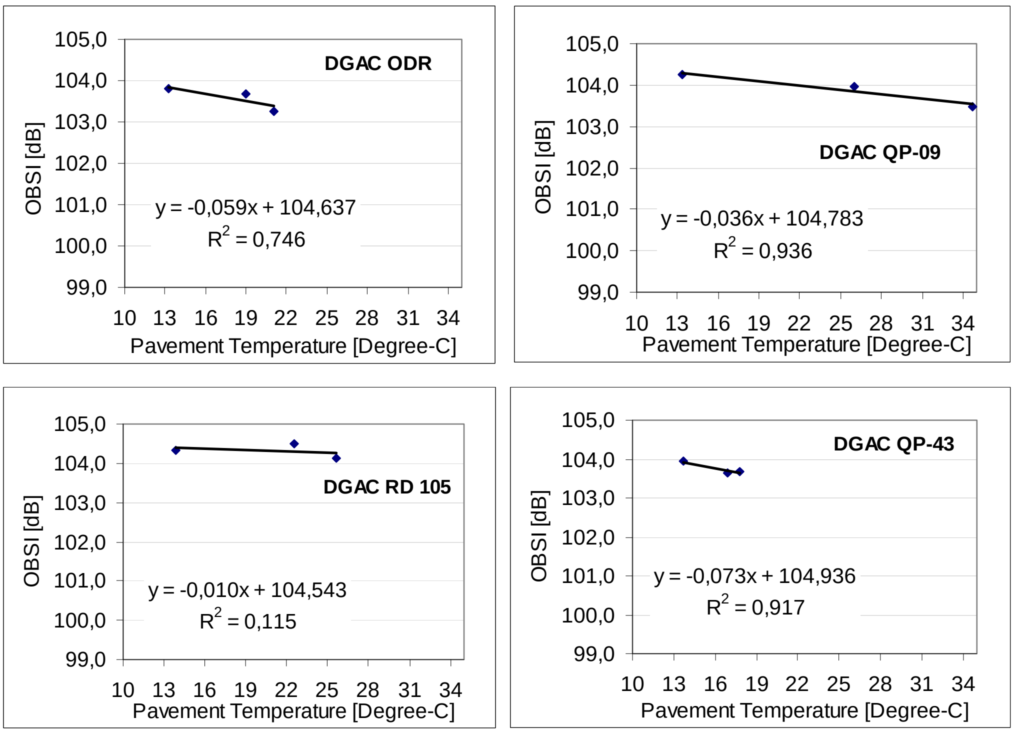

Figure 5.3. Four DGAC pavements. Normalized OBSI noise measurement results with Aquatred tire versus pavement temperature.

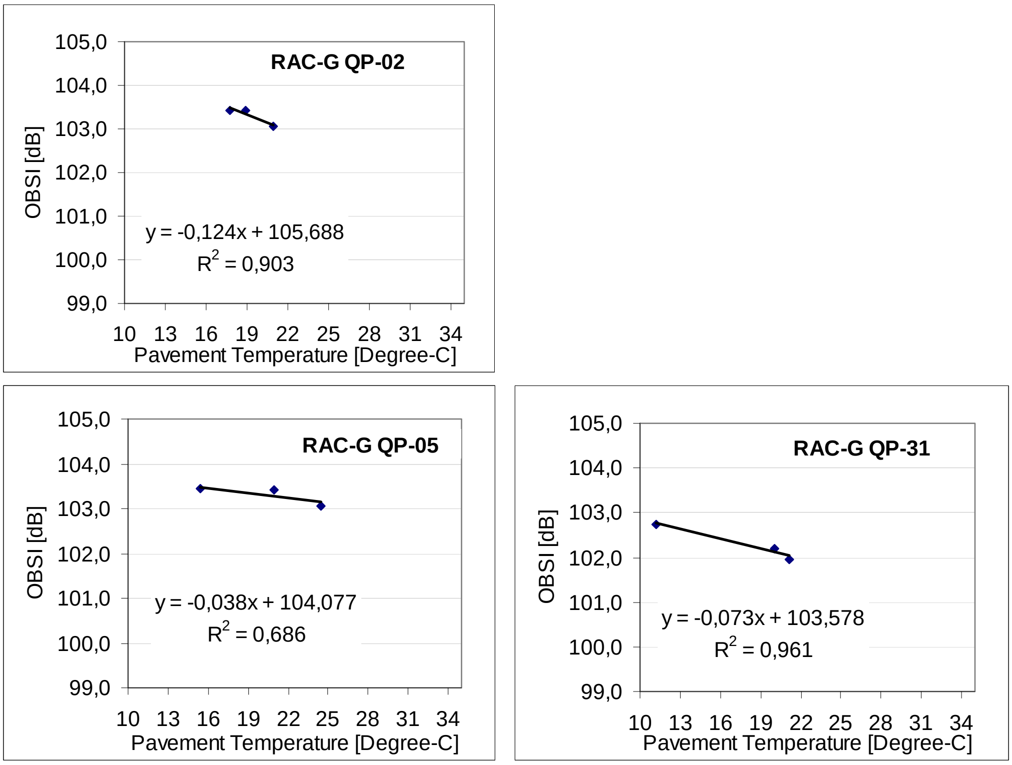

Figure 5.4. Three RAC-G pavements. Normalized OBSI noise measurement results with Aquatred tire versus pavement temperature.

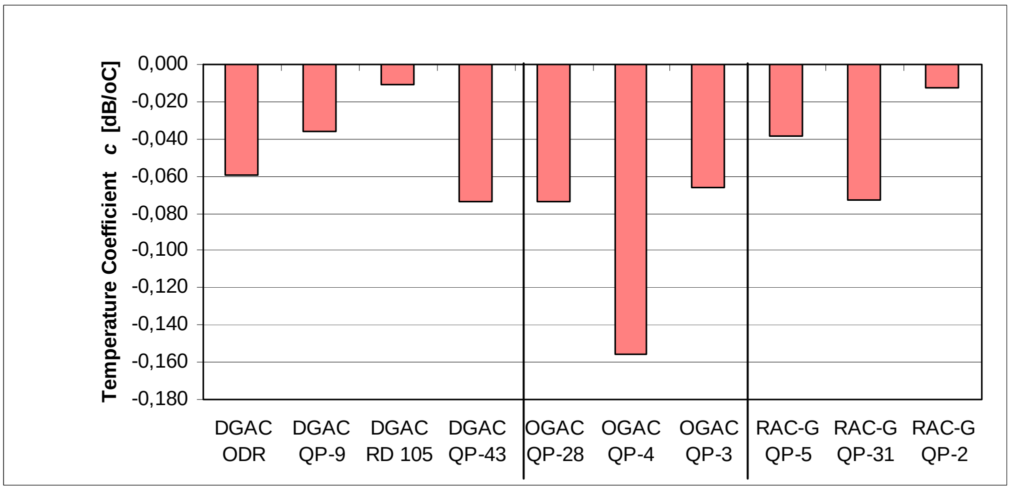

Figure 5.5. Pavement temperature coefficients in dB/°C measured in the range 11 – 34 °C at the Californian pavements using the OBSI method and the Aquatred tire.

The summary of the pavement temperature coefficients from the measurements performed on different Californian pavements can be seen in Figure 5.5. The average coefficients for the different pavement types can be seen in Table 5.1 together with average for all the ten pavements.

The two dense pavement types (DGAC and RAC-DG) have nearly the same coefficient -0.045 dB/°C and -0.041 dB/°C with an average of -0.043 dB/°C. For the open graded pavement type (OGAC), the coefficient is -0.099 dB/°C, which is twice as much. But the higher average for the open graded pavements is caused by the OGAC QP-4 with a very high coefficient. If this pavement is not considered, the difference between the open and the dense pavements is reduced to -0.043 dB/°C versus -0.070 dB/°C.

All data are collected with the OBSI method on different Californian roads using an Aquatred tire.

Table 5.1. Average pavement temperature coefficients for the three pavement types using the OBSI method and the Aquatred tire.

Pavement type	**Pavement temperature coefficient in Celsius**	**Pavement temperature coefficient in Fahrenheit**
DGAC	-0.045 dB/°C	-0.025 dB/°F
RAC-G	-0.041 dB/°C	-0.023 dB/°F
Average dense (DGAC and RAC-G)	-0.043 dB/°C	-0.024 dB/°F
OGAC	-0.099 dB/°C	-0.055 dB/°F
Average all 10 pavements	-0.060 dB/°C	-0.033 dB/°F

6. Discussion and conclusion

It can be discussed if the temperature coefficient shall be applied in relation to the air, pavement or tire temperature. There has so far been an international trend to use the air temperature as the relevant variable, so this will be done in the general comparison of results in the following.

One of the main objectives of this project was to investigate the influence of temperature on OBSI measurements as they are carried out with the methods currently used in California. Here the SRTT is now used as the standard reference tire. Some years ago the Aquatred tire was normally used. The temperature coefficients will also be relevant for the CPX method when the SRTT is applied!

Table 6.1. Average temperature coefficients for the SRTT and the Aquatred tire on different asphalt pavement types (LA138 and California measurements).The air temperature coefficient for the Aquatred tire is predicted based on the ratio between air and pavement temperature coefficients for the SRTT.

Tire	Dense asphalt pavements (DGAC)	Open graded asphalt pavements (OGAC and RAC-O)	Average all asphalt pavements
SRTT air temperature	-0.029 dB/°C	-0.026 dB/°C	-0.027 dB/°C
Aquatred air temperature (predicted)	-0.062 dB/°C	-0.160 dB/°C	-0.090 dB/°C
SRTT pavement temperature	-0.020 dB/°C	-0.016 dB/°C	-0.018 dB/°C
Aquatred pavement temperature	-0.043 dB/°C	-0.099 dB/°C	-0.060 dB/°C

The measurement results from Sperenberg on a series of sixteen different passenger car tires show a large variation in the air temperature coefficients ranging from -0.035 to -0.130 dB/°C for dense and porous asphalt pavements. The measurements at the LA138 test sections using the SRTT and the measurements on the ten Californian sections with the Aquatred tire shows a significant difference for the temperature coefficients for these two tires (see Table 6.1). There is only pavement temperature data available for the California measurements. In order to estimate also the air temperature coefficient for the Aquatred tire, the ratio between air and pavement temperature coefficients for the SRTT is used in Table 6.1. The table then shows air as well as pavement temperature coefficients for these two measurement series.

The average air temperature coefficient for the Aquatred is estimated at -0.090 dB/°C which is three times higher than for the SRTT. This means that the Aquatred tire is much more sensitive to temperature than the SRTT. The rubber hardness was in this investigation slightly lower for the SRTT than for the Aquatred tire (67 versus 69 Shore A).

This might partly explain the difference in temperature coefficients but other tire properties like the chemical composition of the rubber, the tread pattern and the depth differences etc. might play a role. The two tires in the French experiment had higher rubber hardness of 76.3 and 79.5 shore A and the average air temperature coefficient for these two tires is -0.080 dB/°C for asphalt pavements (see Table 6.2).

The average air temperature coefficient for the SRTT is -0.027 dB/°C which is practically the same found by Donavan/Lodico (-0.026 dB/°C).

The results from different international measurement series presented in Chapter 1 indicate that also the pavement type has an influence on the temperature coefficients (see Table 6.2 and Figure 6.1) even though there is some variation in the temperature coefficients for the same pavement type. Most of the measurement series have been performed in temperature spans of 20 to 30 °C. Two measurement series has been performed in more narrow temperature spans of just 10 °C including the Arizona L_{Aeq} measurements.

The trends and ranking between the different pavement types are not very clear. The cement concrete pavements have the lowest temperature coefficient in all except one measurement series. The exception is the L_{Aeq} Arizona results where the coefficient for cement concrete pavements is the highest coefficient reported on any pavement in all the measurement series. Different measurement methods have been used, narrow temperature range, and different sizes of vehicle/tire populations have been included and this is presumably a large part of the explanation for the differences.

From Table 6.2 it can also be seen that the SRTT (see the LA138 OBSI measurements) have significantly lower temperature coefficients than the other tires and tire populations included in the comparison. This indicates that the SRTT is not very sensitive to temperature variations.

Table 6.2. Air temperature coefficients for different pavement types in the 5 different measurement series presented in Chapter 1 given as average values of all the tires used for passenger cars and the SRTT measurements on LA138.

Name of measurements	**Measurement method**	**Air temperature range**	**Dense asphalt pavements (DGAC)**	**Open graded asphalt pavements (OGAC)**	**Average all asphalt pavement types**	**Cement concrete pavements**
Sperenberg	CPB 16 tires	0 – 35 °C	-0.090 dB/°C	-0.061 dB/°C	-0.076 dB/°C	-0.043 dB/°C
France	CPB 2 tires	0 – 30 °C	-0.100 dB/°C	-0.060 dB/°C	-0.080 dB/°C	-0.030 dB/°C
Donavan/Lodico	OBSI 2 tires	30 – 40 °C	-0.064 dB/°C			-0.057 dB/°C
LA138/OBSI	OBSI SRTT	2 – 22 °C	-0.029 dB/°C	-0.026 dB/°C	-0.027 dB/°C	
Arizona	L_{AEQ}	29 – 39 °C		-0.064 dB/°C		-0.130 dB/°C
LA138/SPB	SPB	8 – 32 °C	-0.022 dB/°C	-0.049 dB/°C	-0.036 dB/°C	

Rough averages of all these different results presented in Table 6.2 can be seen in Table 6.3. The very high temperature coefficient for cement concrete pavements (-0.130 dB/°C) reported in the Arizona L_{Aeq} measurements is not included.

Average values of temperature coefficients for different measurement series including many different tires have relevance in relation to noise measurements where many different vehicles/tires are included like SPB and L_{Aeq} measurements.

From Table 6.3 it can be seen that there is no big difference between temperature corrections for dense (-0.061 dB/°C) and open graded asphalt pavements (-0.052 dB/°C). According to these data, an average air temperature coefficient of -0.057 dB/°C for all types of asphalt pavements can be predicted. The correction coefficients for cement concrete pavements is -0.043 dB/°C and lower than for asphalt concrete pavements.

It can be seen that the difference in temperature coefficients for different pavement types almost vanishes when a lot of different tires are included (see Table 6.3).

Generally these results are quite close to the coefficient of -0.05 dB/°C for passenger cars commonly used in Denmark and the Netherlands. The results are in accordance with the generic temperature correction method suggested by Sandberg in 2004 and also reasonably close to the coefficient used in the EU tire noise directive of -0.06 dB/°C up to 20 °C. These factors are approximately double those for the SRTT on asphalt tested in California.

Table 6.3. Rough average of all air temperature coefficients for the different pavement types from the SRTT measurements presented in Table 6.1 and all the data from the different measurements in Table 6. 2. The results for the concrete pavement in Arizona are not included.

Dense asphalt pavements (DGAC)	**Open graded asphalt pavements (OGAC)**	**Average all asphalt pavement types**	**Cement concrete pavements**
-0.061 dB/°C	-0.052 dB/°C	-0.057 dB/°C	-0.043 dB/°C

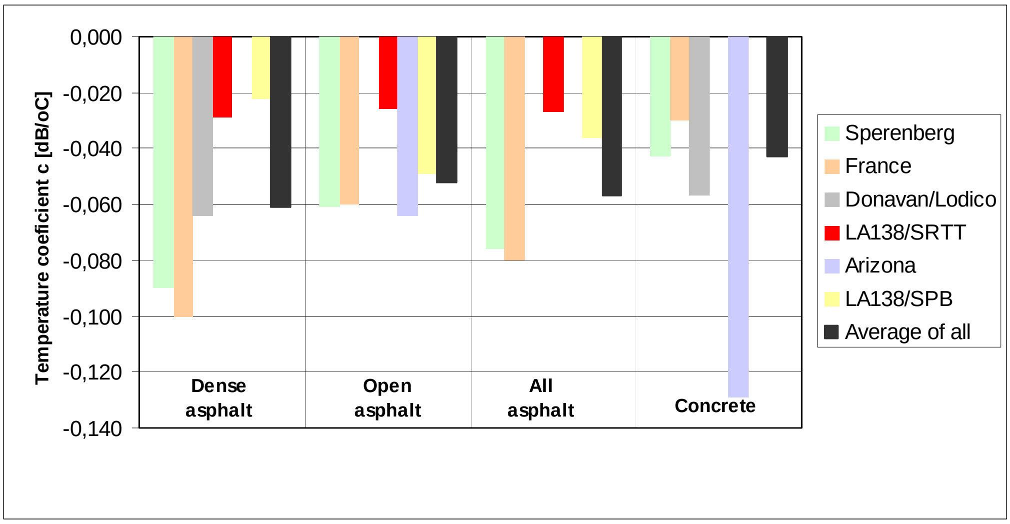

Figure 6.1. Air temperature coefficients for different pavement types in the five different measurement series presented in Chapter 1 given as average values of all the tires used for passenger cars and the SRTT measurements on LA138. In the average for cement concrete the Arizona data are not included.

For OBSI, CPX and CPB measurements only one or a few selected tires are used. The results measured in this project and data collected from other sources clearly show that the above mentioned average temperature corrections (Table 6.3) are not the most relevant for measurement methods using specific tires. Correction coefficients related to the specific tires used seem more appropriate. If measurements at different pavement types show great variation in the temperature coefficient for a specific type of measurement tire, it can be relevant to determine pavement type specific temperature correction coefficient. But as it can be seen from Table 6.1 the SRTT has nearly the same temperature coefficients for different asphalt pavement types so it does not seem relevant to use pavement specific correction factors for this tire when used on asphalt concrete pavements.

There has not been any data available to evaluate the temperature coefficient for the SRTT used on cement concrete pavements. Table 6.2 indicates that the temperature coefficient for cement concrete pavements is lower than for asphalt pavements. But as mentioned above, the temperature coefficients of the SRTT is not so sensitive to pavement type. It could anyway be a recommendation to perform a survey like the LA138 study with the SRTT on a series of different concrete pavements in a desert location with a large temperature variation over the day.

Based on this project, the temperature correction coefficients presented in Table 6.4 for asphalt pavements is suggested for the SRTT used in the OBSI method and the CPX method. The temperature influences the noise differently at different frequencies; therefore it could be relevant to apply frequency dependent correction coefficients. Table 6.5 and 6.6 as well as Figure 6.2 shows third octave band correction coefficients for the SRTT in degrees Celsius and Fahrenheit.

Table 6.4. Suggestion for temperature coefficients for the SRTT used at asphalt pavements in the OBSI method and other methods using SRTT.

	In Celsius	In Fahrenheit
Air temperature correction	-0.027 dB/°C	-0.015 dB/°F
Pavement temperature correction	-0.018 dB/°C	-0.010 dB/°F

Table 6.5. Suggestion for third octave band correction coefficients in dB per degree Celsius for the SRTT used at asphalt pavements in the OBSI method.

Third Octave Band (Hz)	Air Temperature Correction (dB/°C)	Pavement Temperature Correction (dB/°C)
500	-0.040	-0.023
630	-0.054	-0.034
800	0.003	-0.001
1000	-0.023	-0.014
1250	-0.033	-0.020
1600	-0.068	-0.043
2000	-0.054	-0.034
2500	-0.042	-0.026
3150	-0.075	-0.047
4000	-0.067	-0.043
5000	-0.109	-0.068

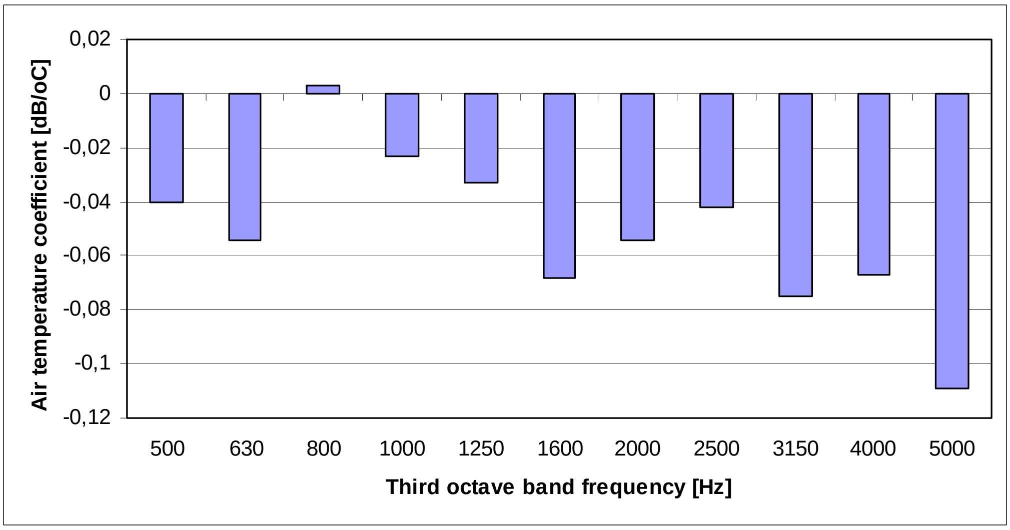

Figure 6.2. Suggestion for third octave band air temperature correction coefficients in dB per degree Celsius for the SRTT used at asphalt pavements in the OBSI method.

Table 6.6. Suggestion for third octave band correction coefficients in dB per degree Fahrenheit for the SRTT used at asphalt pavements in the OBSI method.

Third Octave Band (Hz)	Air Temperature Correction (dB/°F)	Pavement Temperature Correction (dB/°F)
500	-0.022	-0.013
630	-0.030	-0.019
800	0.002	-0.001
1000	-0.013	-0.008
1250	-0.018	-0.011
1600	-0.038	-0.024
2000	-0.030	-0.019
2500	-0.023	-0.014
3150	-0.042	-0.026
4000	-0.037	-0.024
5000	-0.061	-0.038

There is still a need for more research in order to understand the basic mechanisms related to temperature which is important for the generation of tire pavement noise.

The following general conclusions can be drawn regarding temperature corrections to noise measurements:

- The air temperature has an important influence on the tire/road noise measurements results.
- The dependence of tire/road noise on temperature can be approximated by a linear relation.
- The temperature coefficients vary significantly for different tire types.
- The temperature coefficients are generally smaller for truck tires than for passenger car tires.
- At low frequencies, the temperature coefficient is low. At frequencies above 1000 Hz the temperature coefficient is higher.
- The temperature coefficient is different for different pavement types.
- The temperature coefficient seems to be higher for dense asphalt concrete than for open/porous asphalt pavement.
- The temperature coefficient seems to be lower for cement concrete pavements than for asphalt concrete pavements.
- The difference in temperature coefficients for different asphalt pavement types almost vanishes when many different tires are included.
- Temperature coefficients have to be determined specifically for each measurement method taking into consideration the specific test tire(s) or the tire population included in the measurements.

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