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Report

NordTyre – Tyre/road noise testing on various road surfaces - State-of-the-Art

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ABSTRACT
This report is the first deliverable of the NordFoU project NordTyre.
The main purpose of the project is to establish scientific evidence of the tyre/road contribution to road traffic noise emission in the Nordic countries. Furthermore, to establish which combinations of tyres and road surfaces that will yield the lowest noise emissions.

This report is a literature study mainly based on available literature from the period 2005-2011. Focus has been on available data of tyre noise levels on ISO tracks, on other test track road surfaces and on road surfaces representative of pavements used in the Nordic countries.

The main results are that the spread in noise levels on rough-textured road surfaces commonly found in Sweden and Norway is much less than found on ISO surfaces. The noise ranking seems to be significant different on rough-textured pavements compared to an ISO surface, but may be better on the smoother road surfaces, as found for example in Denmark.
It is necessary to improve the knowledge of the performance of passenger car tyres on normally used Nordic road surface, compared to the coming noise labelling system of tyres in the EU. A measuring program of tyres on similar pavement types in Denmark, Sweden and Norway is proposed.

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Table of contents

SUMMARY

This is a state-of-the-art report on the measurement of tyre/road noise on various road surfaces, with emphasis on the tyre behaviour. It is the first delivery of the Nordic NordFoU project NordTyre. The main purpose of the project is to establish scientific evidence on the tyre/road contribution to road traffic noise emission in the Nordic countries.
The report is based on a literature study, mainly on sources in the period 2005-2011. Focus has been on available data regarding overall dB(A)[1]levels rather than on frequency spectra. Neither are papers discussing generation mechanisms for tyre/road noise included in the review.

Data for noise levels of tyres are given for measurements on ISO test track (type testing levels), measurements on trafficked roads (including Nordic pavements) and on test areas.

Databases for type testing noise levels of tyres are presented, with also wet grip and rolling resistance values included. This enables the presentation of the current tyre population (not restricted to Nordic countries), and their relationship with the coming labelling system within the EU and EEC countries, valid from 2012-11-01.

The databases show that the type testing noise levels of tyres of class C1 vary by 10 dB, due to variations in tyre widths, variations within the same width and spread in levels on different ISO tracks. For C2 and C3 tyres, the spread is in the range of 7-11 dB, depending on type of tyre (normal/snow/traction).

Based on measurements on the same ISO track, the spread in levels are lower, in the range of 6-7 dB for summer tyres for cars (class C1).

The spread in tyre/road noise levels on typical rough-textured pavements, especially found in Norway, Sweden and Finland, seems to be much less, in the range of 2-3 dB. The correlation between noise levels on such rough textured pavements and noise levels on the ISO surface (which is a smooth dense asphalt concrete surface with 8 mm maximum chipping size) is apparently weak. It indicates less efficiency from the reduction of the noise limits for the Nordic situation. However, this conclusion is based on a limited number of tyres, and only on measurements in Norway.

Based on a database from 2008 with approximately 200 tyres included for class C1C (195, 205, 215 mm), 55 % of these tyres already meet the new noise limit. In this class, we find the major tyres representing the tyre market in the Nordic countries. Based on a newer database from the Netherlands in 2010, with approximately 100 tyres in the class, about 80 % meet the new limit. It indicates a significant potential for further reduction of the limits in the future.

Tyre/road noise levels on the most commonly used surfaces in Norway, DAC/SMA 0/11 seem to be 2-3 dB higher than on similar surfaces in Denmark and other countries on the European continent. The similar Swedish road surfaces may even give 1-1.5 dB higher levels than the Norwegian pavements, perhaps due to a higher percentage of use of studded tyres in Sweden than in Norway. In Finland, where the most common surface is SMA 0/16 and the use of studded tyres is comparable to Sweden, the tyre/road noise levels could be the same as in Sweden.

[1] The dB levels given in this report are A-weighted sound pressure levels in dB re. 20 µPa,

A tyre imported from Asia (not sold in Europe), Michelin Primacy LC, was found to be 2-3 dB quieter than the "average" summer tyres measured on a range of normally used road surfaces in Denmark. Wet grip and/or rolling resistance values should be required (from manufacturer, if possible) or measured for this tyre. As an example of an extreme case; a comparison of this Michelin tyre on a new Danish AC 6o (open graded dense asphalt with 6 mm max. chipping size) with a "normal" tyre on a rougher and older SMA 0/16 surface in Norway gave 13 dB lower tyre/road noise level at 80 km/h.. This indicates some of the potential for reduction of tyre/road noise, by the use of low-noise tyres and low-noise road surfaces, even without the inclusion of porous surfaces. Of course, one shall not neglect the possibly unavoidable influence of climate and the consequences this has for the use of pavement types and how the noise properties of these develop over time.

A linear regression analysis of the noise levels from tyres measured both on ISO surface and on other, regular road surfaces has been made. From this analysis, the slope of the regression curve is an indicator of the effectiveness of reducing the noise limits for tyres, while the correlation coefficient is an indicator on the ranking of tyres on the regular road surface, compared to the ISO surface.
Based on a limited number of passenger car tyres measured on road surfaces in Norway and on test tracks in the Netherlands, it seems that the correlation is poor for typical rough-textured pavement types normally found in Norway, Sweden and Finland. For some of the porous surfaces, the correlation was also weak. Very high slopes and correlation were found for some surfaces like rubberized surfaces or thin layers with smooth texture.

In general, this analysis indicates a need for a second, more rough-textured surface as test surface for type approval of tyres.

Studded winter tyres seem to give 2-3 dB higher noise levels than non-studded winter tyres. However, this is based on about 10 year old data, and new measurements are recommended. (
A measurement program for summer tyres for cars is proposed. It is recommended to measure around 30-32 pairs of passenger car tyres, primarily covering the classes C1B, C1C and C1D.

The tyres chosen should focus on tyres labelled at or below the noise limit to be introduced in November 2012. The selection should include tyres from the most popular brands in the Nordic countries, such as Michelin, Continental, Goodyear and Nokian.

Measurements on pavement types representing the most commonly applied wearing courses in the Nordic countries are recommended. Such pavements are dense asphalt concrete surfaces (AC or SMA) with maximum chipping sizes between 6 and 16 mm.

A two-wheeled trailer is recommended for the measurements.

Rolling resistance (here abbreviated as RR) is part of the tyre labelling system and a brief summary of the basic generation mechanisms, measuring methods and legal requirements are given in the report. RR is the main focus of two international projects; TYROSAFE and MIRIAM. Some recommendations are given for the NordTyre project for measurements of RR for tyres/road surfaces.
Measurements of rolling resistance on a combination of tyres and road surfaces have, to some extent, been made on Swedish and Danish road surfaces. Such measurements should be extended to include Norwegian and Finnish road surfaces and more tyres to give a broader documentation of the status in the Nordic countries.

SAMMENDRAG

Denne statusrapporten om måling av dekk/veibanestøy på ulike typer veidekker, med fokus på bildekkenes egenskaper er første leveranse tilt NordFoU-prosjektet NordTyre.
NordTyre har som hovedformål å etablere en vitenskapelig basis for bidraget fra dekk/veibanestøy til den generelle veitrafikkstøyen i de nordiske land. I tillegg, å undersøke hvilke kombinasjoner av bildekk og veidekker som gir de laveste støyemisjonsnivåene.

I 2006 ble det publisert to rapporter av organisasjonen FEHRL, som oppsummerte kunnskap omkring dekk/vekbanestøy, inklusive litteraturgjennomgang fram til og med 2005. Denne rapporten er derfor basert på en litteraturstudie med fokus på publikasjoner i perioden 2005-2011.

I rapporten fokuseres det på litteratur der totalt A-veid maksimalt støynivå for bildekk på ulike veidekker belyses. Artikler av mer teoretisk art, som for eksempel beskrivelse av støygenereringsmekanismer for dekk/veibane, er ikke omtalt.

I tillegg til litteraturgjennomgang, er det tatt kontakt med eksperter rundt i verden, som har bidratt med kommentarer/rapporter.

Resultatene fra litteraturstudiet viser at det er begrenset med nyere data fra målinger av bildekks støyegenskaper på andre veidekker enn ISO-dekke. Det gjøres målinger i laboratorier som for eksempel TUG (Polen), BASt og TÜV(Tyskland), men dette er i stor grad klientmålinger og ikke offentlig tilgjengelige resultater.

SINTEF har gjennomført flere måleprosjekter på oppdrag fra norske myndigheter, som omfatter både målinger på ISO-dekker (i Nederland), på ulike teststrekninger (Kloosterzande), og på norske og danske veidekker. De viktigste resultatene fra disse målingene er gitt i denne rapporten.
I tillegg har konsulentselskapet M+P i Nederland gjennomført tilsvarende målinger av bildekk (både personbildekk og lastebildekk) på ulike veidekker (Sperenberg/Kloosterzande).

Rapporten gir en oversikt over eksisterende støykrav til bildekk og kommende EU-direktiv med nye støykrav til bildekk (EC 661/2009) og for støymerking av dekk (EC 1222/2009).

Målemetoder for måling av bildekks støyegenskaper presenteres, både for typegodkjenning (ECE Reg.117), og andre metoder som CPX-måling (med tilhenger/bil) eller måling på trommel i laboratorium.

Data for dekk/veibanestøy presenteres for:

- Målinger på ISO-dekke; enten ved typegodkjenningsmålinger eller ved CPX-type av målinger
- Målinger på trafikkerte veier, med prioritering av data fra representative, nordiske veidekker
- Målinger på ulike veidekker på testbaner (ikke trafikkerte)

Ulike databaser (og rapporter) med støynivå for bildekk (ISO-nivåer) er gjennomgått. En nederlandsk liste fra 2010 gir en oversikt over støynivå, rullemotstand og våtgrepsegenskaper for i alt 376 bildekk. (personbildekk og varebildekk/vans). Disse data er prosessert slik at en kan se at det ikke er noen signifikant positiv eller negativ korrelasjon mellom disse tre parametere. Dvs. at det ikke er slik at et støysvakt bildekk nødvendigvis har høy rullemotstand eller dårligere våtgrep,

Databasene viser at typegodkjenningsnivåer for bildekk av klasse C1 (personbildekk) kan variere med opptil 10 dB. Denne variasjonen skyldes en blanding av dekkbredde, dekk-konstruksjon, og spredning i støynivå mellom ulike ISO-dekker. En nederlandsk undersøkelse av 7 ISO-dekker har vist at ett og samme bildekk kan variere støynivået med mer enn 4 dB mellom ulike ISO-dekker. Måles bildekkene på det samme ISO-dekket, er spredningen i nivåer mindre, i størrelsesorden 6-7 dB.

Basert på en gjennomgang av en database fra 2008 med ca. 200 bildekk i klassen C1C (dekkbredde 195, 205, 215 mm) viser at allerede så tilfredsstiller ca. 55 % av bildekkene det nye støykravet gjeldende fra 2012-11-01. Denne dekkbredden antas å dominere på biler på det nordiske markedet (med unntak av Island).
Dersom man legger den nederlandske databasen fra 2010 til grunn (ca. 100 bildekk i denne kategorien) øker dette tallet til ca. 80 %. Dette viser tydelig potensial for ytterligere reduksjon av støy fra bildekk, og muligheter for skjerping av støygrenser.

Støymålinger på typiske, grove veidekker som finnes i Norge, Sverige og Finland viser at spredningen i støynivå for bildekk er vesentlig lavere enn på et slett/jevnt ISO-dekke, i størrelsesorden 2-3 dB. Dette indikerer at selve mønstertypen har mindre betydning og at det først og fremst er vibrasjonseksitert støy (mer lavfrekvent) som dominerer. I og med at bildekkene typegodkjennes på ISO-dekket, kan det medføre optimalisering av bildekkene for dette veidekket, og som da ikke får betydning for støynivå på vanlige veidekker, spesielt i Norge, Sverige og Finland. Siden man i Danmark ikke bruker piggdekk om vinteren, har de ikke samme negative utvikling av teksturen på veidekkene som i de øvrige nordiske landene. Sammenlignende målinger gjort på norske og danske veidekker viser også at man i Danmark får en større spredning i støynivå fra ulike bildekk.

Analyser av den støymessige rangeringen av bildekk på ISO-dekker er forskjellig fra rangeringen på vanlige, norske veidekker. Imidlertid er antall bildekk undersøkt, relativt få, så det er behov for ytterligere undersøkelser her, også i forhold til svenske og danske veidekker.
En manglende sammenheng mellom rangering av støynivå på ISO-dekke og på vanlige veidekker i Norden, gir redusert effekt av strengere støykrav til bildekk. Alternative veidekker til dagens ISO-dekke, ved typegodkjenning av bildekk bør vurderes og fremmes i aktuelle fora som ISO og GRB.

Målinger viser også at man i Norge i gjennomsnitt har 2-3 dB høyere dekk/veibanestøy enn i Danmark, målt på sammenlignbare veidekker av type Ab/Ska. I Sverige er det målt 1-1.5 dB høyere nivåer enn i Norge, noe som antakelig skyldes vesentlig høyere piggdekkandel her enn i Norge (spesielt i bystrøk). Det foreligger ikke konkrete målinger i Finland som kan sammenlignes med tilsvarende målinger i Norge/Sverige, men det er grunn til å anta at situasjonen er tilnærmet den i Sverige.

De mest vanlige veidekkene i de nordiske landene (Island unntatt) er av type Ska (skjelettasfalt) eller Ab (asfaltbetong) med maksimal steinstørrelse 11-16 mm.
I Danmark anvendes Ab11t som referansedekke ved støyberegninger og målinger av støysvak asfalt.

Et sommerdekk for personbil, Michelin Primacy LC, beregnet først og fremst for det asiatiske markedet er anvendt under målinger på ulike danske veidekker. Resultatene viser at dette bildekket, uavhengig av veidekke, hadde et støynivå 2-3 dB lavere enn "gjennomsnittsdekket". Rullemotstand og våtgrepsegenskaper til dette bildekket er ikke kjent.

Målinger av et piggfritt vinterdekk på danske veidekker, angir et støynivå 4-5 dB lavere enn gjennomsnittsdekk for personbiler.
I og med at det foreligger begrenset kunnskap om bildekks støyegenskaper på vanlige veidekker brukt i nordiske land, så foreslås det et måleprogram som bør omfatte minimum 30-32 bildekk. I denne omgang gjelder det bare personbildekk (klasse C1).
Utvalget bør omfatte både sommerdekk, helårsdekk og et mindre antall piggfrie vinterdekk.
Det anbefales å velge dekk som allerede har et støynivå (fra merkeordningen) som er likt eller lavere enn støykravet gjeldende fra 2012-11-01. Utvalget må omfatte dekk fra Michelin, Continental, Goodyear og Nokian, som representerer den største andel av dekk på det nordiske markedet.

Det foreslås målinger i Norge, Sverige og Danmark på veidekketyper representative for disse landene. I hovedsak bør målingene begrenses til tette veidekker av typen Ab/Ska, med maksimal steinstørrelse i området 8-16 mm.
For å effektivisere målingene, foreslås det at målingene gjøres med en CPX-tilhenger med plass til to hjul.

Rullemotstand

Rullemotstand for bildekk er en del av NordTyre-prosjektet. I denne rapporten gis det bare en summarisk omtale om prinsippene for rullemotstand (genereringsmekanisme), målemetoder og kravnivå. For en mer detaljert beskrivelse vises det til rapporter fra de internasjonale prosjektene TYROSAFE og MIRIAM.

For videre arbeid i NordTyre gis det noen anbefalinger for måling av rullemotstand, både av dekk i laboratorium og på representative, nordiske veidekker.

Målinger av rullemotstand med en kombinasjon av dekk og veidekker, har i en viss utstrekning, blitt gjennomført på svenske og danske veidekker. Slike målinger bør utvides til også å omfatte norske og finske veidekker og med et større antall bildekk.

1 Introduction

This report is the first deliverable of the Nordic project NordTyre. The report is mainly a literature study, focusing primarily on tyre noise characteristics on both ISO surfaces and normally used road surfaces in the Nordic countries. A brief discussion on the status of rolling resistance of tyres and road surfaces is also included.

The report gives some advice for topics where measurement campaigns or other additional studies are needed.

2 Background, aim and method applied

According to the specifications for the project, the aim is to establish a platform based on scientific evidence on the tyre/road contribution to traffic noise emission from the roads in the Nordic countries. Furthermore, the project shall clarify which combinations of tyres and pavements that will yield the lowest noise emissions, influencing the environment along roads and highways. This knowledge will be the basis for qualified decision concerning actions to mitigate traffic noise in the Nordic countries.

The measurement results and information given in this report are mainly based on a literature study and on contacts with international experts in the field of tyre/road noise. Data for the relationship between noise levels from tyres and types of surfaces are presented in three different categories:

1. Noise levels on ISO surfaces
2. Noise levels on other road surfaces
3. Noise levels in laboratory situations (drums)

In 2006, a comprehensive study on tyre/road noise was presented by FEHRL [FEHRL, 2006-1/2], focusing on noise levels on ISO surfaces (type testing levels), the possibilities for further reduction of the limits for tyre noise, rolling resistance and a cost/benefit analysis. The report included a comprehensive literature survey (Part 2) on the relationship between tyres and road surfaces (primarily ISO surface) up to 2005. In order not to repeat the main findings in this study, this author has been focusing on additional studies and measurement data published in the period 2006-2011. However, some data from the FEHRL study are also included in chapter 4.2.1.

The noise from a rolling tyre is of course very much depending on the type and condition of the road surface. As this report will show, the variation in noise levels depending on the type of road surface intended for various purposes in various climates and in different conditions used in the Nordic countries is much larger than the variation in noise levels between different types of new tyres for the same purpose (primarily passenger car tyres). A significant part of this is of course due to the climate differences between primarily Denmark on the one hand and Norway, Sweden and Finland on the other hand.

The report does not focus on describing the physical interaction between tyres and road surfaces, as this topic is very well described in available literature, such as [Sandberg, Ejsmont, 2002].

2.1 Literature databases

For the literature review, the following sources have been used:

Conference papers:

- Internoise 2004-2011
- Euronoise 2006-2009
- DAGA 2008-2010

In addition, papers from other conferences, such as BNAM (Baltic Nordic Acoustic Meeting) and Tire Technology Expo have been reviewed.

Databases:

- Google Scholar
- Science Direct (Elsevier)
- Scirus (Elsevier)

The majority of papers from the search in the databases mainly focused on theoretical articles about the generation mechanisms for tyre/road noise and are as such not relevant for this project.

Reports from international projects:

- SILVIA
- SILENCE
- QCITY
- TYROSAFE
- MIRIAM

3 Tyre regulations – noise, rolling resistance and wet grip

3.1 Regulations for tyres with regard to wet grip, rolling resistance and noise

The present limits for noise from tyres are specified in the EU directive 2001/43/EC [EC 43, 2001]. In 2009, a new set of limits was introduced in the Regulation (EC) No.661/2009. This regulation includes requirements for wet grip and rolling resistance. In addition, the classification of the different tyre categories was changed somewhat from the directive of 2001. The new noise limits are introduced from 2012-11-01 for C1/C2 tyres and 2016-11-01 for C3 tyres [EC 661, 2009].
From 2012-11-01 a new regulation on the labelling of tyres with respect to their fuel efficiency (rolling resistance), wet grip and noise becomes effective; Regulation (EC) No.1222/2009 [EC 1222, 2009].

The rolling resistance and the wet grip are classified in categories A-G, while the noise level is given by a symbol, in addition to a measured exterior noise level (type approval level at 80 km/h). Figure 3.1 shows an example of this labelling of a tyre (valid for EU and countries part of the Economic Agreement, EEA).
One "bar" indicates a noise level -3 dB or more below the limit value, 2 bars a noise level 1-2 dB below the limit value and 3 bars indicates a noise level on the limit.

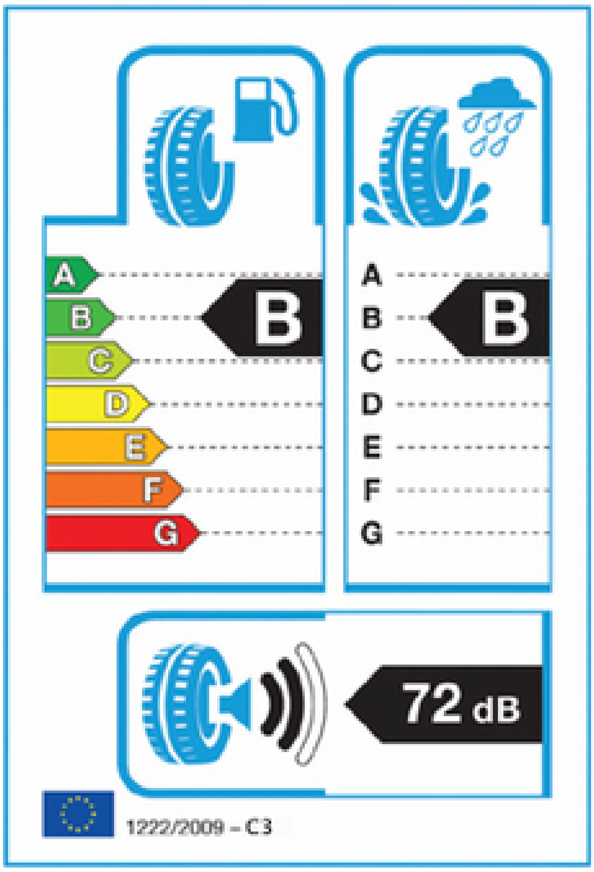


Figure 3.1 Label for new tyres in the EU from November 2012

The labelling is not applicable for some categories of tyres such as:

- Reinforced tyres
- Tyres fitted for vehicles type approved before October 1st,1990
- Emergency tyres of class T
- Tyres with a maximum speed of 80 km/h
- Studded tyres
- Special tyres for motor sport

In tables 3.1 and 3.2, the present and new noise limits for the different classes of tyres are shown. In the new regulation, for snow tyres, extra load tyres or reinforced tyres, the limits are 1 dB(A) higher than shown in the tables.

Table 3.1 Present and new noise limits for class C1 tyres

Tyre class	Nominal section width (mm)	Present noise limit 2001/43/EC, dB(A)	Noise limit from 2012-11-01, EC/661/2009, dB(A)
C1A	≤ 145 > 145 ≤ 165 >165 ≤ 185	72 73 74	70
C1B	> 185 ≤ 215	75	71
C1C	> 215 ≤ 245	76	71
C1D	> 245 ≤ 275	76	72
C1E	> 275	76	74

Table 3.2 Present and new noise limits for class C2 and C3 tyres

Tyre class	Category of use (mm)	Present noise limit 2001/43/EC, dB(A)	Noise limit from 2012-11-01, EC/661/2009, dB(A)[1)]
C2	Normal tyres	75	72
	Traction tyres	77[2)]	73
C3	Normal tyres	76	73
	Traction tyres	78[3)]	75

[1)] Noise limits for C3-tyres valid from 2016-11-01
[2)] Traction tyres categorised as snow tyres
[3)] Traction tyres categorised as snow tyres and special tyres with noise limit of 80 dB(A)

All limit values are nominal limits. When tyres are type approved, the measured values can be up to 1.9 dB ***higher*** than the noise limit, due to a) truncation and b) subtraction of 1 dB (due to measurement uncertainty).

As the tables show, the noise limits will be sharpened by 2-5 dB from November 2012, depending on tyre class. In Norway, most of the new passenger cars have tyres in the classes C1B and C1C, which means a reduction of noise limits of 4-5 dB.

3.2 Measurement methods for noise of tyres

3.2.1 Type approval

The measuring method for type approval of noise from tyres is described in ECE Reg.117 [ECE R117, 2007]. The method is based on the "vehicle method" defined in [ISO 13325, 2003].

In principle a vehicle fitted with four tyres is measured at a distance of 7.5 m and microphone height 1.2 m, in coast-by situation (engine off, gear in neutral). The vehicle speeds are in the range of 70-90 km/h (light vehicle tyres, classes C1 and C2) and 60-80 km/h (truck tyres, class C3). The final, measured sound level at 80 km/h (cars) and 70 km/h (trucks) is then calculated from the regression line of sound pressure level versus speed.

The measurements shall be made on an ISO test track [ISO 10844, 2011]. The measurement area and microphone positions are shown in figure 3.2.

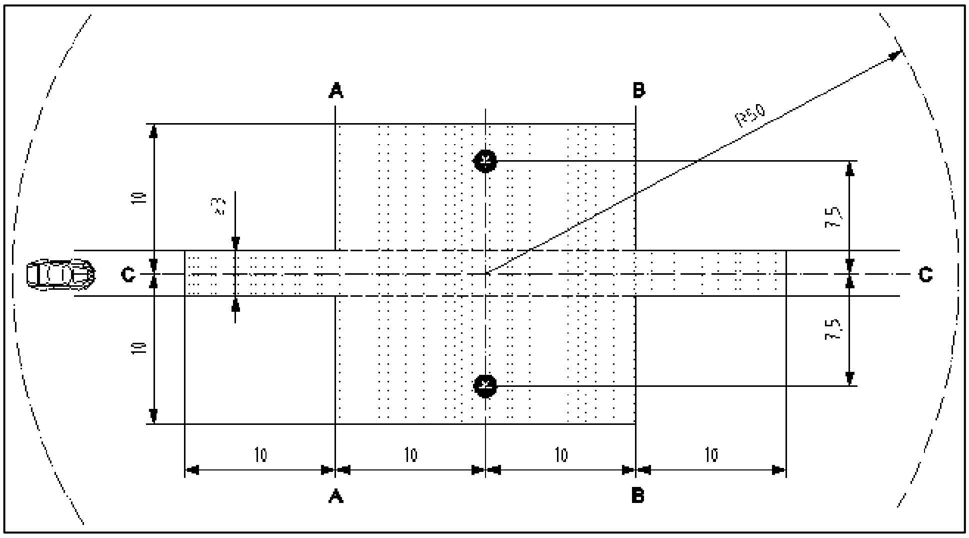


Figure 3.2 Set-up for tyre noise measurements on an ISO 10844 test track

All measurement values shall be air temperature corrected to +20 °C. For C1 tyres, the correction is -0.03 dB/°C for air temperatures > 20 °C, and -0.06 dB/°C for temperatures < 20 °C. For C2 tyres, the correction is -0.02 dB/°C. No correction applies for C3 tyres.

Many of the sources for the data presented in this report are not coming from real type approval measurements. Instead, the term "type testing" is therefore used throughout the report, indicating that the procedure of subtraction and truncation of data has been applied.
Real type approval levels may .be higher than the actual levels measured for a specific tyre, since type approval is usually granted as the maximum level in a tyre line, and in that line some tyres may be somewhat quieter.

3.2.2 Other methods

3.2.2.1 CPX method/trailer method

Another method, for example used for research purposes to compare tyre noise levels, is to use the so-called CPX method, [ISO/WD 11819-2, 2011]. In this method, two microphones are positioned close to the tyre (20 cm), 45° to the front and rear of the tyre. Measurements can be made, either using a test vehicle or a CPX trailer (basically designed to measure the road surface contribution to tyre/road noise).

The measured sound pressure levels are in the range of 22-23 dB ***higher*** (somewhat frequency dependent) than measured at 7.5 m distance from the vehicle centre line. Comparison of the noise ranking of the different tyres can be made by measurements on the same surface with different tyres.

The Dutch consultant M+P has developed a trailer for measuring truck tyre noise, used as part of the AOT-project (Acoustic Optimisation Tool) [Schwanen et al, 2007].

3.2.2.2 Coast-by method

Measurements can be done with four tyres mounted on a vehicle passing by at 7.5 m distance from roadside microphones, at a microphone height of 1.2 m. The coast-by method is described in ISO 13325 and in various regulations. In principle, the method is the same method as the method for type approval.

3.2.2.3 Laboratory measurements

Measurements of the tyre noise levels on different surfaces can be made on a drum in a laboratory. Replicas of different road surfaces are fitted to the drum and measurements are made, normally with microphones close to the tyre (CPX positions). Normally, the tyre is in a fixed position and the road surface is rotated. Such facilities can be found at the Technical University at Gdansk (TUG), at the BASt laboratory near Cologne in Germany and at Purdue University, Indiana, USA, among others.

Laboratory measurements are well suited for comparison of noise behaviour between different tyres, where the measurement conditions are closely controlled (temperature, humidity, speed, load, etc.). Since the conditions are quite different from outdoor situations, the measured noise levels are not suited for comparison to outdoor measurements. For example, the radius of the drum can influence the air pumping generation mechanism. The horn effect may then be different from how it works on a real road.

The measurements results presented in this report are mainly based on type testing levels, CPX-type of measurements and some laboratory results (see chapter 4.5).

3.2.2.4 Modelling of tyre/road noise

Different models have been developed to calculate the rolling noise of tyres and combinations of road surfaces. Examples of such models are the SPERoN model [Beckenbauer, Kropp, 2007], the HyRoN model [Klein, Hamet, 2007] and the TRIAS model [de Roo, Gerretsen, Mulder, 2001].

Up till now, it seems difficult to simulate the complete acoustic behaviour of a tyre on different types of road surfaces, by using these types of models. In 2006-2007, SINTEF conducted a study to compare measurement (CPX) with modelling using the SPERoN model and drum measurements [Berge, Haukland, Ustad, 2009]. Some results are presented in chapter 4.5.

4 Literature review - tyre/road noise

4.1 General considerations

Due to the technical development of tyres, different tyre properties like structural design, material design, tread pattern, etc. it is not too much of value to look at tyre performance data for example more than 10 years old, as they would not represent design and performance of current tyres. This is basically why this report is focusing on investigations and publications in the period 2005-2011.

4.2 Measurements on ISO surface

The available noise data for C1, C2 and C3 tyres were measured under different conditions and on different ISO surfaces. A common factor is that all the different ISO surfaces are based on the original standard published in 1994. Since the original standard was published, it has been noticed that the tolerances and methods to check them given in the standard (absorption, texture and laying requirements among others) have allowed ISO surfaces with too large noise variations. This is because in 1994 there were no good standards for measuring these tolerances. In a study by M+P [van Blokland, Peeters, 2006], the difference between two ISO surfaces (ISO7 and ISO2 in figure 4.1) was found to be in the area of 5 dB, averaged over 4 different tyres (reduced to 4 dB if the slick tyre is neglected).

The 4 tyres were:
Tyre A: Pirelli, slick tyre, 225/45 R16
Tyre B: Pirelli P6000, summer tyre, 225/45 R17
Tyre C: Goodyear Eagle UltraGrip, winter tyre, 225/45 R16
Tyre D: Goodyear Wrangler 4x4, off-road tyre, 215/65 R16

It was concluded that the differences between ISO surfaces mainly were caused by differences in texture and absorption properties.

The variation is clearly tyre dependent, as figure 4.1 shows. The biggest variation is for tyre A (the slick tyre). Of course, the slick tyre would not be subject to regulations, as it is illegal to use slick tyres on roads.

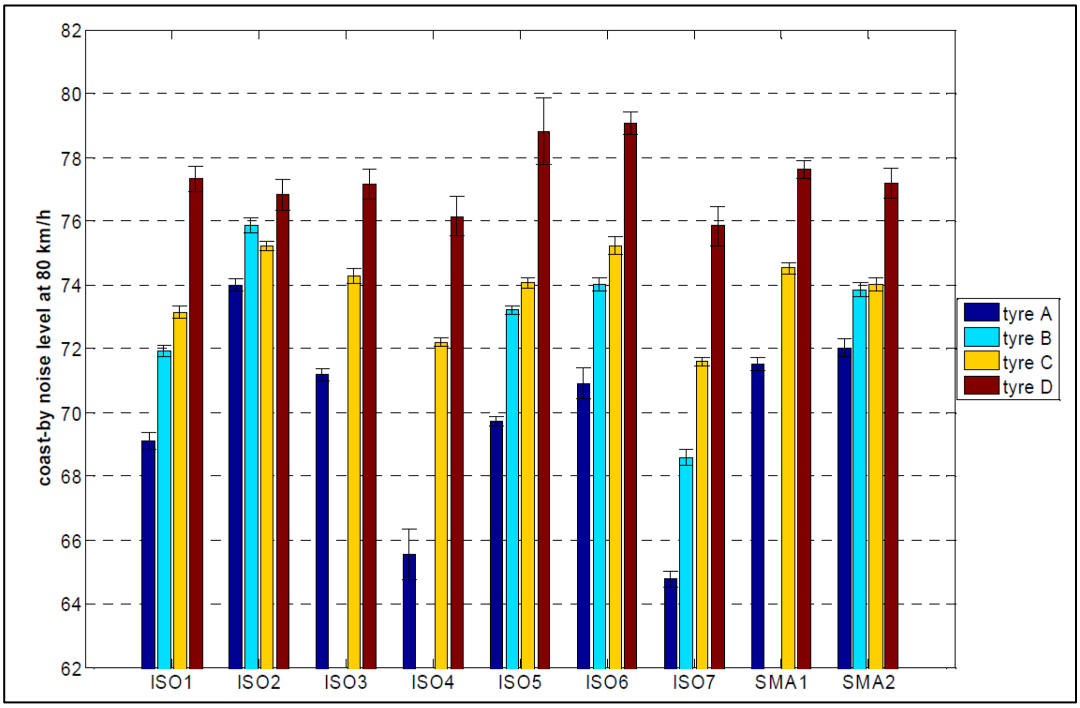


Figure 4.1 Coast-by noise levels at 80 km/h [van Blokland, Peeters, 2006]

Tyre B is the most "common" tyre (summer tyre) and the variation is from 0 to 7 dB due to the surface.

4.2.1 The FEHRL study

There are several presentations listing type testing levels for tyres, many of them based on partly the same source of data.
In the FEHRL study from 2006, the noise data is presented both in the main report [FEHRL, 2006-1] and in the Appendices [FEHRL, 2006-2].

In Part 1, the data is based on the following sources:

- UBA/TÜV Automotive 2000, 2002 and 2004
- TRL 2003/2005
- SINTEF 2004
- UTAC
- BASt/M+P 2003

For each of the previous classes C1b (over 145 up to 165 mm), C1c (over 165 up to 185 mm), C1d (over 185 up to 215 mm) and C1e (over 215 mm), the noise level distribution is shown and compared with the noise limit. Figure 4.2 gives an example of the presentation for class C1c.

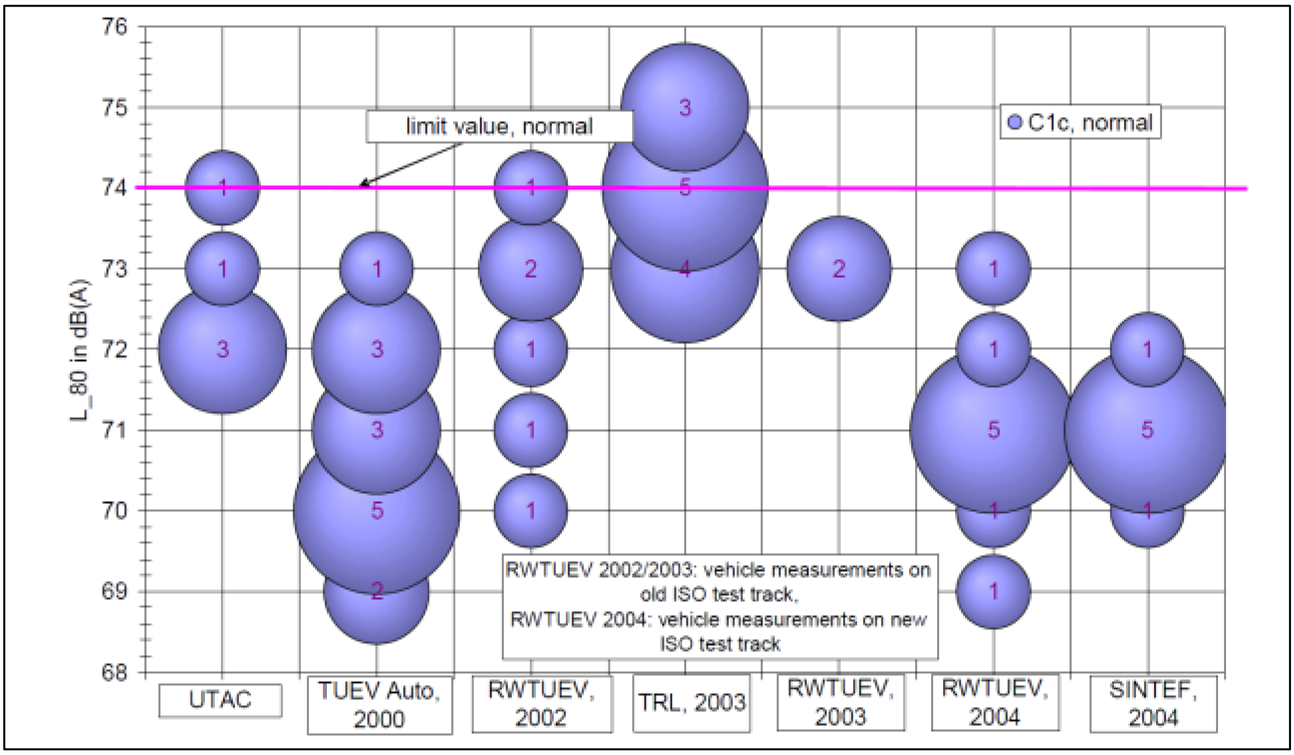


Figure 4.2 Measured ISO levels (type testing) for class C1c (old definition) [FEHRL, 2006-1]

According to the new regulation from 2012, tyres with this width shall meet a new limit of 70 dB(A) (table 3.1).

In Part 2 of the FEHRL-report, some additional noise data is included (from the Netherlands and Austria).

The noise levels for all classes of C1 are combined and shown as a function of section width, together with both the present nominal limits and the actual limits (+ 1.9 dB(A)).

The data for C1, C2 and C3 tyres are shown in figures 4.3 and 4.4.

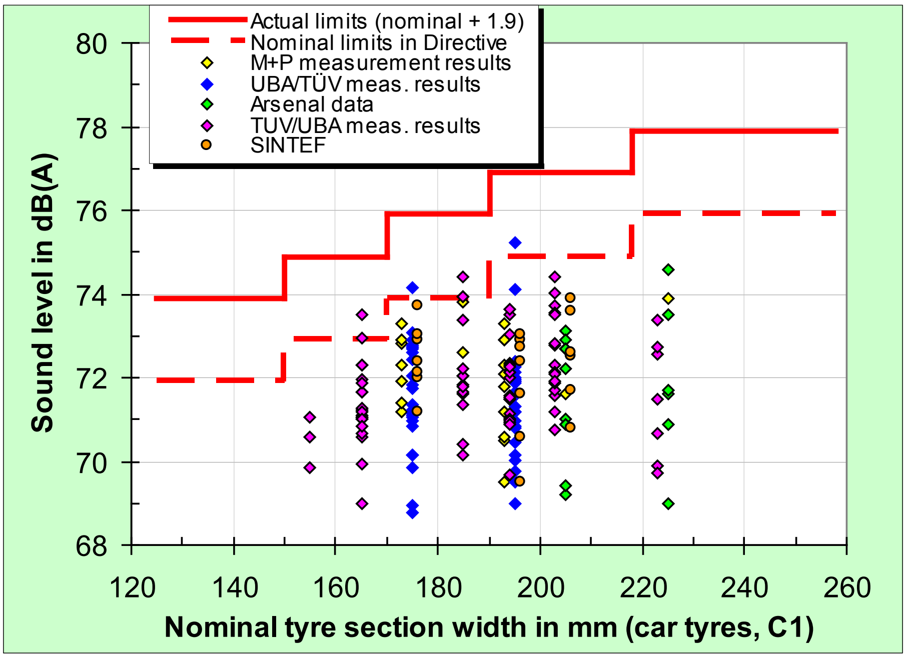


Figure 4.3 Measured sound levels for 174 car tyres at 80 km/h on ISO surfaces. No truncation of values [FEHRL, 2006-2]

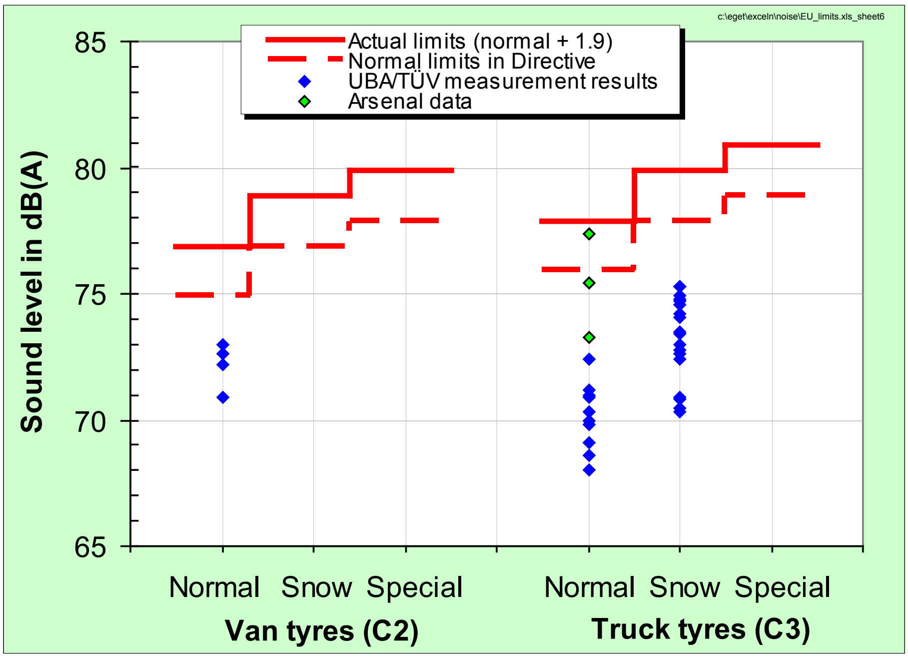


Figure 4.4 Measured sound levels for 45 truck tyres (C2) at 80 km/h and at 70 km/h (C3) on ISO surface. No truncation of values [FEHRL, 2006-2]

4.2.2 ETRTO data

In 2007 the European Tyre and Rim Technical Organization (ETRTO) presented a figure showing the measured noise levels of 536 passenger car tyres, with section widths ranging from 145 mm or less up to 315 mm or above. The sources of these data are not known, but it may be a collection of data that TÜV Süd has made for ETRTO and presented for GRB in Geneva. The data is shown in figure 4.5, together with the present limit values (author comment: the lines in the figure do not quite match the limits as they are stated in the directive). The figure can also be found in a report from Switzerland [Schguanin, 2010].

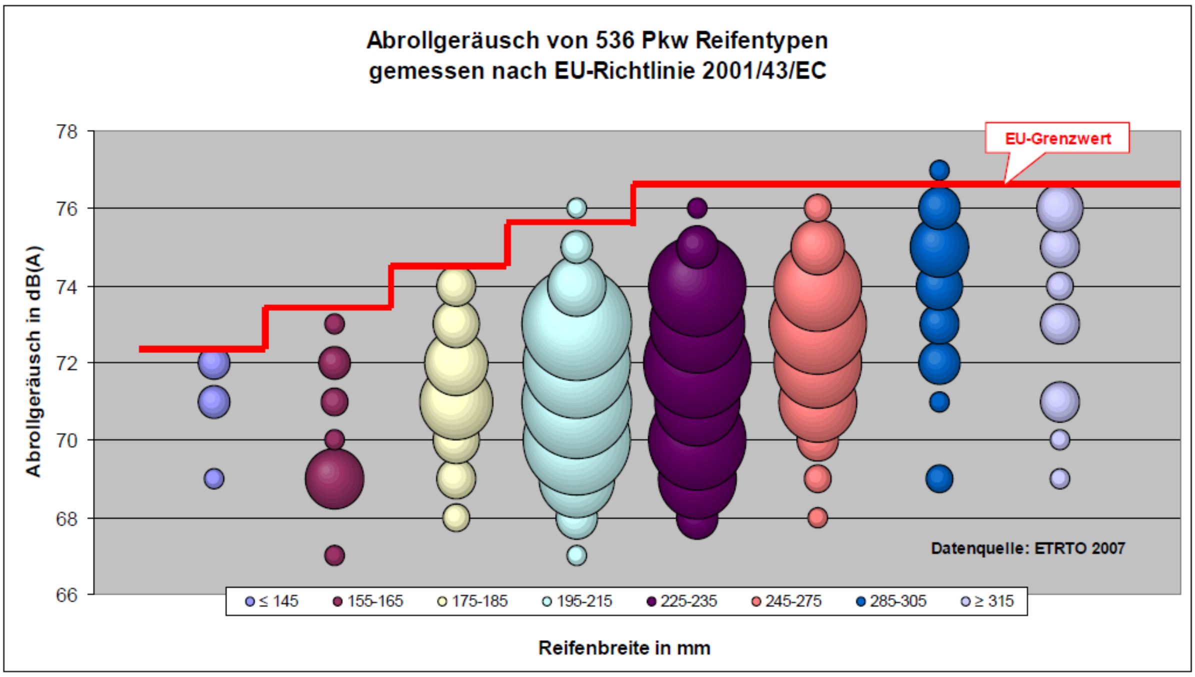


Figure 4.5 Measured rolling noise levels of passenger car tyres, according to 2001/43/EC. All data truncated [Schguanin, 2010]

The figure shows that within each of the tyre width category above 155 mm, there is a spread in noise levels of 7-10 dB. From the category 195-215 mm and above, there seems to be little relationship between noise and tyre width, which can be related to the fact that the noise limit is the same for all tyres above 225 mm. Below 195 mm, the limit is stricter, and this has apparently an effect on the noise levels.

4.2.3 Dutch fact sheet from 2008

In preparation to promote new noise limits for tyres (compared to 2001/43/EC), the Netherlands compiled a fact sheet in 2008, a list as complete as possible of tyres (C1, C2 and C3), based on the data from FEHRL, ETRTO, Sweden and the Netherlands (new measurement data) [de Graaff, Kortbeek, 2008]. The compilation was presented to the EU Commission.

Table 4.1 shows the number of tyres with available data within each of the (new definition) classes:

Table 4.1 Number of tyres with noise levels in the Dutch database

Tyre class	Number of Tyres	Total per class	Sources
C1A	252	1048	FEHRL ETRTO The Netherlands
C1B	424		
C1C	216		
C1D	101		
C1E	55		
C2 Normal	56	71	FEHRL The Netherlands Sweden
C2 Snow	15		
C2 Special	-		
C3 Normal	61	131	FEHRL The Netherlands Sweden
C3 Snow	64		
C3 Special[1)]	6		
Total	1250	1250	

[1)] In 2009, the list of C3 Traction tyres (C3 special) was extended to include a total of 28 tyres

In the Dutch fact sheet, all data are compared with different proposals for new noise limits. Since this compilation was made, the new limits have been approved. It is therefore more appropriate to compare the data with the new limits, as shown in figures with the cumulative distribution of levels (all levels are truncated and rounded down). The tabled data has been processed by this author and presented in figures 4.6 to 4.23. It should be noted that even if this fact sheet is from 2008, rather old datasets (as the FEHRL data) are part of the data,

The most frequent used tyre class in the Nordic countries is likely to be class C1B (except Iceland, where larger vehicles like SUVs are more widely used). Based on the database, it seems that more than 55 % of the tyres already meet the coming noise limit. If the distribution is shifted about 1 dB to the left (figure 4.9), nearly 80 % of the tyres will meet the limit.

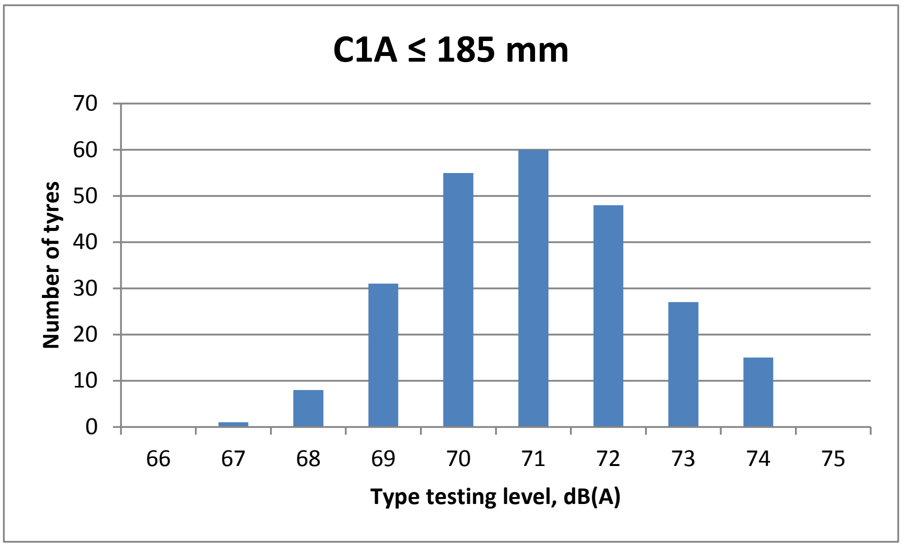


Figure 4.6 Type testing levels of tyre class CIA

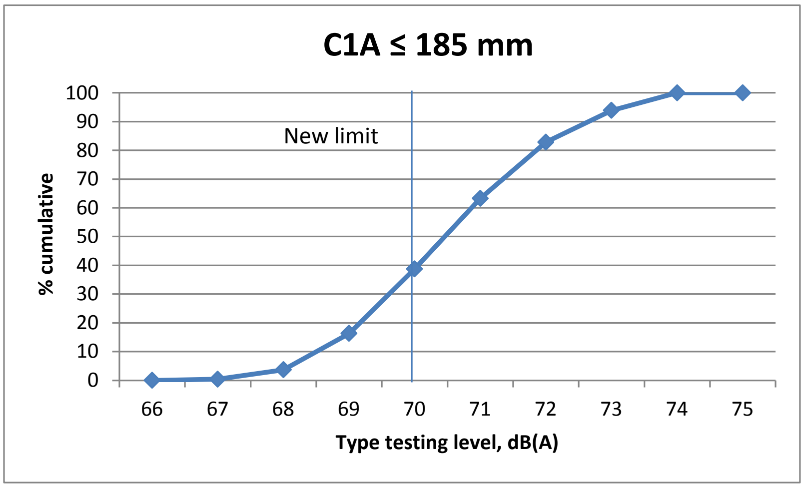


Figure 4.7 *Cumulative distribution of type testing levels of class C1A tyres and new noise limit*

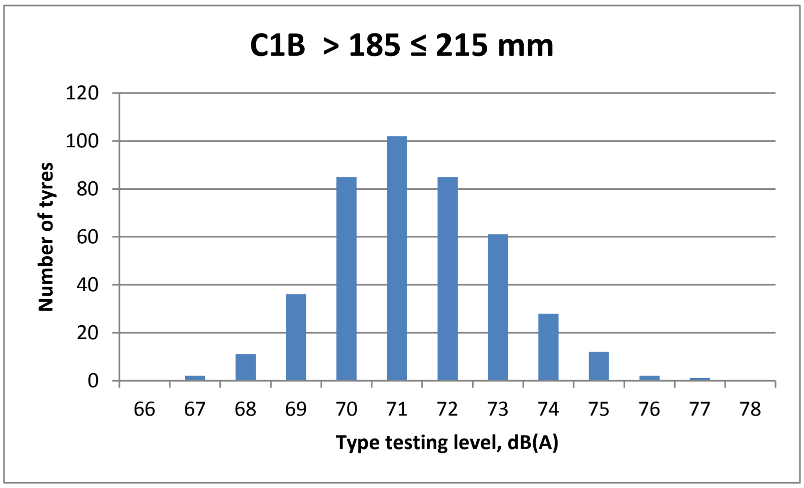


Figure 4.8 *Type testing levels of tyre class C1B*

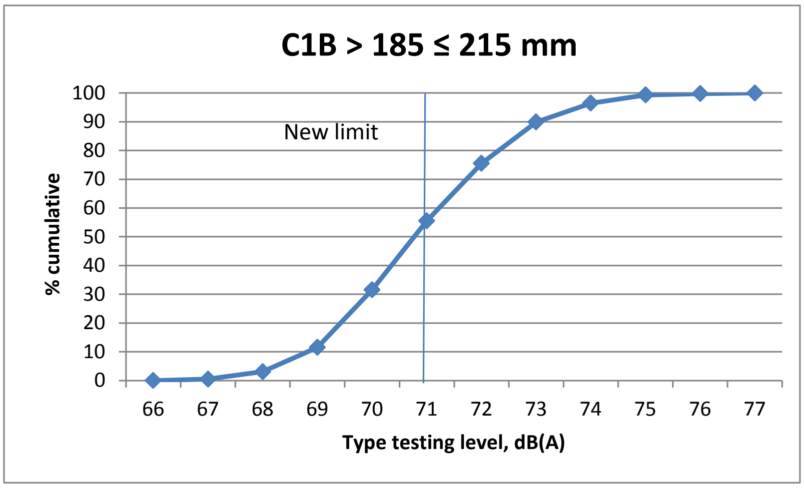


Figure 4.9 *Cumulative distribution of type testing levels of tyre class C1B and new noise limit*

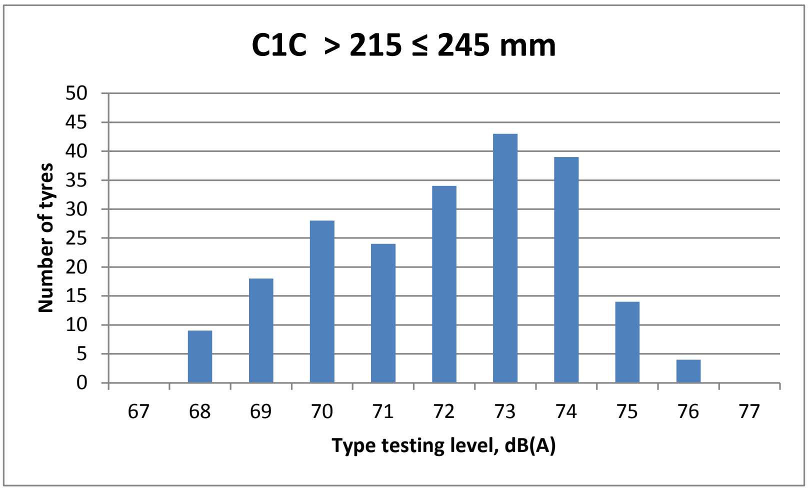


Figure 4.10 Type testing levels of tyre class C1C

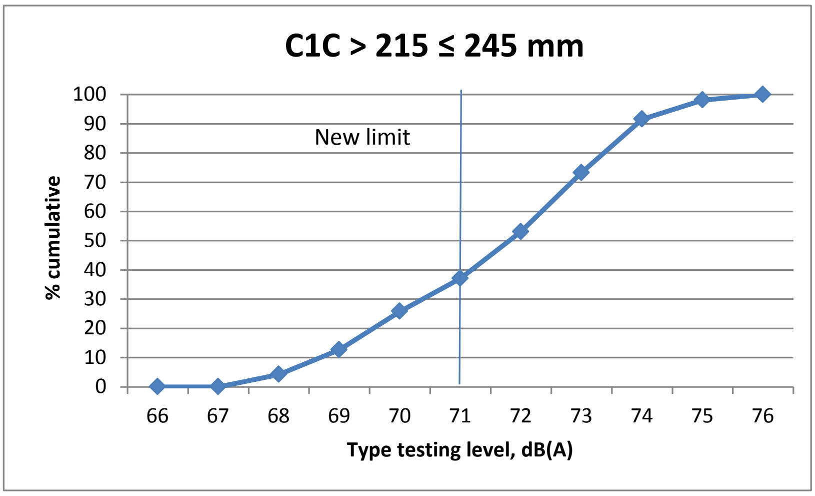


Figure 4.11 Cumulative distribution of type testing levels of tyre class C1C and new noise limit

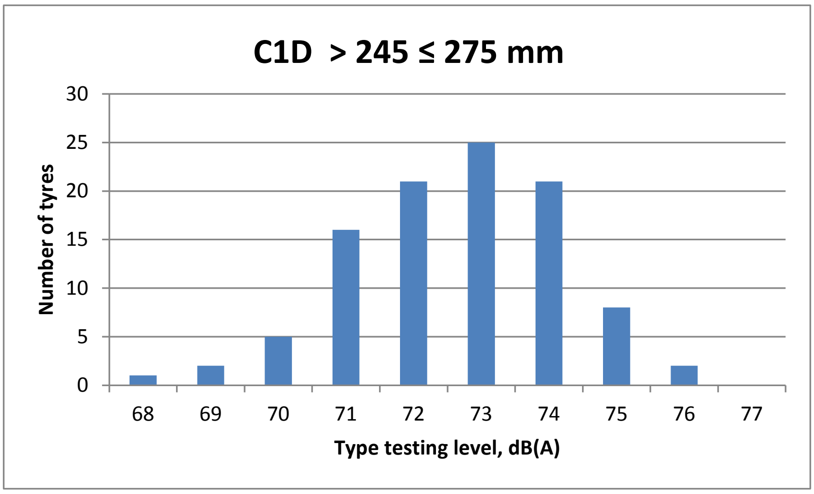


Figure 4.12 Type testing levels of tyre class C1D

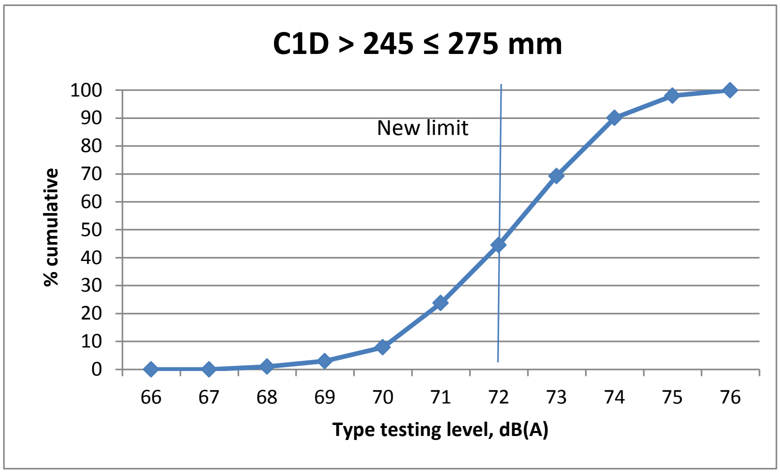


Figure 4.13 Cumulative distribution of type testing levels of tyre class C1D and new noise limit

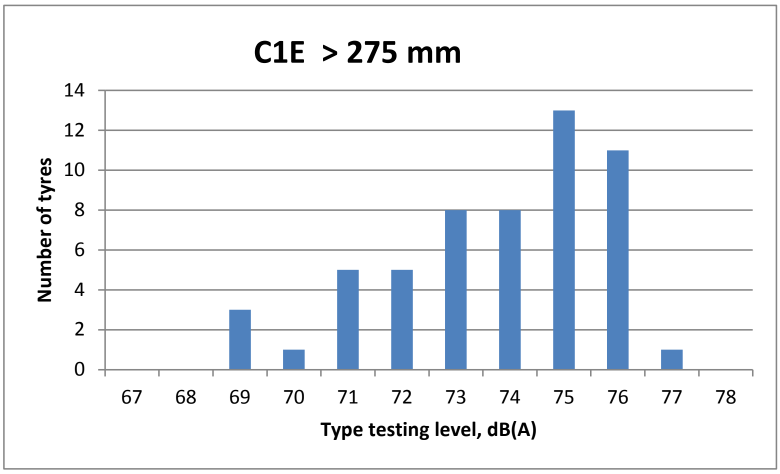


Figure 4.14 Type testing levels of tyre class C1D

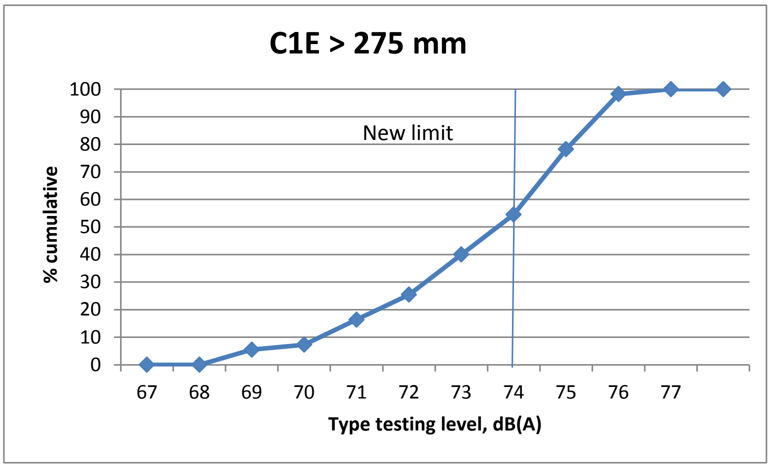


Figure 4.15 Cumulative distribution of type testing levels of tyre class C1D and new noise limit

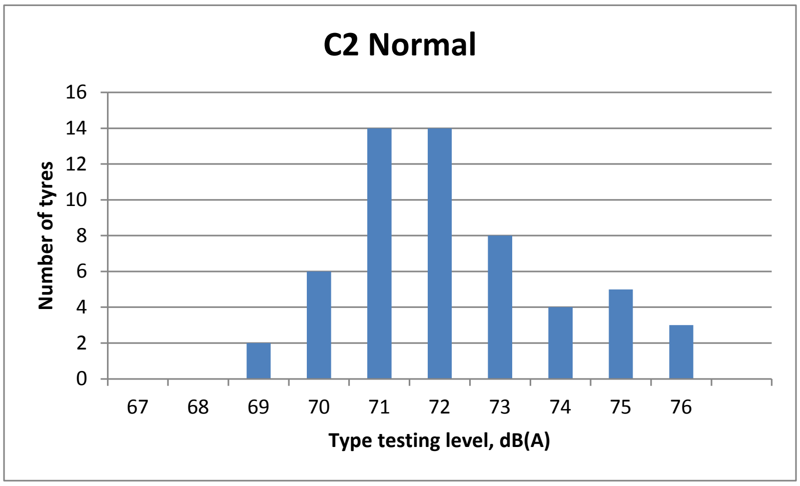


Figure 4.16 Type testing levels of C2 Normal tyres

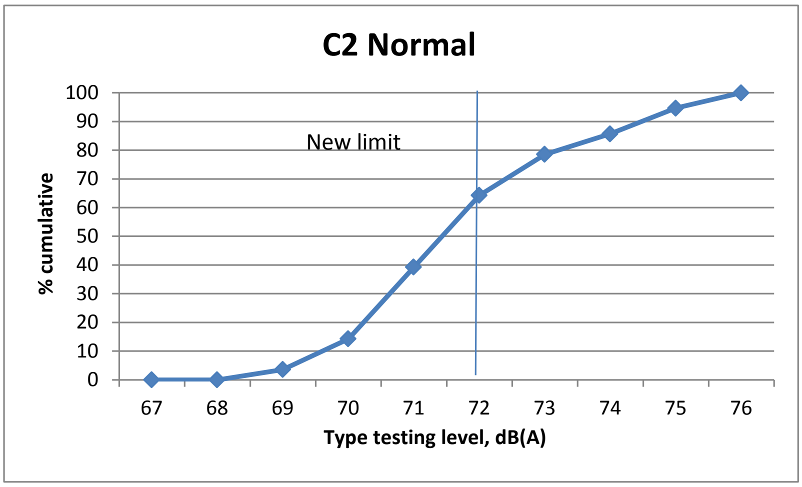


Figure 4.17 Cumulative distribution of type testing levels of C2 Normal tyres and new noise limit

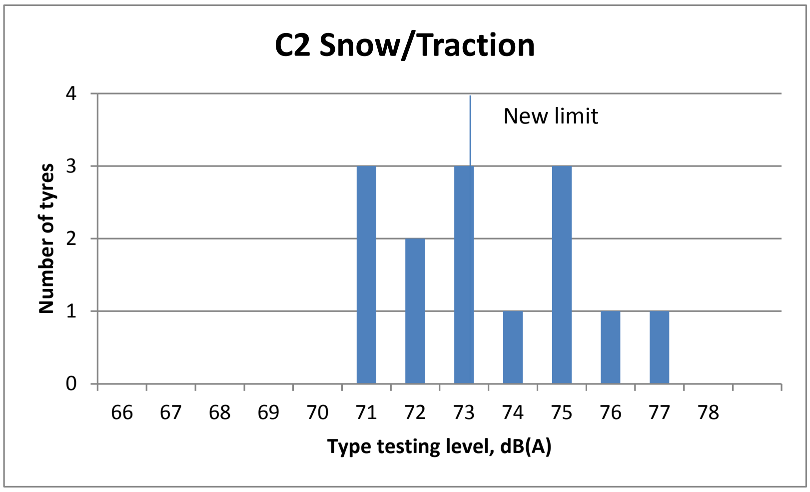


Figure 4.18 Type testing levels of C2 Snow/Traction tyres

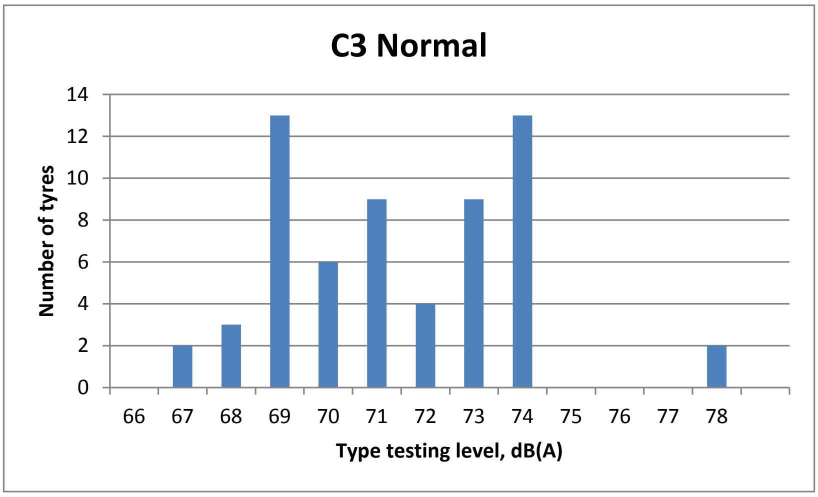


Figure 4.19 Type testing levels of C3 Normal tyres

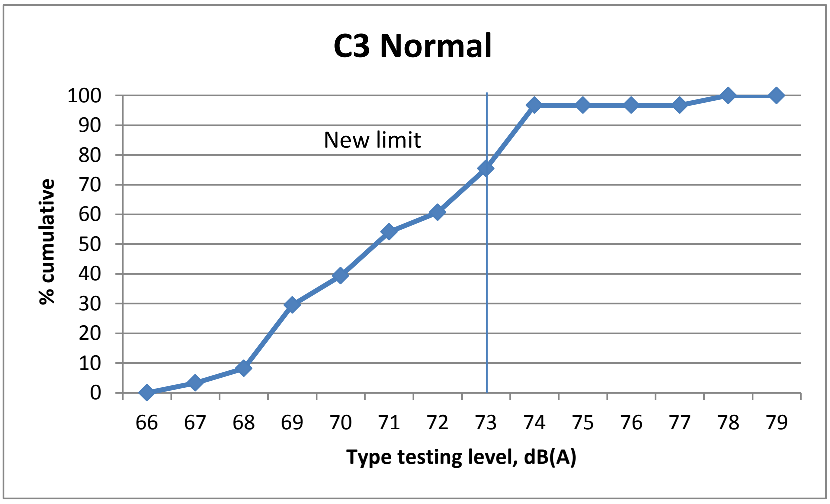


Figure 4.20 Cumulative distribution of type testing levels of C3 Normal tyres and new noise limit

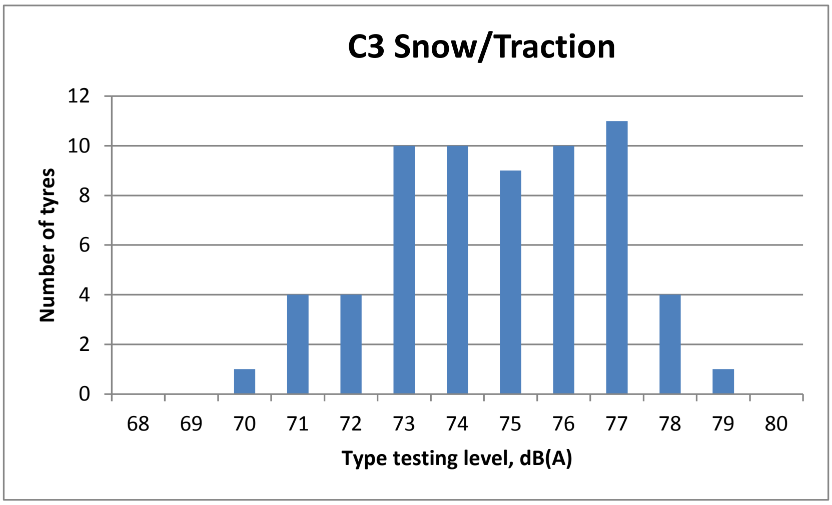


Figure 4.21 Type testing levels of C3 Snow/Traction tyres

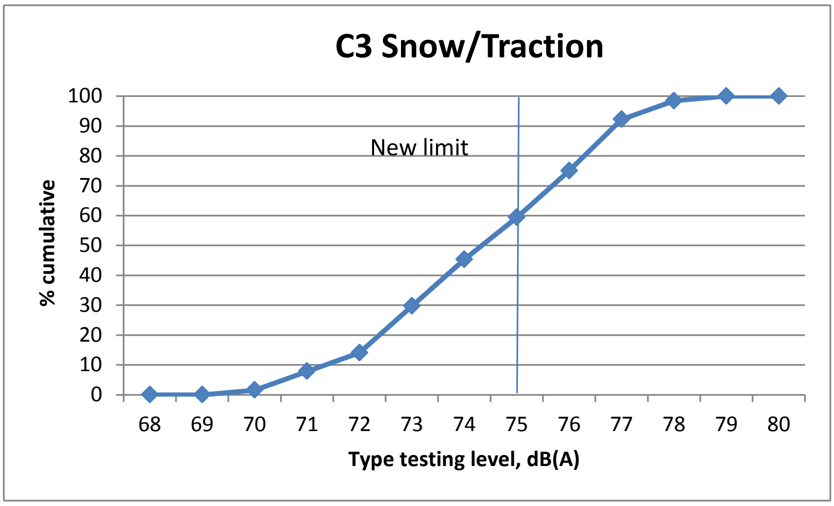


Figure 4.22 Cumulative distribution of type testing levels of C3 Snow/Traction tyres and new noise limit

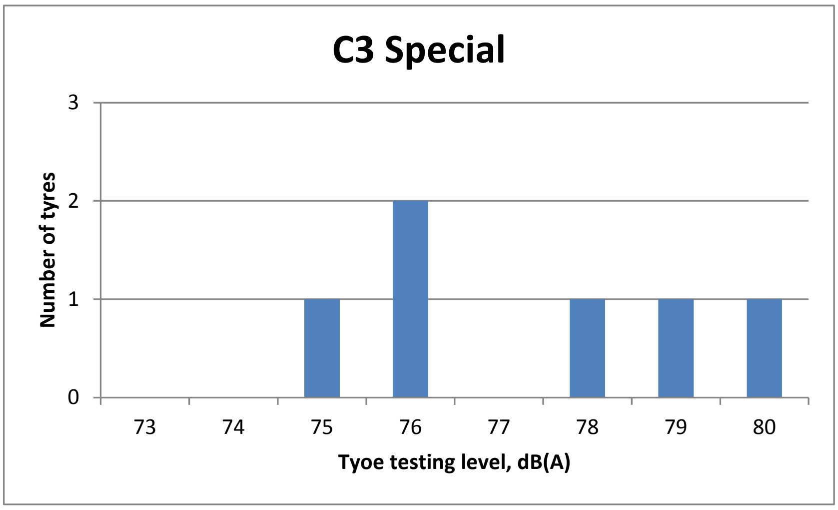


Figure 4.23 Type testing levels of C3 Special tyres

The percentage of tyres in each class that already meet the new limits is shown in table 4.2 (C2 Snow is not included, due to few samples in the database).

Table 4.2 Percentage of tyres passing new noise limit [Source: de Graaff, Kortbeek, 2008]

Tyre class	Percentage pass, new noise limit
C1A	39
C1B	56
C1C	37
C1D	45
C1E	55
C2 Normal	64
C3 Normal	75
C3 Snow/Traction	59

As the table shows, between 37 and 56 % of C1 tyres already meet the limits effective from Nov. 2012, and 60-75 % of the current population of truck tyres (C3) already meets the noise limit effective from 2016.

4.2.4 SINTEF and M+P measurements, 2009

In 2009, SINTEF conducted tests of 22 passenger car summer tyres on 23 different road surfaces (including an ISO surface) at the Kloosterzande test area in the Netherlands [Berge, Haukland, 2010; Berge, Haukland, Storeheier, 2011]. The noise was measured using the CPX trailer of the Norwegian Public Roads Administration, see figure 4.24.

The Kloosterzande test area is a former part of a normal road (N60), which was closed due to a re-routing of the road. In 2006, 41 different road sections were constructed; each section about 80 m long. The sections included an ISO surface, thin layers, single and double layer porous surfaces, poroelastic surfaces and dense surfaces, including SMA, DAC and surface dressing. In 2009, one of the double layers (S12) was replaced by a new type of poroelastic surface, named Rollpave PERS.

Figure 4.24 The CPX trailer of the Norwegian Public Roads Administration

The measurements were performed at 50 and 80 km/h. The tyres are listed in table 4.3.

The ISO surface at Kloosterzande was designed as an "average" ISO surface, concerning noise "performance". The absorption coefficient was measured to have an absorption coefficient α = 0.06 (shall be below 0.10) and texture was found to be a little on the smooth side (MPD = 0.33 mm in the west wheel track, on the left side of trailer) and 0.39 in the east (right side), but within the range specified in the revised ISO 10844; MPD = 0.5 ± 0.2 mm) [Schwanen et al., 2007]. According to M+P, it is also performing as an "average" ISO surface compared to other ISO surfaces in Europe.

Table 4.3 Technical data of tyres measured by SINTEF at Kloosterzande

Tyre no	Tyre brand and line	Dimensions	Load/ Speed index	Prod. week/ year	Shore hardness, Shore A
1	Dayton D110	175/70 R14	84 T*)	1207	68
2	Sportiva G70	175/70 R14	84 T	0307	65
3	Barum Brilliantis	185/65 R15	88 T	1607	67
4	Toyo 330	185/65 R15	88 T	4705	70
5	Goodyear Excellence	195/65 R15	91 H	0206	69
6	Conti Premium Contact 2	195/65 R15	91 V	0307	70
7	Toyo Proxes T1R	205/55 R16	91 W	1407	69
8	Nokian Hakka H	205/55 R16	94 H	3407	69
9	Michelin Pilot Primacy HP	215/55 R16	93 H	0206	68
10	Firestone Firehawk TZ200	215/55 R16	97 H	1007	66
11	Conti EcoContact 3	195/65 R15	91 T	0706	71
12	Yokohama AVS dBV500	185/65 R15	92 H	1604	73
13	Pirelli P7	205/65 R15	94 V	0707	64
14	Hankook Ventus Prime K105	205/65 R15	95 W	5207	67
15	Michelin Energy Saver	205/65 R15	94 T	1508	70
16	Michelin Energy Saver	205/65 R15	94 T	1508	70
17	Michelin Energy Saver	205/65 R15	94 T	1709	68
18	Michelin Energy Saver	205/65 R15	94 T	1709	69
19	Uniroyal Tigerpaw SRTT	225/60 R16	97 S	4206	65
20	Uniroyal Tigerpaw SRTT	225/60 R16	97 S	4206	66
21	Avon Supervan AV4	195/80 R14	106/104N	0607	62
22	Avon Supervan AV4	195/80 R14	106/104N	0607	62

*) Speed codes: S=180, T=190, H=210, V=240, W=270 km/h.

The number of tyres in each tyre class (new class definition) is:
C1A: 5
C1B: 15
C1C: 2 (SRTT)

The results for the measurements on the ISO surface are shown in figure 4.25.

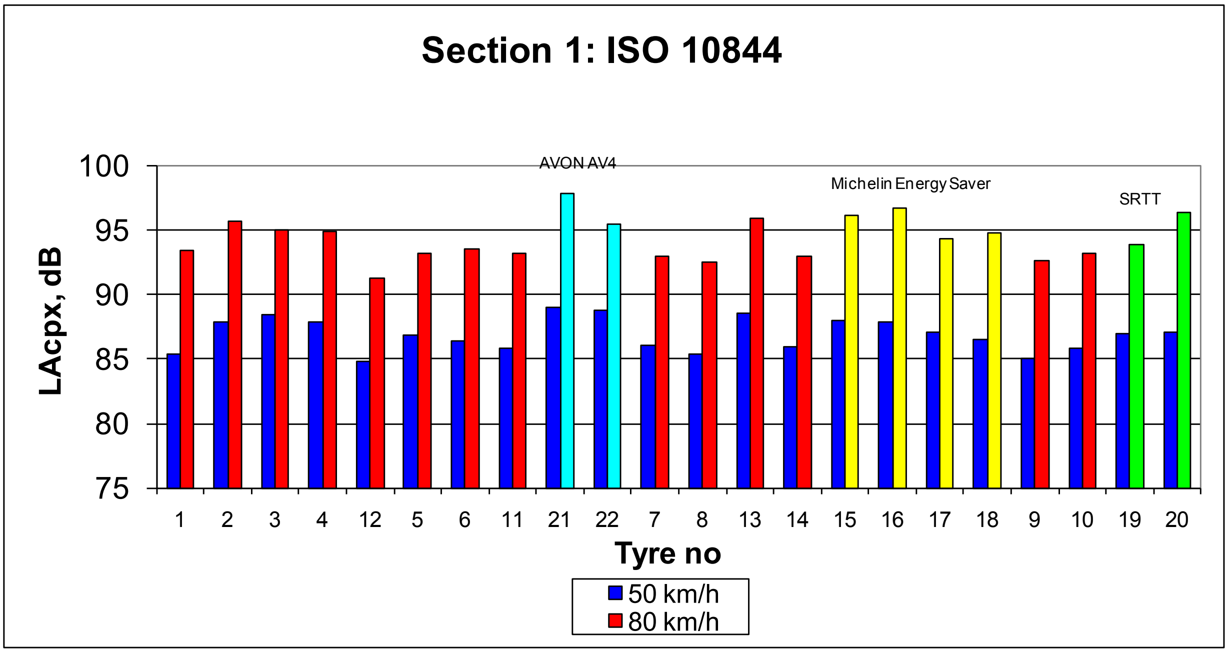


Figure 4.25 Measured noise levels, Lcpx in dB(A), of passenger car tyres on the ISO surfaces at the Kloosterzande test track. No truncation of data [Berge, Haukland, 2010]

The tyres with the narrowest section width are shown to the left in the figure. The tyres preliminary chosen to be reference tyres in the CPX standard (ISO/CD 11819-2/3) are also included in the tyre fleet tested (tyres No. 19-22, marked out in figure 4.25; SRTT = green; Avon AV4 = light blue). Note that a difference of 2-3 dB was found for the reference tyres at 80 km/h, while the difference was less than 1 dB at 50 km/h. Obviously; the speed dependence is different for these tyres, which is not very desirable for tyres chosen as reference tyres. On other surfaces, like some of the porous surfaces at Kloosterzande, such differences were not found for the SRTT tyres [Berge, Haukland, Storeheier, 2011].

Because these measurements have been done with the CPX trailer (near field), the levels are in the range 22-23 dB higher at 80 km/h than typical type testing values for tyres.

The spread in levels is 6.5 dB at 80 km/h (standard deviation of 1.5 dB) and 4.2 dB at 50 km/h (std. dev. 1.3 dB).

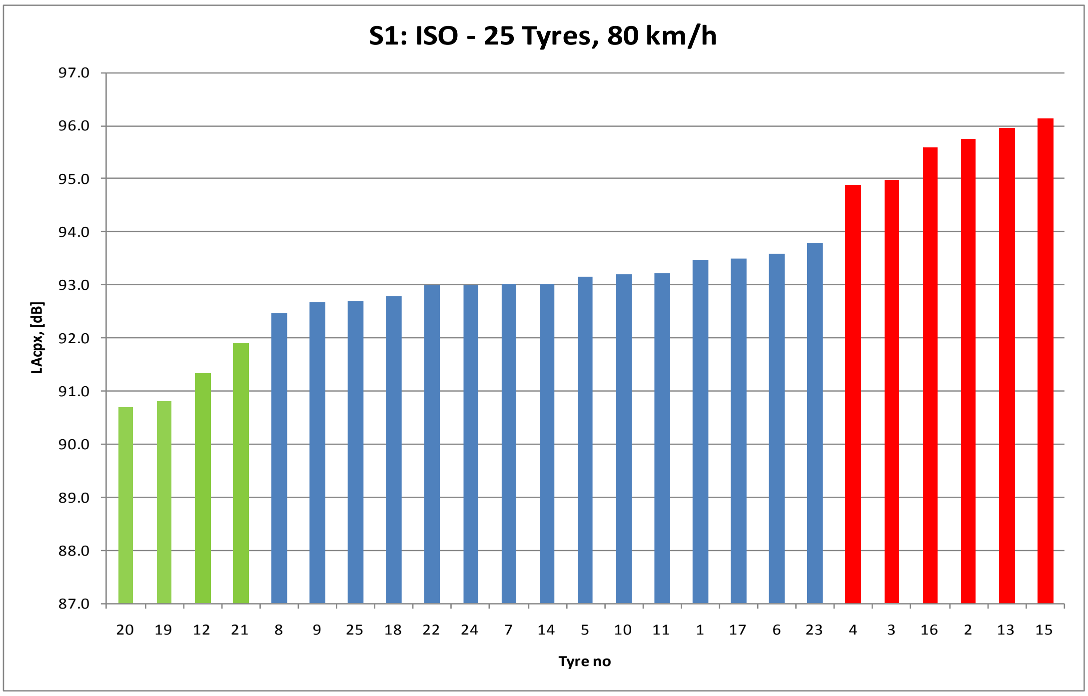
In 2009, M+P did also measure 10 summer tyres for cars (section width ranging from 185 to 205 mm) at the same ISO surface at Kloosterzande [van Blokland, van Leeuwen, 2009a]. M+P used their CPX trailer, which is identical to the Norwegian trailer (built by M+P).

This enabled a comparison of the SINTEF and the M+P measurement results. Of the 22 tyres in table 4.3, 15 tyres were chosen for comparison. The SRTT and Avon AV4 tyres were excluded and only one of the four Michelin Energy Saver tyres were included (No.15 in table 4.3).
The complete list of the 25 tyres is shown in table 4.4.

Table 4.4 Passenger car tyres measured by SINTEF and M+P at the Kloosterzande test track

Tyre No	Tyre brand and line	Dimensions	Source	Shore hardness
1	Dayton D110	175/70 R14	SINTEF	68
2	Sportiva G70	175/70 R14	SINTEF	65
3	Barum Brilliantis	185/65 R15	SINTEF	67
4	Toyo 330	185/65 R15	SINTEF	70
5	Goodyear Excellence	195/65 R15	SINTEF	69
6	Conti Premium Contact2	195/65 R15	SINTEF	70
7	Toyo Proxes T1R	205/55 R16	SINTEF	69
8	Nokian Hakka H	205/55 R16	SINTEF	69
9	Michelin Pilot Primacy HP	215/55 R16	SINTEF	68
10	Firestone Firehawk TZ200	215/55 R16	SINTEF	66
11	Conti EcoContact3	195/65 R15	SINTEF	71
12	Yokohama AVS dBV500	185/65 R15	SINTEF	73
13	Pirelli P7	205/65 R15	SINTEF	64
14	Hankook Ventus Prime K105	205/65 R15	SINTEF	67
15	Michelin Energy Saver	205/65 R15	SINTEF	70
16	Vredestein Hi-Trac	205/55 R15	M+P	68
17	Goodyear Optigrip	205/55 R15	M+P	67
18	Pirelli Cinturato P6	205/55 R15	M+P	65
19	Interstate Sport IXT-1	205/55 R15	M+P	68
20	Yokohama AVS dBV500	185/60 R14	M+P	68
21	Dunlop SP Sport Maxx	205/55 R15	M+P	71
22	Conti EcoContact3	195/65 R15	M+P	65
23	Bridgestone B-250	195/65 R15	M+P	68
24	Conti Premium Contact2	195/65 R15	M+P	67
25	Goodyear GT3	195/65 R15	M+P	67

In figure 4.26, the combined results for the 15 SINTEF tyres (excluding tyres 16-22 in table 4.3) and the 10 M+P tyres are shown for the speed of 80 km/h.



<u>Figure 4.26</u> Measured CPX levels of passenger car tyres at the ISO surface at Kloosterzande, SINTEF and M+P data. No truncation of data [Berge, Haukland, Storeheier, 2011]

The spread in levels is 5.4 dB (standard deviation 1.5 dB). The four green tyres are labelled by this author as "low noise" tyres; the red ones are "noisy" tyres. The "average" tyres are the blue ones. This "classification" of tyres is almost identical at 50 km/h.

As table 4.4 shows, there are three sets of identical (same width) tyres tested by SINTEF (tyres 6, 11 and 12) and by M+P (tyres 20, 22 and 24):

- Conti PremiumContact2 (tyres 6 and 24): 93.6 and 93.0 dB(A)
- Conti EcoContact3 (tyres 11 and 22): 93.2 and 93.0 dB(A)
- Yokohama AVS dB500 (tyres 12 and 20): 91.3 and 90.7 dB(A)

These results are very close to each other; within the normal uncertainty of CPX-type of measurements. Note that the difference in Shore A for tyres 6 and 24 is 3 units, and between tyres 11 and 22, the difference is 6 units. Still, the difference in noise levels is highest for the first pair of tyres.

As shown in table 4.4, the Shore A hardness has been measured for all the tyres. It has been documented that the hardness of the tyre has an influence on the noise levels [Sandberg, Ejsmont, 2007; Sandberg, Glaeser, 2008]. The influence is, however, related to the wear of the tyre (aging). A regression analysis between the measured noise levels (in figure 4.26) and the Shore A values in table 4.4 showed that there is no significant correlation between these two quantities.

4.2.5 Dutch list from 2010

In 2010, the Netherlands issued a new list of type testing levels for tyres. (http://kiesdenieuweband.nl/)

All measurements of these tyres have been made on the ISO track at Lelystad in the Netherlands. In addition to noise levels, the list also includes data for wet grip and rolling resistance.
The data set consists of summer and winter tyres for cars (C1A, C1B and C1C), and summer tyres for vans (C2). In total 376 tyres.

The number of tyres for the different categories in the data set is shown in table 4.5. Since the list consists of type testing sound levels, it is assumed that the levels have been truncated and rounded down (maximum 1.9 dB subtraction of actual measured level).

Table 4.5 Dutch list of 2010, passenger car and van tyres

Tyre class	Summer	Winter	All seasons
C1A	67	33	10
C1B	101	45	11
C1C	55	32	2
Vans	20	-	-
Total	243	110	23

In figures 4.27 to 4.43, the combined results for wet grip, rolling resistance and noise levels are presented for each tyre category (data processed by the author).

In each graph, two areas are marked with colours:
Green area:
Wet grip index: Meets future EU standards for A, B and C labels for wet grip
Rolling resistance coefficient: Meets future EU standards for A, B and C labels for rolling resistance coefficient
Rolling sound emission: Meets future EU standard for rolling sound emission
Yellow area:
Wet grip index: Meets future EU standard for E label for wet grip
Rolling resistance coefficient: Meets future EU-standards for E and F labels for rolling resistance coefficient
Sound emission levels: Meets current EU-standard for sound emission level

In addition, the list also has a red category for tyres which fail to meet future standards for wet grip and rolling resistance, and fail to meet the current standard for sound emissions. This category is not shown in the figures. Note that the yellow area is not to be considered "a second" best area to the green area. There are tyres in the green area for wet grip, but have a noise levels only 1 dB above the future noise limit, (see for example figure 4.28).

For the wet grip index, the axis is reversed, i.e. the higher the number (to the left) is, and the better the wet grip is.

SUMMER TYRES:

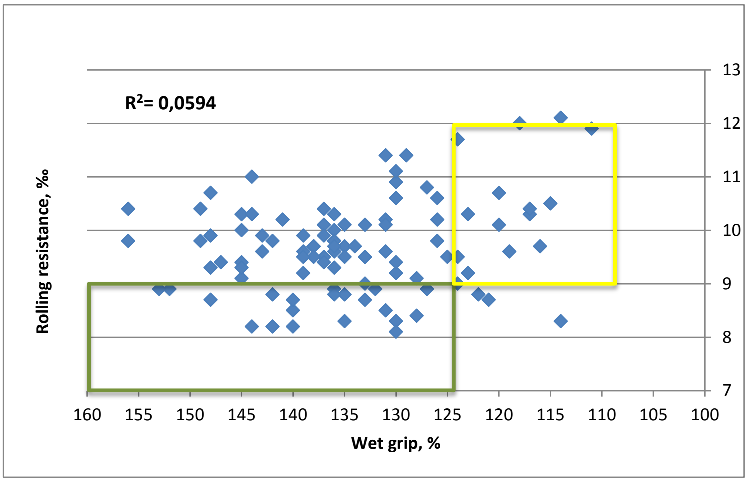


Figure 4.27 Wet grip index and rolling resistance coefficient
Summer tyres for cars (C1A, C1B, C1C)

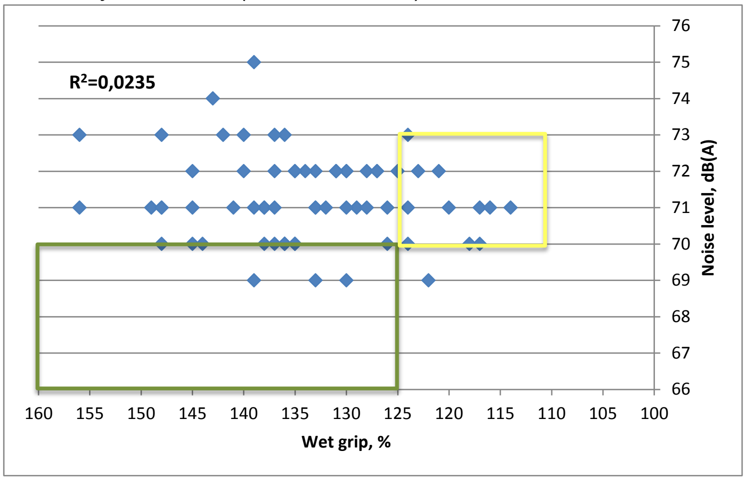


Figure 4.28 Wet grip index and noise levels
Summer tyres for cars; class C1A ≤ 185 mm

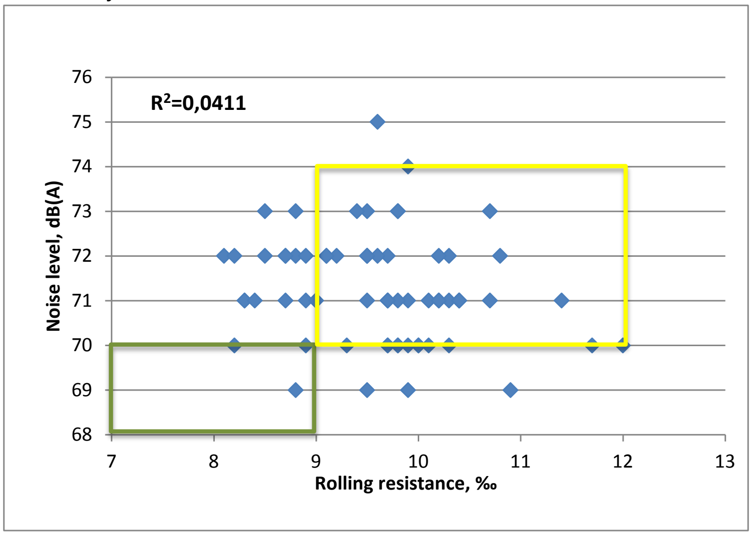


Figure 4.29 Rolling resistance and noise levels
Summer tyres for cars; class C1A ≤ 185 mm

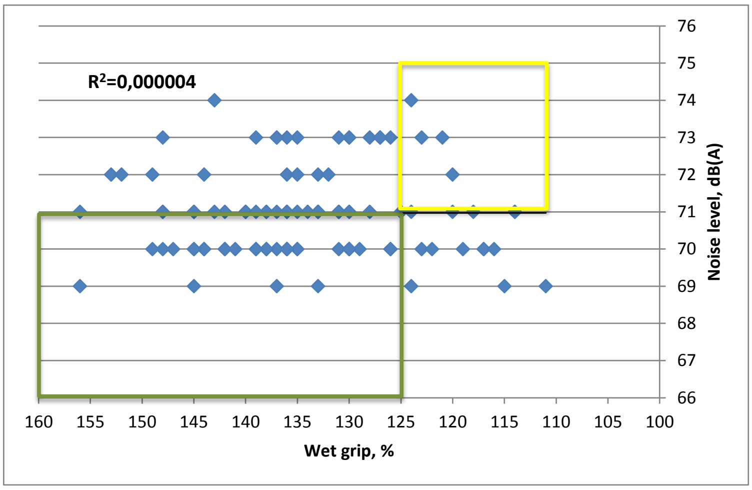


Figure 4.30 Wet grip index and noise levels
Summer tyres for cars; class C1B 195, 205, 215 mm

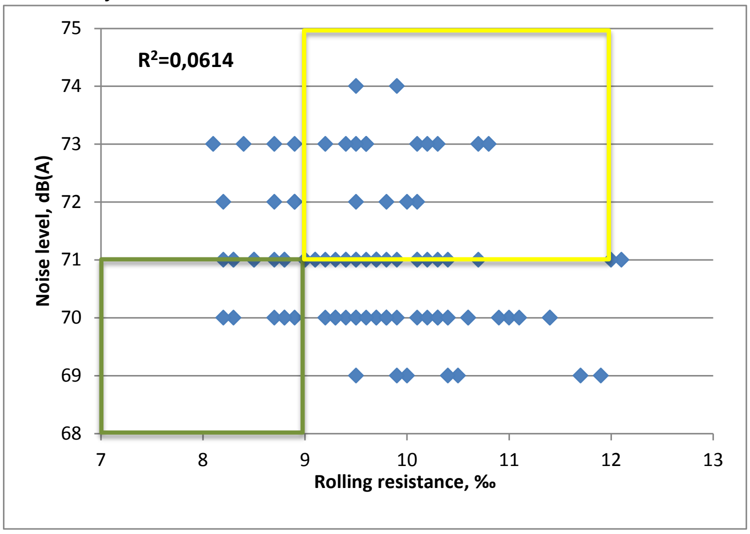


Figure 4.31 Rolling resistance and rolling noise levels
Summer tyres for cars; class C1B 195, 205, 215 mm

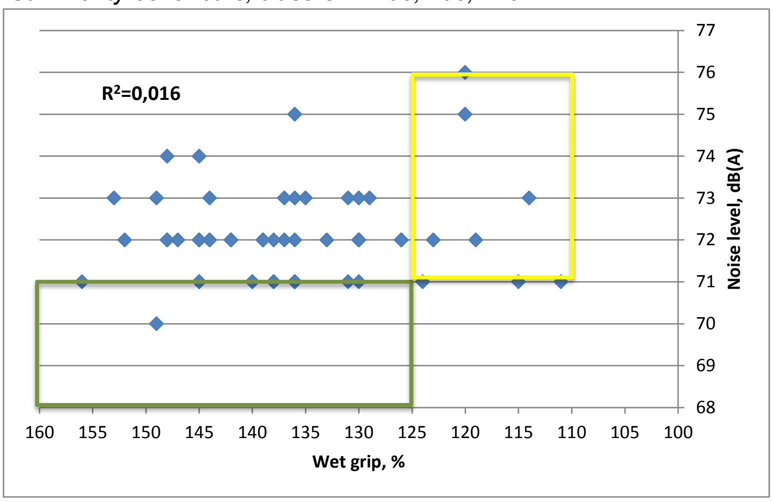


Figure 4.32 Wet grip index and noise levels
Summer tyres for cars; class C1C 225, 235, 245 mm

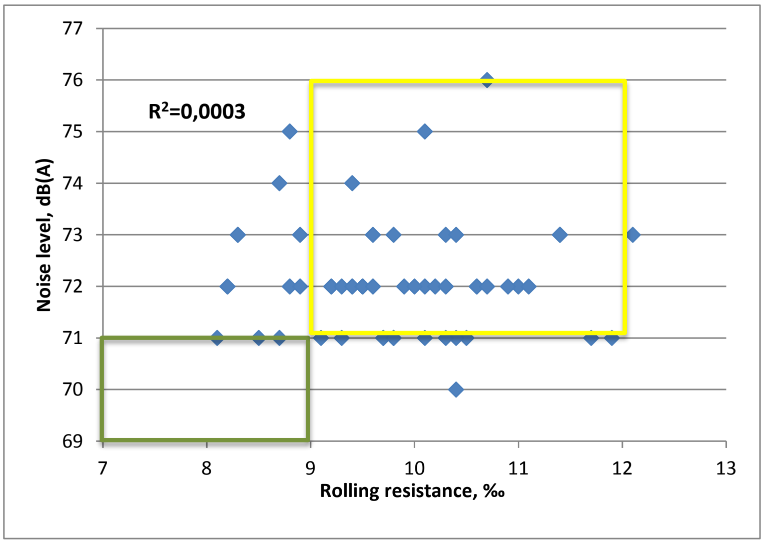


Figure 4.33 Rolling resistance and noise levels
Summer tyres for cars; class C1C 225, 235, 245 mm

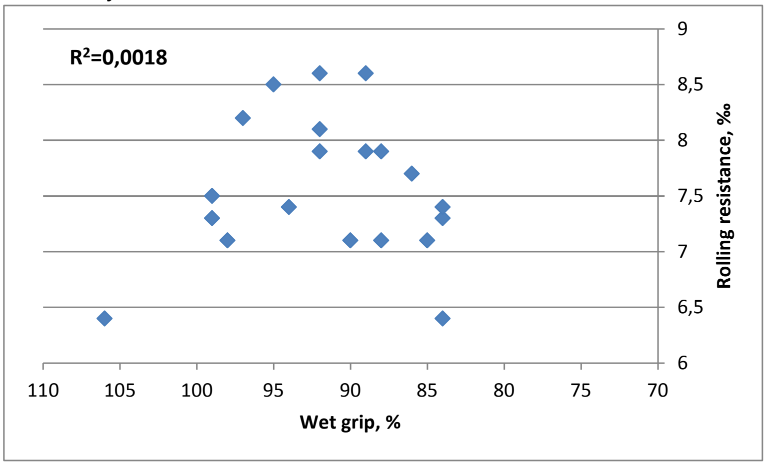


Figure 4.34 Wet grip index and rolling resistance
Summer tyres for vans; C2

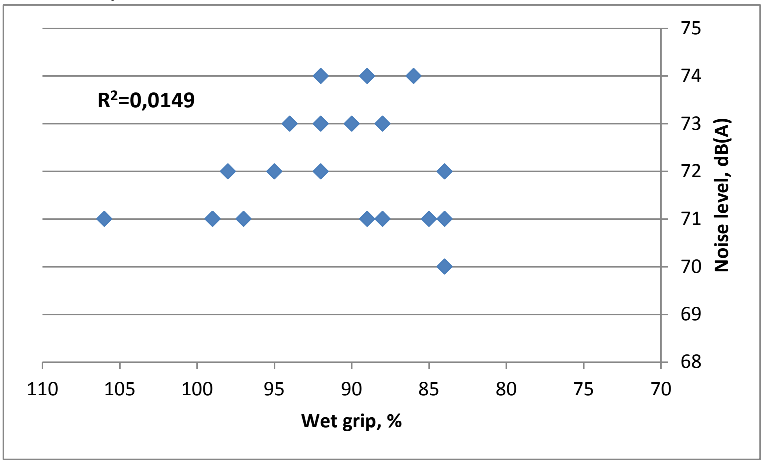


Figure 4.35 Wet grip index and noise levels
Summer tyres for vans; C2.

Since there is no requirement for wet grip for class C2 tyres, no areas are marked in figures 4.34 and 4.35.

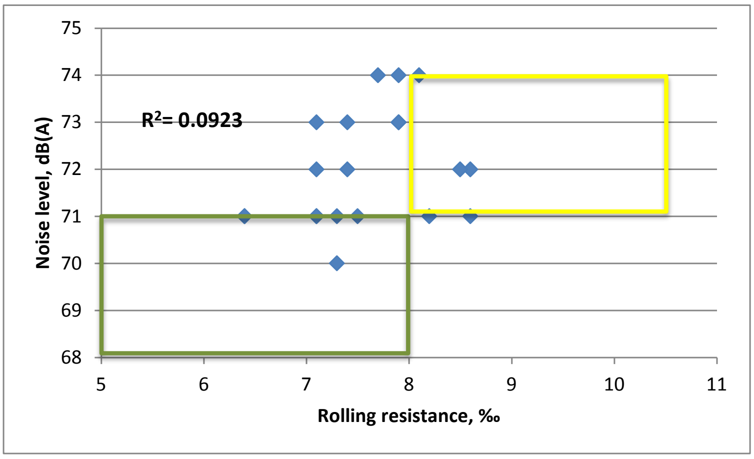


Figure 4.36 Rolling resistance and noise levels
Summer tyres for vans; class C2

Based on these figures for summer tyres of classes C1 and C2, there is no positive correlation between the three parameters, wet grip, rolling resistance and noise levels. On the other hand, there is no negative correlation either.

WINTER TYRES:

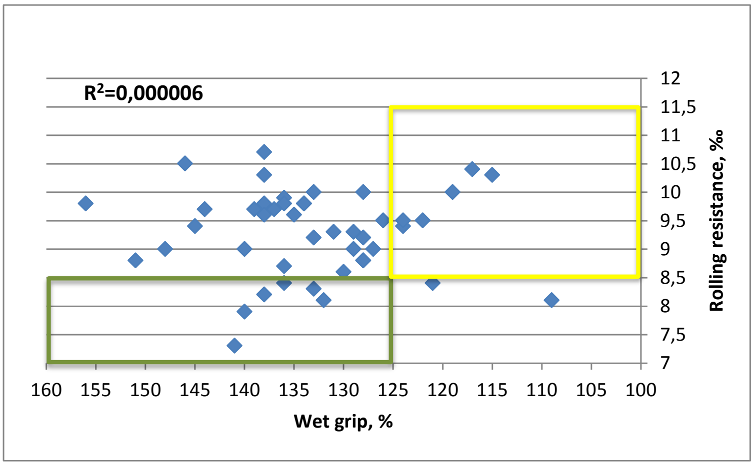
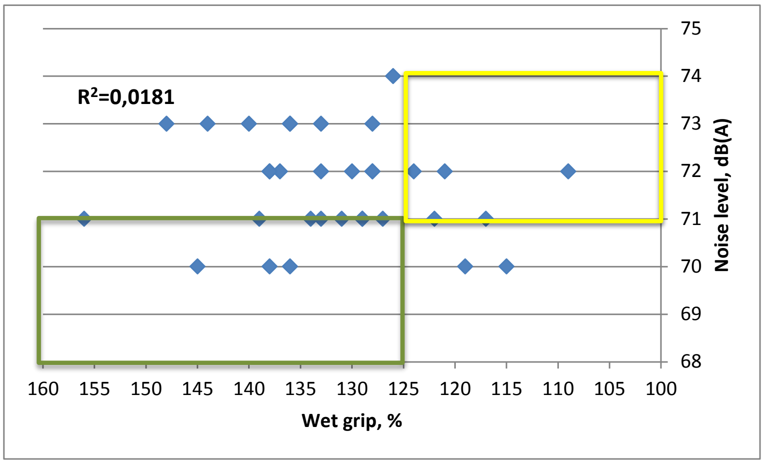
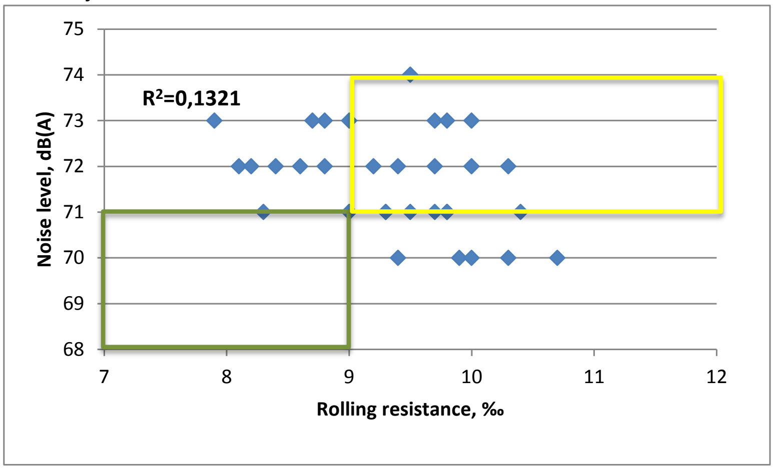


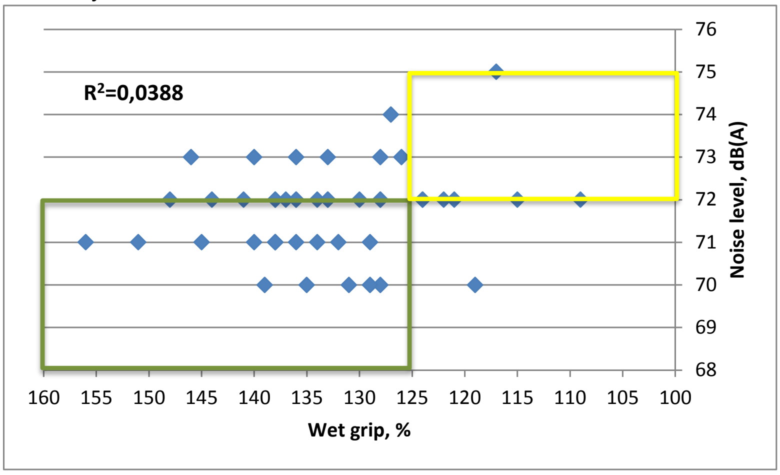
Figure 4.37 Wet grip index and rolling resistance
Winter tyres for cars (C1A, C1B, C1C)



<u>Figure 4.38</u> Wet grip index and noise levels
Winter tyres for cars; class C1A ≤ 185 mm



<u>Figure 4.39</u> Rolling resistance and noise levels
Winter tyres for cars; class C1A ≤ 185 mm



<u>Figure 4.40</u> Wet grip index and noise levels
Winter tyres for cars; class C1B 195, 205, 215 mm

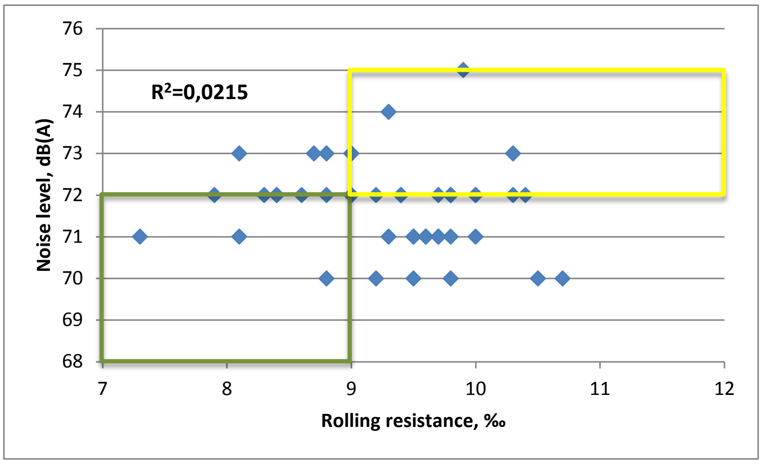


Figure 4.41 Rolling resistance and noise levels
Winter tyres for cars; class C1B 195, 205, 215 mm

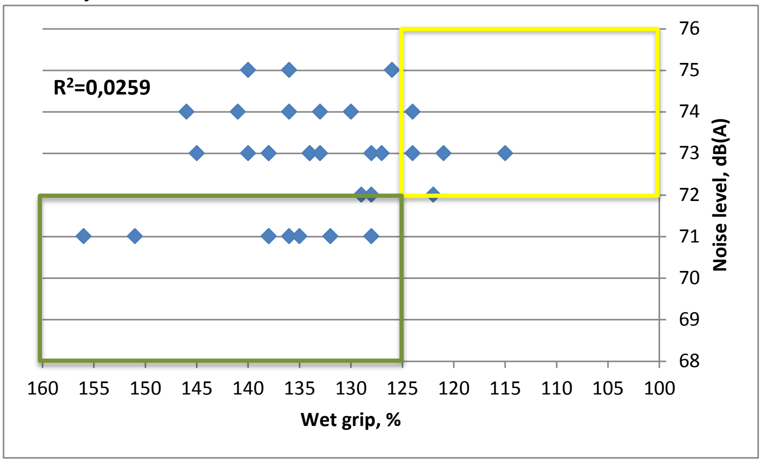


Figure 4.42 Wet grip index and noise levels
Winter tyres for cars; class C1C 225, 235, 245 mm

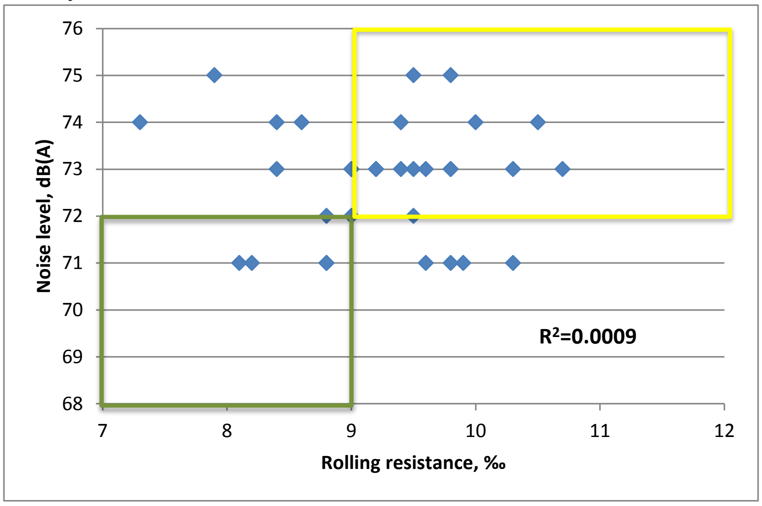


Figure 4.43 Rolling resistance and noise levels
Winter tyres for cars; class C1C 225, 235, 245 mm

For the winter tyres of class C1, the same conclusion can be made as for the summer tyres; no positive or negative correlation between wet grip, rolling resistance and noise levels is found.

Concerning the spread in noise levels in this database, it is found to be in the range of 5-6 dB, which is comparable to what was measured on the Kloosterzande test track by SINTEF and M+P.

4.2.6 Comparison of results

There is about 10 years difference between some of the data presented in the FEHRL study and the data in the Dutch list from 2010 (http://kiesdenieuweband.nl/). In order to compare any changes over this period, the data from these two data sets have been combined. In addition, the CPX data measured by SINTEF and M+P have been modified to "type testing" levels, by subtraction of 22.6 dB (distance correction) and rounding down (truncation) to the nearest integer.

The distribution of these 3 sets of data for C1A, C1B and C1C tyres are shown in figures 4.44 to 4.46. The present and new noise limits are indicated. In figures 4.47 to 4.49, the cumulative distribution is shown for the data from the Dutch list (2010) and from the FEHRL study (only summer tyres are included).

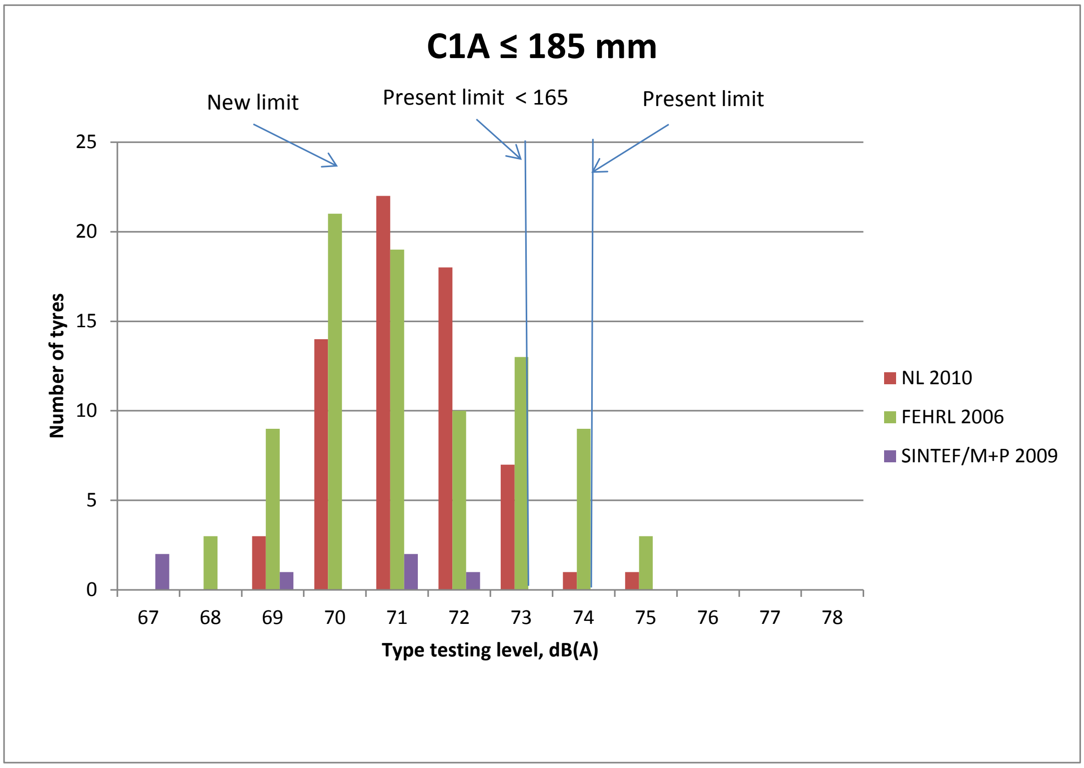


Figure 4.44 Type testing levels from 3 sets of data, class C1A

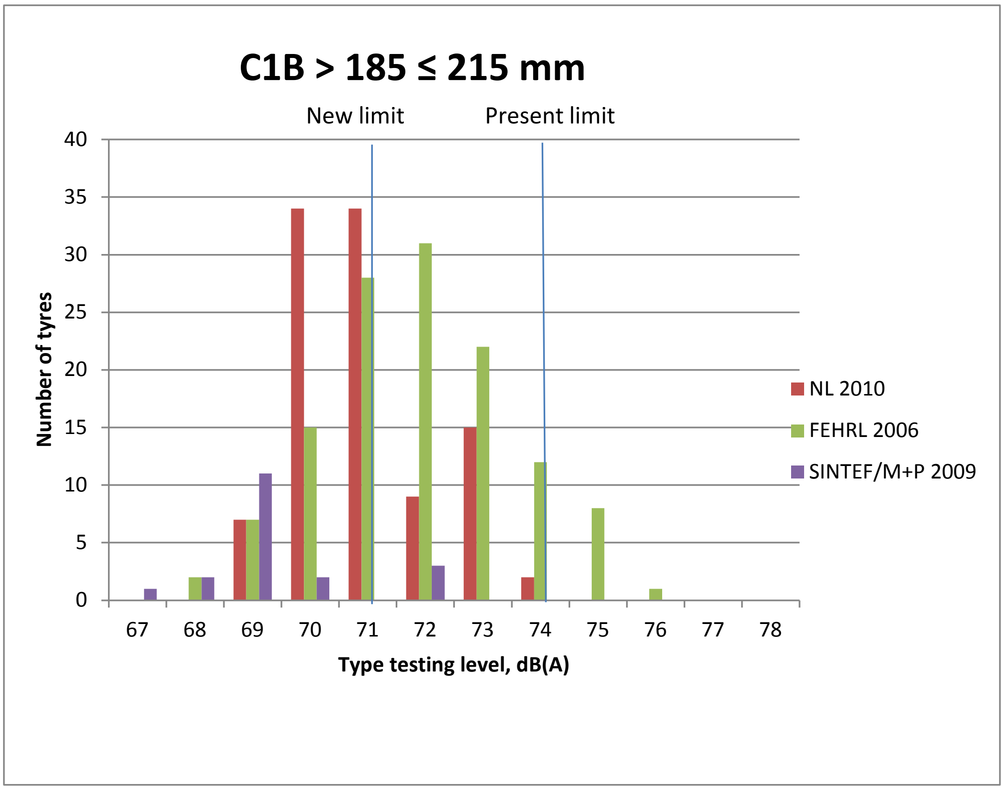


Figure 4.45 Type testing levels from 3 sets of data, class C1B

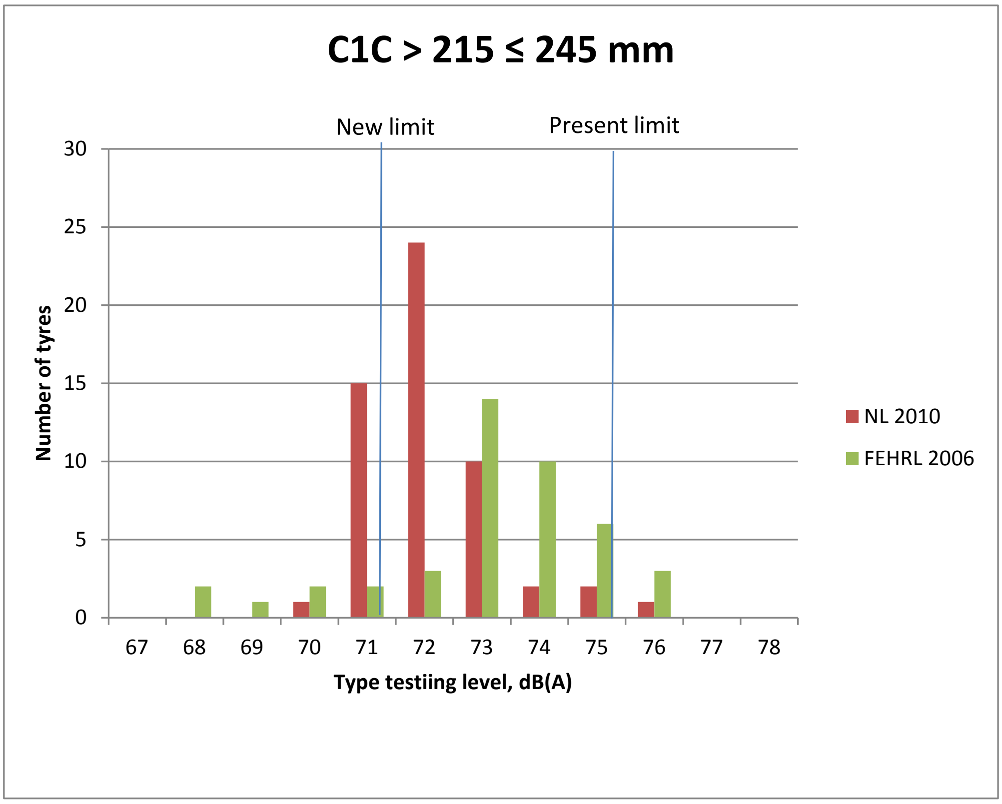


Figure 4.46 Type testing levels from 2 sets of data, class C1C

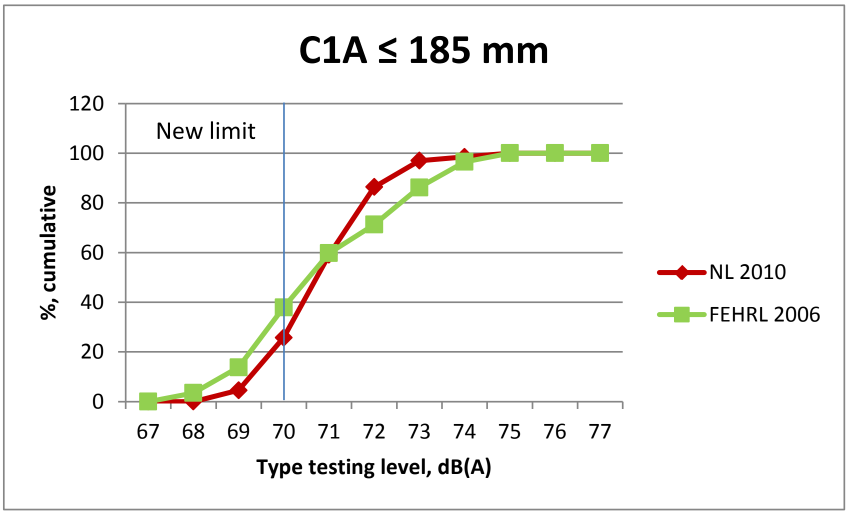


Figure 4.47 Cumulative distribution of type testing levels, class C1A

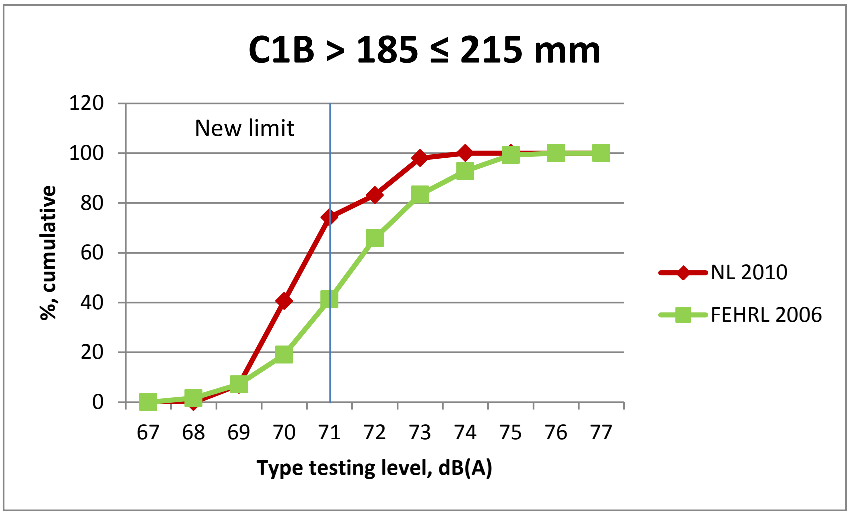


Figure 4.48 Cumulative distribution of type testing levels, class C1B

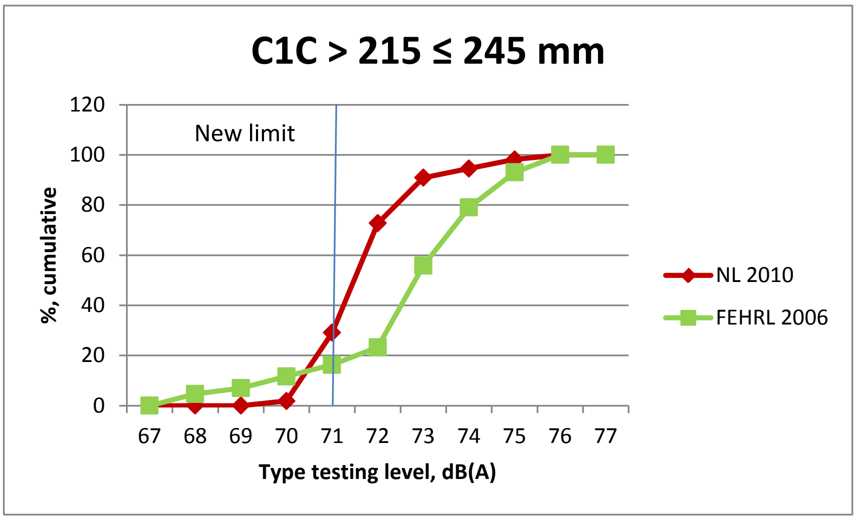


Figure 4.49 Cumulative distribution of type testing levels, class C1C

From this comparison, it seems that for the smaller sizes of tyres (C1A ≤ 185 mm), the two data sets are quite similar, only slightly fewer tyres in the noisy range for the 2010 data (figure 4.47). For the wider tyres, C1B and C1C, there is clearly a shift to the left in the distribution of levels. For class C1B, nearly 80 % of the tyres seem to meet the new limit, but only 30 % of the wider tyres (C1C).

4.3 Measurements on other road surfaces than ISO

4.3.1 Measurements in Norway and the Netherlands, 2004

In 2004, SINTEF and M+P conducted measurements on 20 summer tyres for cars on different road surfaces [Berge, Storeheier, 2005]. Two typical SMA surfaces in Norway (Rv2 near Kongsvinger) and two surfaces on the Lelystad test track in the Netherlands (ISO + Twin layer (2LPA)). The tests were performed with four sets of tyres mounted on a vehicle, and test conditions according to 2001/43/EC. In table 4.6, the tested tyres are listed, and the measurement results are shown in figure 4.50.

Table 4.6 Tyres measured in Norway and the Netherlands

Tyre no	Tyre brand and line	Dimensions, load and speed index
1	Goodyear GT3	175/65 R14 82T
2	Michelin Energy X	175/65 R14 82H
3	Semperit Sportlife	175/65 R14 82T
4	Continental EcoContact EP	175/65 R14 82T
5	Michelin Energy XT-1	175/65 R14 82T
6	Pirelli P3000	175/70 R13 82T
7	Pirelli P3000	175/65 R14 92T
8	Firestone Firehawk 680	195/65 R16 91V
9	Michelin Pilot Primacy XSE	205/55 R16 91V
10	Goodyear Eagle F1	205/55 R16 91W
11	Nokian NRHi	205/55 R16 94H
12	Yokohama C-drive	205/55 R16 94V
13	Yokohama AVS dB500	195/65 R15 91H
14	Hankook K406	195/65 R15 91H
15	Goodyear Eagle NCT5	195/60 R15 88H
16	Continental PremiumContact	205/55 R16 91V
17	Bridgestone Turanza ER70	195/60 R15 88H
18	Pirelli P6	195/65 R15 91H
19	Vredestein Sportrac	205/55 R16 91W
20	Michelin Energy XH-1	195/60 R15 88H

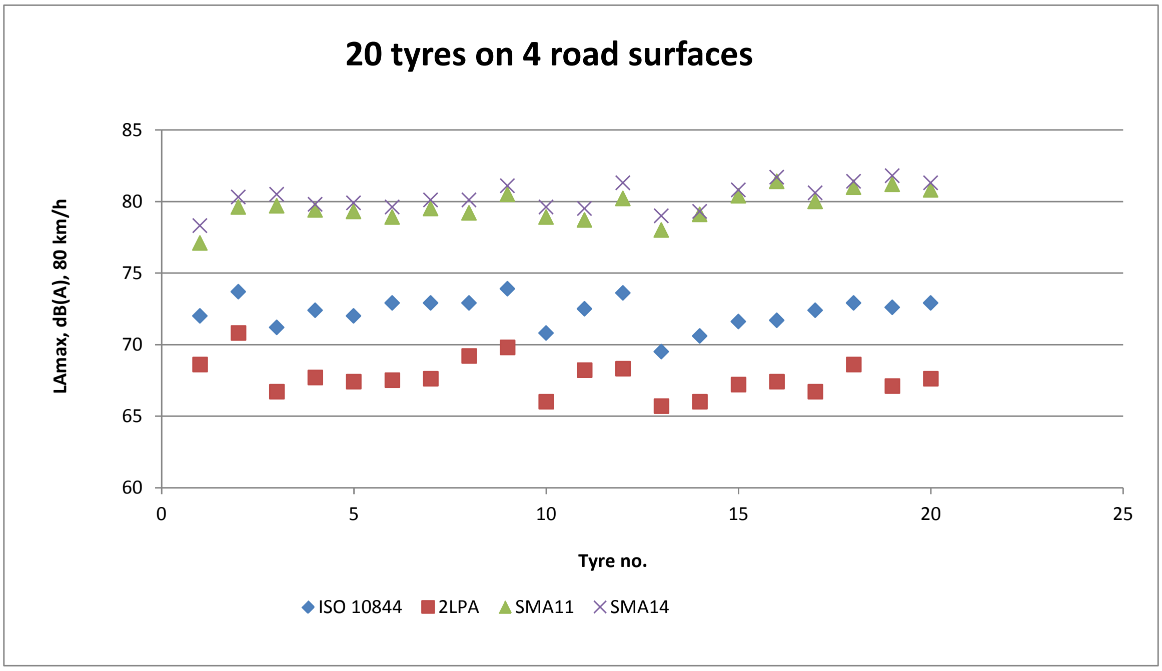


Figure 4.50 Measured noise levels of passenger car tyres on 4 surfaces. No truncation of data

On average, the noise levels on the two SMA surfaces in Norway are 7.5 dB ***higher*** than on the ISO surface. The range of noise levels on the ISO surface was found to be 4.4 dB, while it was 3.5 dB on the SMA 0/14. The highest individual difference was 14.7 dB, using the same tyre, same type of vehicle (VW Passat Variant), same measurement equipment/personnel; just moving from the two layer porous surface at Lelystad, to the SMA 0/14 road surface in Norway.

4.3.2 Measurements in Norway, 2007-2008

In 2007-2008, SINTEF measured a selection of summer tyres for cars on normally used SMA/DAC surfaces in Norway [Berge, Haukland, Ustad, 2009a]. The old and new CPX reference tyres (Tyre A; Avon ZV1 and the SRTT) were among the tested tyres.

In addition to the dense surfaces, some test surfaces with single and double layer porous surfaces were also included.

The measurements were done with the Norwegian CPX trailer. The tyres were part of the same tyre batch as listed in table 4.3 and table 4.4 (Chapter 4.2.4).

The measurement results at 50 and 80 km/h are shown in figures 4.51 and 4.52. The surfaces are sorted according to age, the oldest to the left. The SMA11 2007 and SMA11 2008 had not been exposed to winter conditions at the time of measurements.

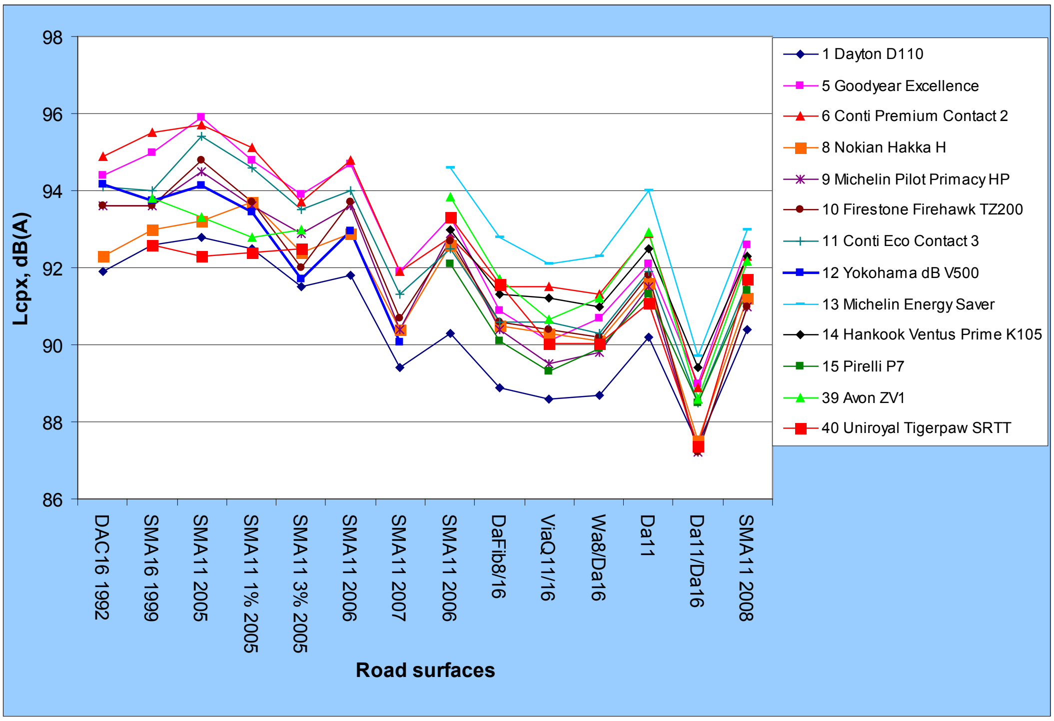


Figure 4.51 Measured CPX levels on Norwegian road surfaces. Speed: 50 km/h [Berge, Haukland, Ustad, 2009a]

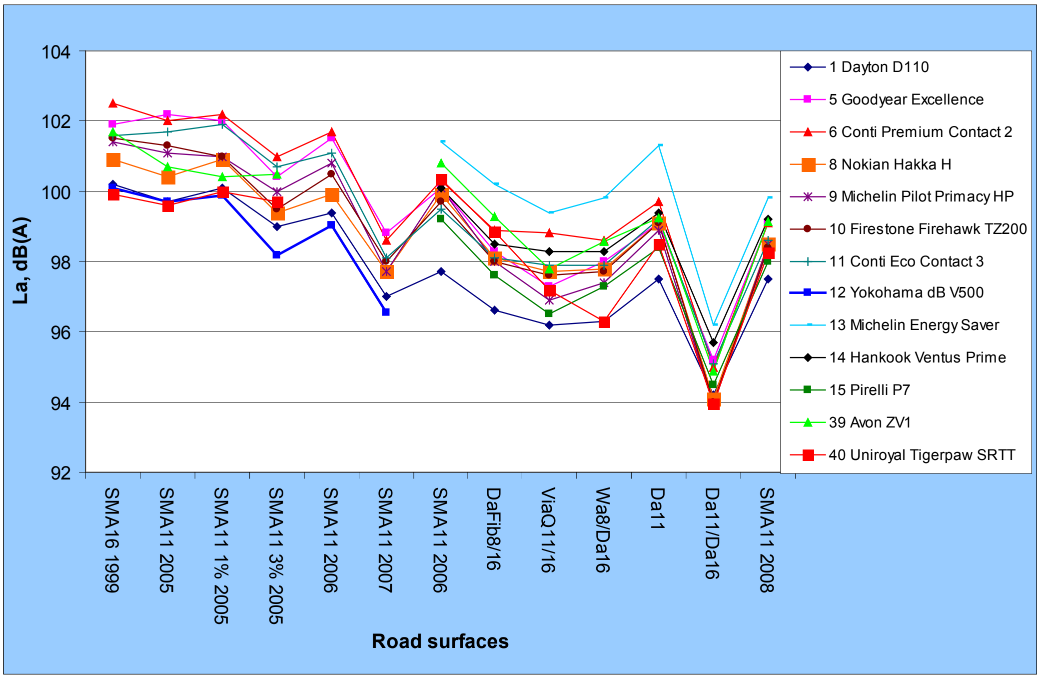


Figure 4.52 Measured CPX levels on Norwegian surfaces. Speed: 80 km/h [Berge, Haukland, Ustad, 2009a]

The noise levels on the newer surfaces, are about 2-3 dB lower than on the older surfaces. The spread in noise levels is 2-3 dB.

There seems to be no significant differences between the results at 50 and 80 km/h, except for the actual levels.

On the ISO surface at Kloosterzande the Yokohama AVS dB500 tyre is the quietest tyre (see figure 4.26, chapter 4.2.4). As shown in figure 4.52, is the quietest tyre on nearly all surfaces it was measured on, at the speed of 80 km/h. At 50 km/h, the Hankook Ventus Prime is the quietest tyre on most of the surfaces (figure 4.51).

4.3.3 Measurements in Norway and Denmark, 2010

In 2010, SINTEF performed a measurement series with 8 passenger car tyres, partly selected from the fleet of tyres measured in 2007 (chapter 4.3.2) [Berge, Haukland, 2011]. However, in this project, a vehicle was used with 2 microphones in the CPX positions, instead of the trailer. Four identical sets of tyres were available for five of the tyres. With these tyres, coast-by measurements at 7.5 m were made, simultaneously with the CPX measurements.

Table 4.7 lists the tyres used for measurements. Tyre D1 was only available for measurements in Norway and tyres D2 and D8 were only available for measurements in Denmark.

Five surfaces were measured in Norway, as listed in table 4.8, and 13 surfaces were measured in Denmark, see table 4.9.

Table 4.7 Tyre specifications

Tyre No.	Tyre brand and line	Type	Dimensions	Production week/year	Shore hardness	Comments
D1	Bridgestone B250	Summer	195/65 R15 91H*)	4809	Not meas.	4 tyres, original summer tyres of the car
D2	Michelin Primacy LC (Green)	Summer	205/60 R15 91V	1210	Not meas.	2 tyres, mounted on rear axles
D3	Michelin Energy Saver (Green)	Summer	205/65 R15 94T	1508/1709	67-68	4 tyres, 2 from 2008 and 2 from 2009
D4	Conti Premium Contact 2E	Summer	205/55 R16 91H	2310	67	4 tyres, OE tyres for VW
D5	Conti Premium Contact 2	Summer	205/55 R16 91V	2210	67	4 tyres, OE tyres for Volvo
D6	Yokohama C-Drive2	Summer	205/65 R16 91W	0510	68	1 tyre
D7	Vredestein HI-TRAC	Summer	205/55 R16 91H	0410	64	1 tyre
D8	ContiVikingContact5	Winter (non-studded)	195/65 R15 95T	0810	Not meas.	4 tyres, original winter tyres of the car

*) Speed codes: H=210, V=240, T=190, W=270 km/h.

Table 4.8 Road surfaces in Norway

Surface No.	Road/Location	Surface	Construction year
S1	E6 Støren	AC16d	2010
S2	E6 Støren	SMA16 Novachip	1994
S3	E6 Horg	SMA11	2010
S4	E6 Horg	SMA11	2008
S5	E6 Horg	Da11/Da16	2008

Table 4.9 Road surfaces in Denmark

Surface No.	Road/Location	Surface	Construction year
S6	Ringstedvej, Igelsø	AC6o	2010
S7	Ringstedvej, Igelsø	AC8o	2010
S8	Ringstedvej, Igelsø	AC11d	2010
S9	Ringstedvej, Igelsø	SMA6+8	2010
S10	Ringstedvej, Igelsø	SMA6+11	2010
S11	Ringstedvej, Igelsø	SMA8	2010
S12	Kastrupvej	AC11d	2007
S13	Kastrupvej	OGAC6	2007
S14	Kastrupvej	SMA4	2007
S15	Kastrupvej	SMA6	2007
S16	Kastrupvej	SMA4+/5/8	2007
S17	Kastrupvej	SMA6+/5/8	2007
S18	Kastrupvej	SMA6+/5/8 (Opt.)	2007

On the road surfaces S12-S18 (Kastrupvej), the posted speed limit was 50 km/h, so only measurements at this speed were possible. At all other locations, both speeds 50 and 80 km/h were used.

The measured noise levels at the two speeds are shown in figures 4.53 and 4.54.

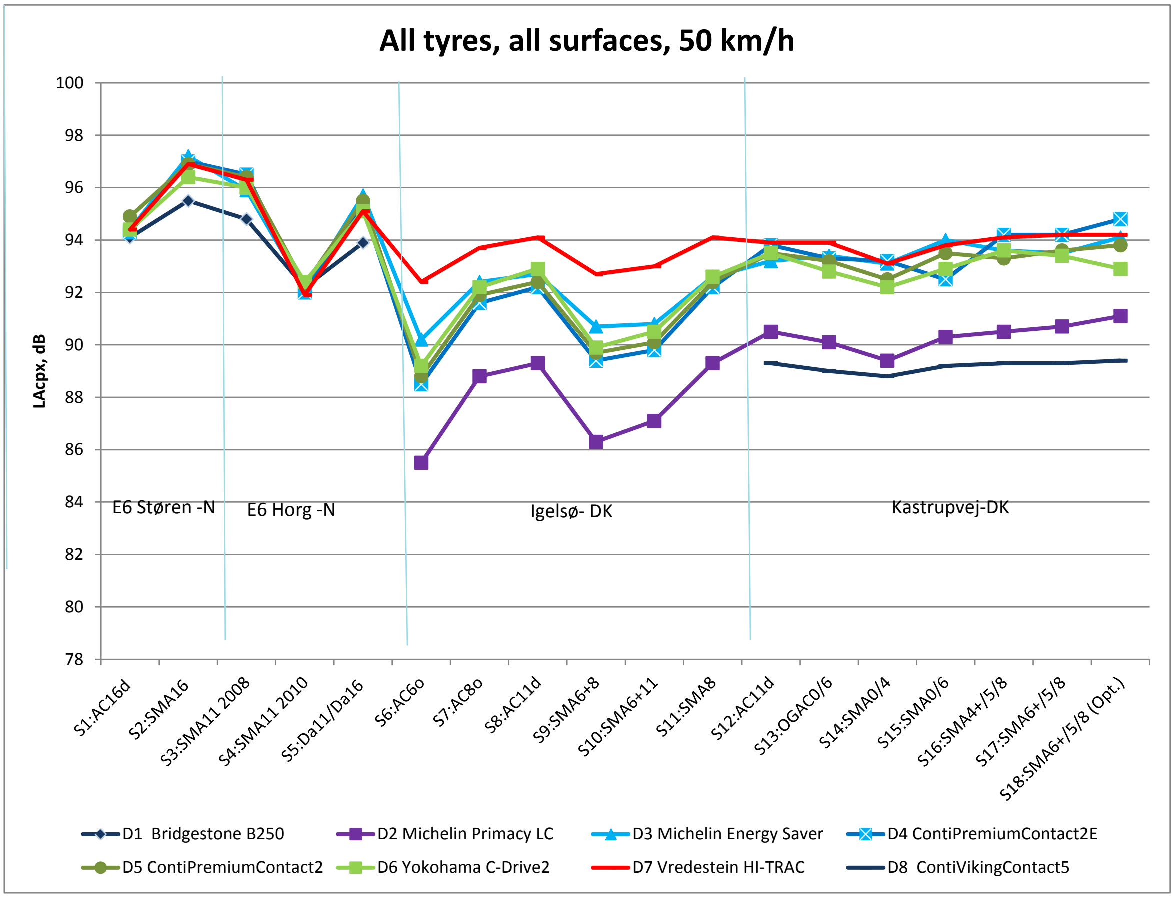


Figure 4.53 Measured CPX levels of passenger car tyres on road surfaces in Norway and Denmark. Speed: 50 km/h. [Berge, Haukland, 2011]

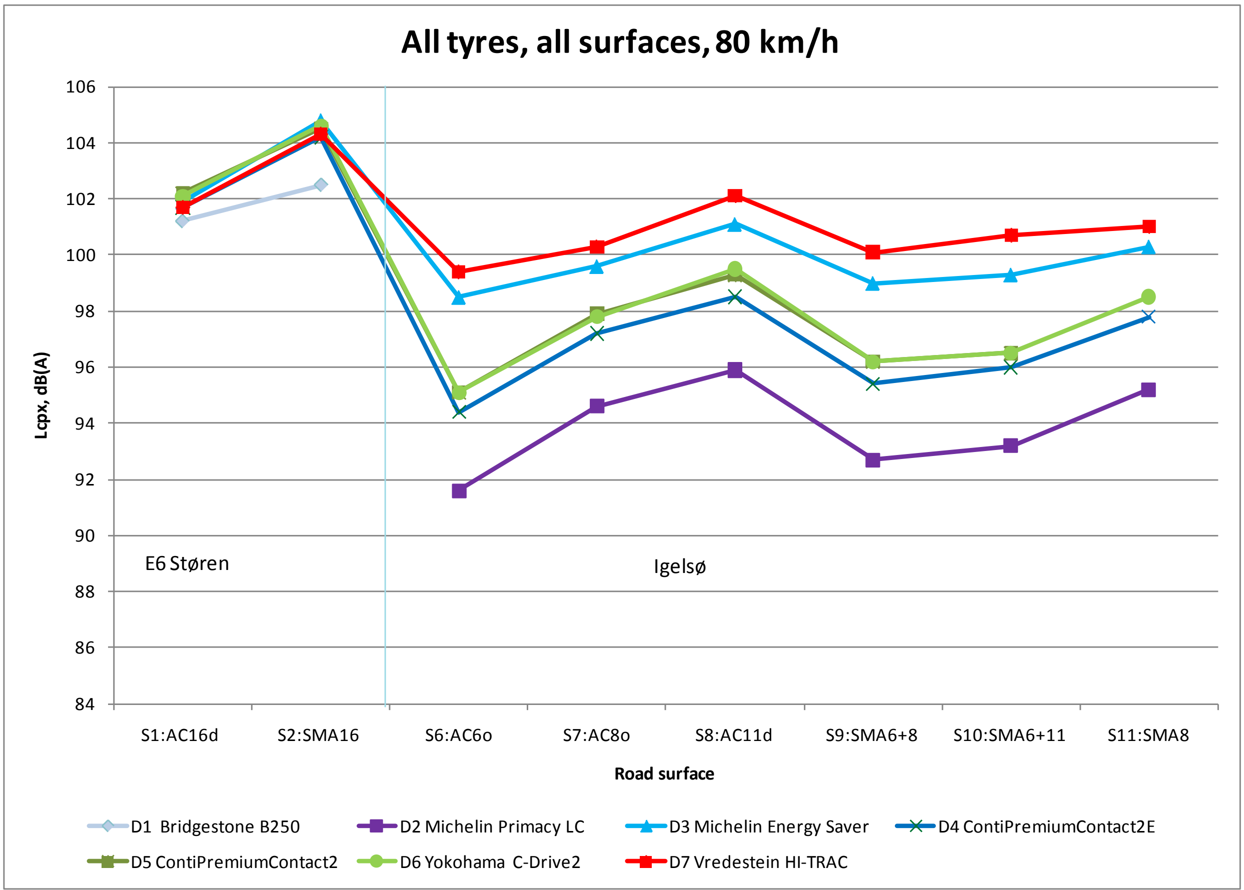


Figure 4.54 Measured CPX levels of passenger car tyres on road surfaces in Norway and Denmark. Speed: 80 km/h. [Berge, Haukland, 2011]

From these results, several conclusions can be made:

- In general, the Norwegian surfaces do not separate much between the tyres, regarding noise levels, with the exception of tyre D1 (Bridgestone B250), which is 1-2 dB quieter than the others. However, none of the "low noise" tyres (such as D2 and D8) were measured on the Norwegian road surfaces.
- From the measurements on the new test surfaces at Igelsø, Denmark, it is clear that these surfaces do rank tyres. Tyre D2 (Michelin Primacy LC) is clearly the quietest tyre on all the surfaces at Igelsø. It would have been interesting to see how this tyre also performs on Norwegian and Swedish road surfaces.
- At 50 km/h on the Igelsø surfaces, the tyres can be grouped in three categories:
    - Low noise tyre: D2
    - Average tyres: D3, D4, D5, D6
    - Noisy tyre: D7

  At 80 km/h, the only difference is that tyre D3 can be grouped together with tyre D7 as a noisy tyre.
- Tyre D7 (Vredestein HI-TRAC) has a type approval level in the upper range (74 dB(A)), according to the Dutch list from 2010 (chapter 4.2.5), and this tyre is also the one with the highest noise levels on the Igelsø road surfaces.
- On the road surfaces on Kastrupvej, the situation is somewhat different; tyre D2 also gave 3-4 dB lower noise levels than the average and the non-studded winter tyre (D8) was even 0.5-1 dB quieter than D2. However, there is no clear noise ranking of the rest of the tyres (figure 4.52) on these surfaces.

- At 80 km/h, the difference between the highest (104.6 dB(A)) and the lowest (91.6 dB(A)) measured (CPX) noise level which is for tyres D3/D6 on surface S2 (SMA16 1994) and tyre (D2) on surface S6 (AC6o) is 13 dB. This is surprisingly high, as the comparison only involves dense surfaces and no porous surfaces. However, the AC6o surface is a new surface, and it is open graded, with a specified void content of approximately 12 %. It probably has a very favourable texture, such as is typical of many thin asphalt layers and it is likely that it will soon lose much of its low noise properties.
- At 50 km/h, the difference is somewhat lower (11.7 dB between tyres D3 and D2 on the same two surfaces), but still it is high. Similar differences were found in the joint project between SINTEF and M+P in 2004 (see figure 4.50), but then the difference was between an SMA14 surface in Norway and the double-layer porous road surface at the Lelystad test track in NL [Berge, Storeheier, 2005].
- Only one sample of a non-studded winter tyre has been measured (D8). At an air temperature around + 13 °C, this tyre was about 4-5 dB quieter than the average of the summer tyres included (except tyre D2), most likely due to a much softer rubber compound (shore hardness was not measured).

As shown in the figures, the Michelin Primacy LC is remarkably quiet, independent of the type of surface (in Denmark), 2-3 dB quieter than the others. The tyre is a "normal" tyre with regard to dimensions and speed index (V= 240 km/h, see table 4.7), so it has obviously not been designed to meet common lower speed limits found in Asia, than in Europe. This tyre is not currently available on the European market. The reason for this is unknown, but should be investigated.

In figure 4.55, the tread pattern of this tyre is shown. It may have a "good" tread design for low noise performance, but also probably some material/rubber features, that give a reduction in radiation efficiency.

Further investigation and measurements with this tyre is recommended.

Figure 4.55 Tread pattern of Michelin Primacy LC

To compare the influence of the different road surfaces in Norway and Denmark, the average noise levels of 5 tyres measured in both countries (D3-D7 in table 4.7) have been calculated.
A comparison will depend on the choice of the reference road surface. In figure 4.56, the noise differences in noise levels compared to the oldest surface tested in Norway, SMA16 1994, are shown. The following can be observed:

At 50 km/h, the new SMA11 surface (2010, not having been exposed to winter conditions) is nearly 5 dB quieter than the SMA16 1994. However, comparing this surface with the older SMA11 from 2008, the difference is less than 1 dB. The Danish surfaces at Kastrupvej (orange columns) are 3-4 dB quieter than the SMA16. The new surfaces at Igelsø (green columns) are 4-7 dB quieter than the SMA16.

It should be emphasised that this comparison includes the newly laid surfaces at Igelsø, and this clearly is the reason for the relatively large differences. One must also remember that the surfaces are designed for different climates and for different traffic; thus they are not generally interchangeable.

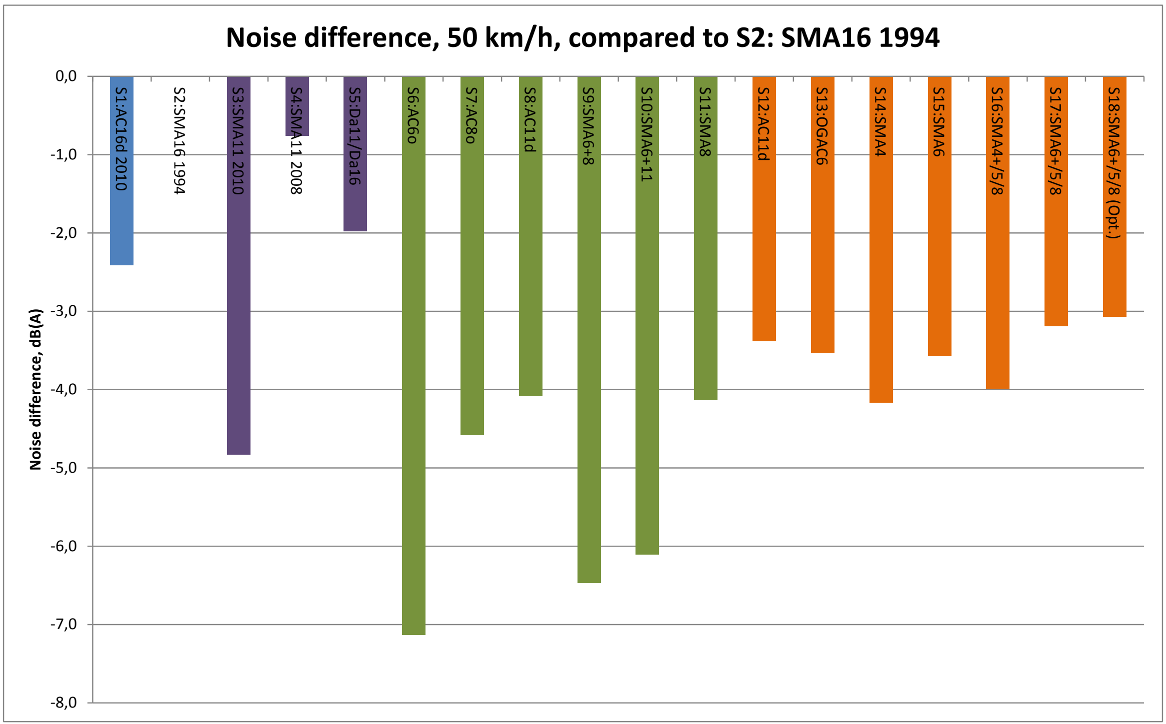


Figure 4.56 Norwegian and Danish road surfaces. Measured noise differences, average of 5 tyres at 50 km/h, compared to surface: S2 (SMA16 1994)

At 80 km/h, measurements were done only on two surfaces in Norway (E6 Støren) and at Igelsø in Denmark. The calculated noise difference compared to SMA16 1994 is shown in figure 4.57. At this speed, the difference is even higher than at 50 km/h. The Danish surfaces were from 4.5 to 8 dB quieter than the SMA16.

It would be interesting to see what the noise properties would be if an SMA16 designed for Norway would be laid and trafficked for several years in Denmark.

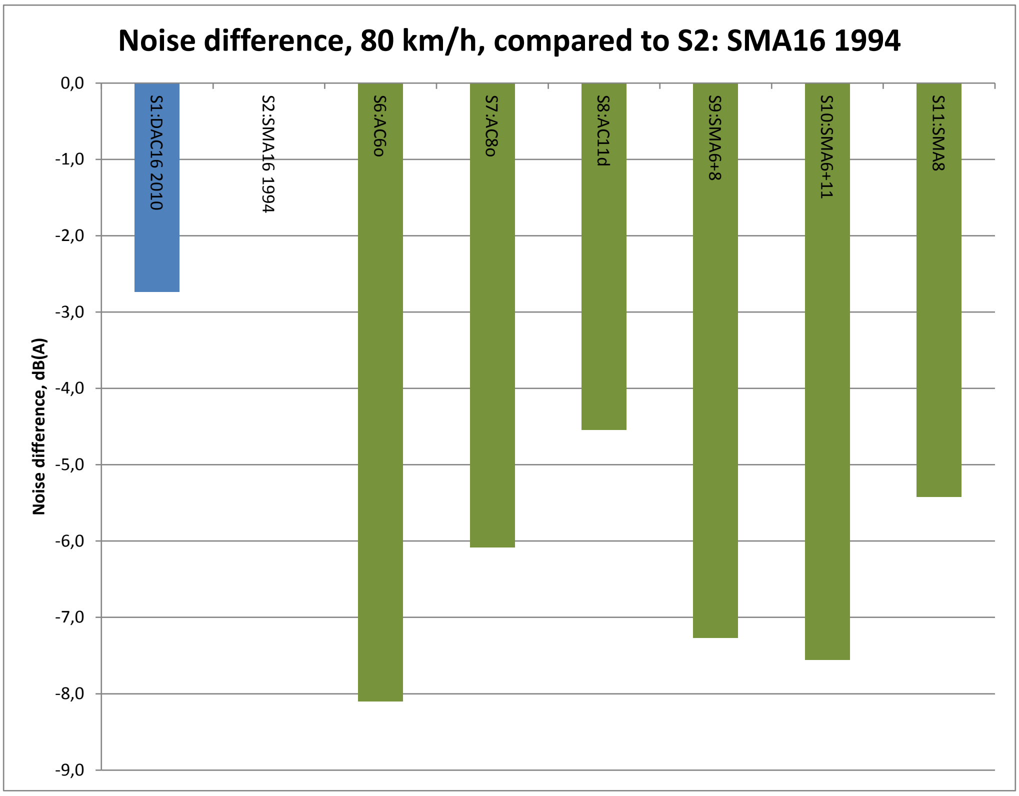
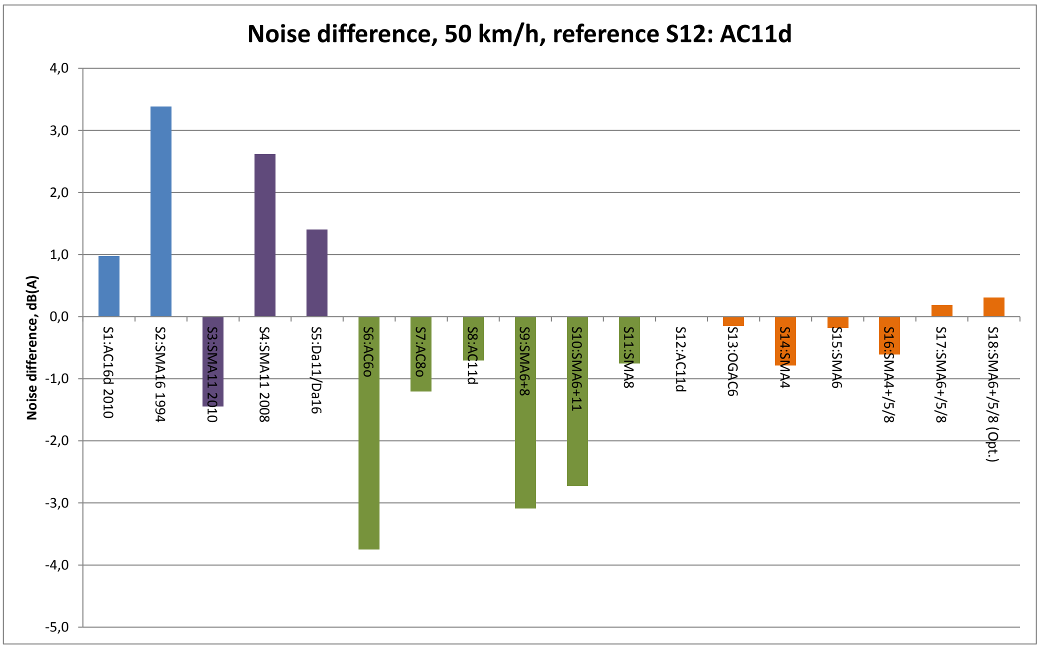


Figure 4.57 *Norwegian and Danish road surfaces. Measured noise reduction, average of 5 tyres at 80 km/h, compared to surface S2 (SMA16 1994)*

In Denmark, the reference road surface for traffic noise measurements/calculations is a dense asphalt concrete surface 8-9 years old (AC11d). Such surface was located both at the Igelsø and Kastrupvej locations (newly laid and 3 years old). If the surface at Kastrupvej (surface S12 in table 4.9) is used as a reference surface, the results are somewhat different from the SMA16 surface, as shown in figure 4.57. Again, the difference is calculated from the average levels of the 5 tyres, D3-D7.



<u>Figure 4.58</u> Norwegian and Danish road surfaces. Measured noise difference, average of 5 tyres at 50 km/h. Reference surface: S12 (AC11d)

Since the Igelsø surfaces were quite new, it is probably most correct to use the DAC11 surface at Kastrupvej (S12) as the road surface to compare with Norwegian road surfaces. Then the difference is in the range of 2-3 dB, which is the same range of increase we can see on dense surfaces in Norway, after being exposed to winter conditions/studded tyres.

4.3.4 Measurements in Norway, 2011

In 2011, SINTEF measured 10 summer tyres for cars on a selection of 5 new (not exposed to winter) and 14 old road surfaces in Norway [Berge, Haukland, 2012]. The tyres are part of the tyre fleet tested in 2009 (see table 4.3 and 4.4). All measurements have been made with the Norwegian CPX trailer. The project has been financed by the Norwegian Climate and Pollution Control Agency and the main purpose was to study the noise ranking of tyres on a wide range of road surfaces, with maximum stone sizes varying from 6 to 16 mm and to compare this with the noise ranking on an ISO surface (Kloosterzande).

Tyres tested are shown in table 4.10. The shore hardness has been measured both during the measurements in 2009 and in 2011. Tyre No. 2 is identical to tyre No.16 in table 4.3 and 4.4.

Table 4.10 *Technical data for tyres tested in Norway, 2011*

Tyre No.	Tyre brand and line	Dimensions	Load/ Speed index	Prod. week/ year	Shore hardness Shore A 2009	2011
1	Toyo 330	185/65 R15	88 T	4705	70	72
2	Michelin Energy Saver	205/65 R15	94 T	1508	70	70
3	Conti Premium Contact 2	195/65 R15	91 V	0307	70	72
4	Conti EcoContact 3	195/65 R15	91 T	0706	71	72
5	Nokian Hakka H	205/55 R16	94 H	3407	69	72
6	Michelin Pilot Primacy HP	215/55 R16	93 H	0206	68	70
7	Pirelli P7	205/65 R15	94 V	0707	64	65
8	Yokohama AVS dBV500	185/65 R15	92 H	1604	73	75
9	Uniroyal Tigerpaw SRTT(R)	225/60 R16	97 S	4206	65	70
10	Uniroyal Tigerpaw SRTT(L)	225/60 R16	97 S	4206	66	70

As the table shows, the tyres were from 3 to 7 years old, and the ageing factor expressed as increasing hardness is clearly shown for several of the tyres. Especially, the SRTT tyres have become harder. According to [Sandberg, Glaeser, 2008] an increase in Shore A hardness of one unit implies a noise level increase of 0.1 dB on smooth surfaces and 0.22 dB on rough-textured surfaces (see also chapter 7). An increase of 4-5 units, could then give an increase of nearly 1 dB on typically rough-textured surfaces, as found in Norway and Sweden.

Table 4.11 *Norwegian road surfaces – test program, 2011*

Road surface type	Number of surfaces < 1 year (new)	Number of surfaces > 1 year
DAC/SMA 6	-	2
DAC8/SMA8	2	4
DAC11/SMA11	3	6
DAC16/SMA16	-	2

Since all of the tyres have been measured on the ISO surface at Kloosterzande in 2009, it is possible to compare the results. The ISO surface is a dense asphalt surface with 8 mm maximum aggregate size, and a comparison with the same type of surfaces has been done. In figure 4.59 the results for old (more than one year) DAC8/SMA8 surfaces are shown. The tyres are sorted according to their ISO level (measured, not truncated). On the ISO surfaces, there is a range of 5.1 dB between the quietest tyre (the Yokohama tyre) and the noisiest one (SRTT (L)). (R and L indicate position on the CPX trailer).

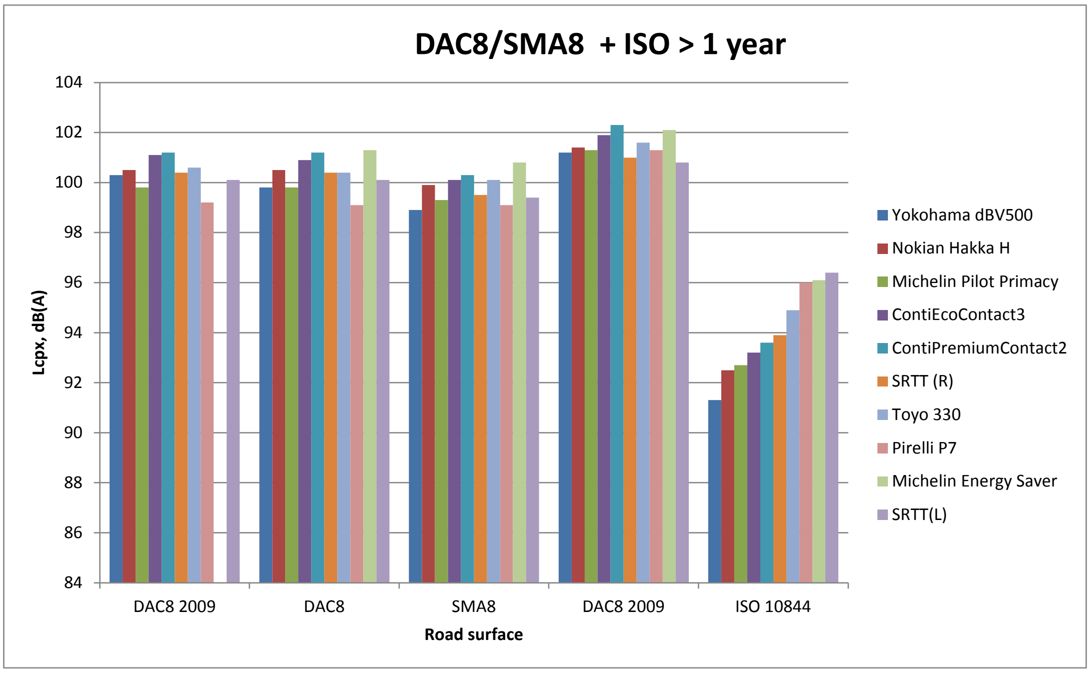


Figure 4.59 Measured CPX levels of 10 summer tyres for cars on DAC8/SMA8 surfaces > 1 year old. Speed: 80 km/h

It is obvious from this figure that the ranking of tyres on these types of surfaces differ quite considerably from the ranking on the ISO surface. The range of levels is also much less, about 1-2 dB, depending on surface. Figure 4.60 shows the lack of correlation between the ISO levels and one of the DAC8 surfaces.

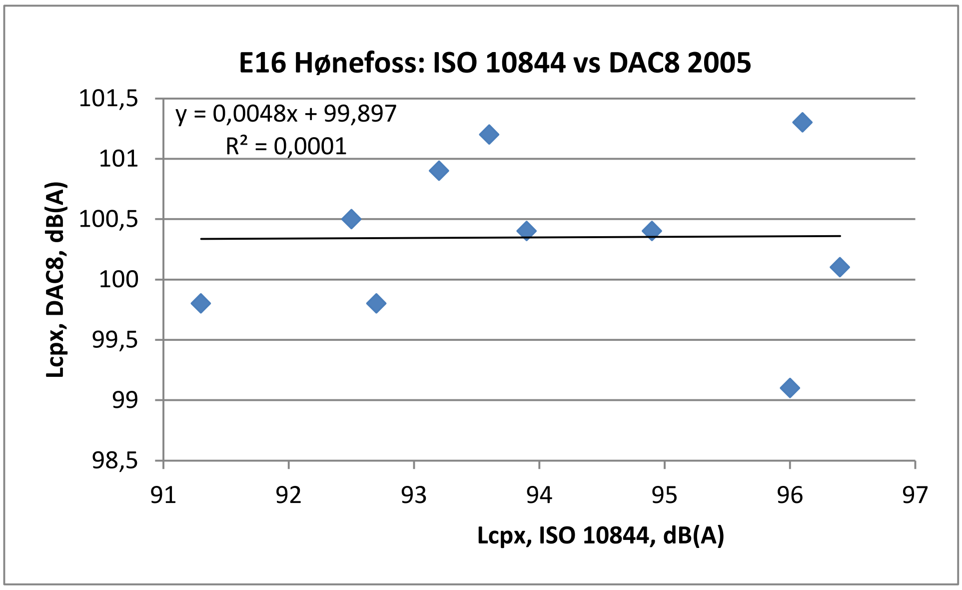


Figure 4.60 Linear regression analysis between measured levels on the ISO surface and on a DAC8 surface in Norway

Since we are aware of the important influence of the winter conditions, a similar comparison has been made with new road surfaces (DAC8/DAC11) and the results are shown in figure 4.61.

For some of the surfaces, there seems to be less lack of correlation, as shown in figure 4.62, where the regression analysis has been made for the DAC11 surface (third from the left in figure 4.61).

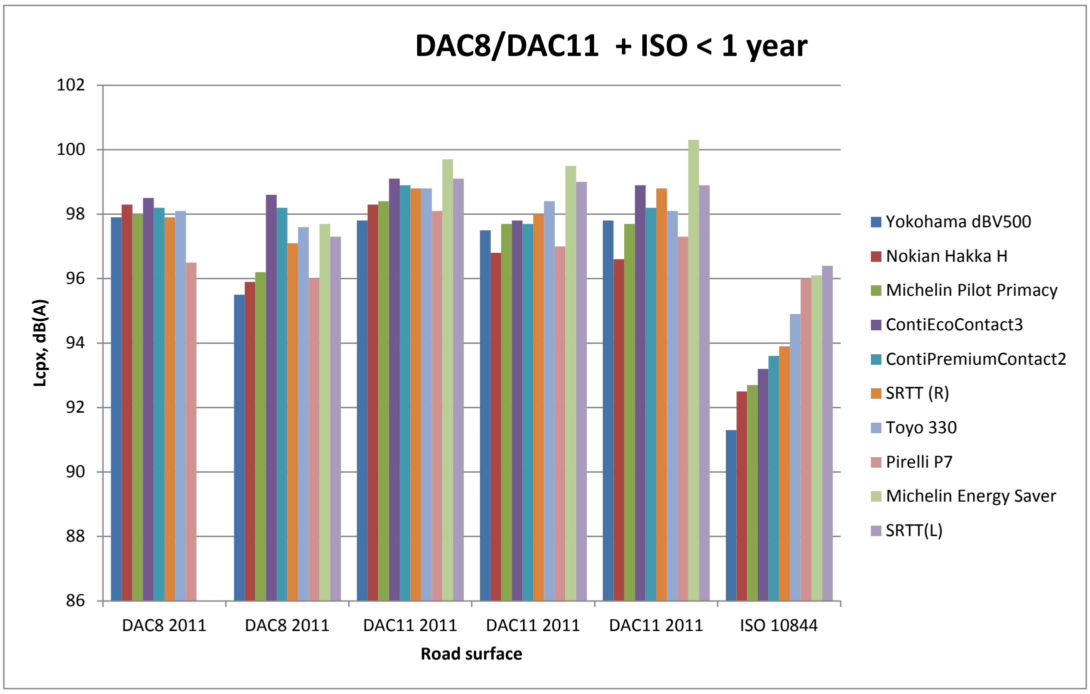


Figure 4.61 Measured CPX levels of 10 summer tyres for cars on DAC8/SMA8 surfaces > 1 year old. Speed: 80 km/h

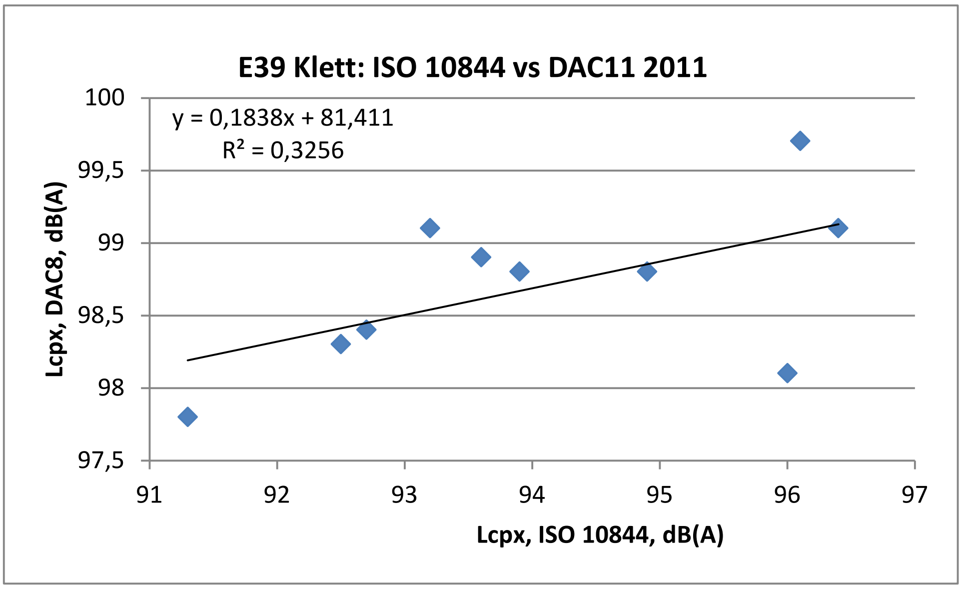


Figure 4.62 Linear regression analysis between measured levels on the ISO surface and on a new DAC11 surface in Norway

Measurements made by SINTEF on the Kloosterzande test track showed a very good correlation between the ISO surface and the SMA6 surface at this test location (R^2 = 0.98, see also figure 4.83). The measurements in Norway also included two surfaces with 6 mm, and the results are shown in figure 4.63, compared to the ISO levels.

It is clear that the ranking is very different from that on the ISO surface. See also chapter 5.4 for further analysis.

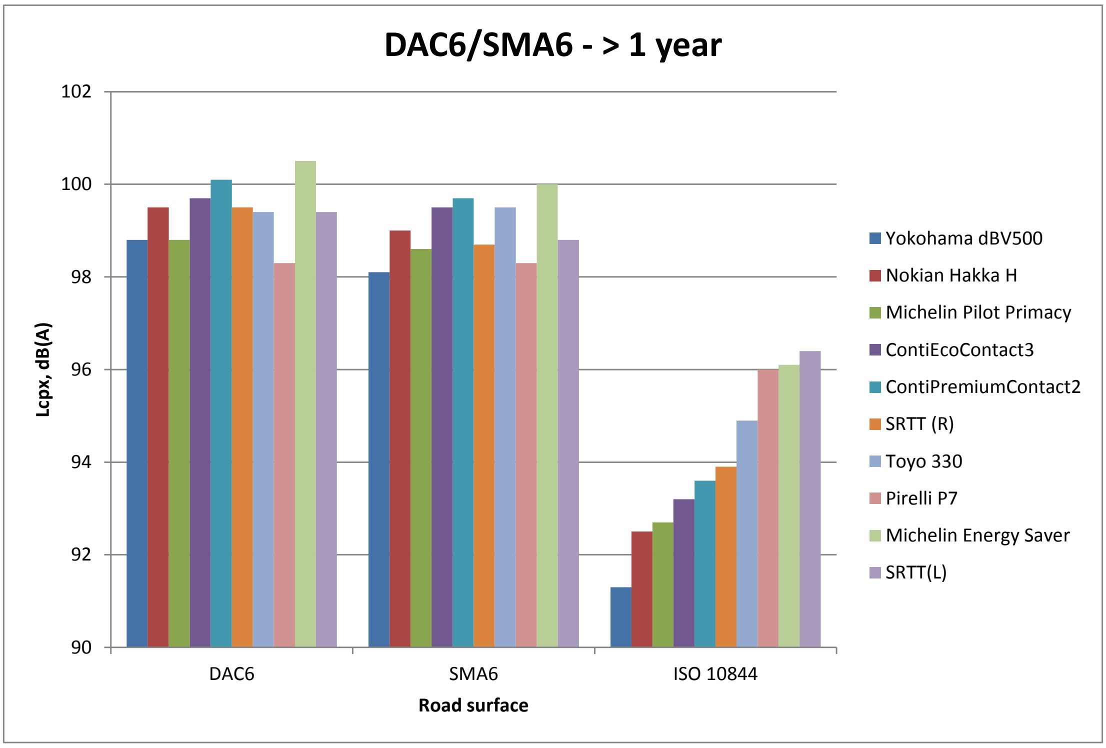


Figure 4.63 Measured CPX levels of 10 summer tyres for cars on DAC6/SMA6 surfaces + ISO > 1 year old. Speed: 80 km/h

The most commonly used surfaces in Norway are dense asphalt concrete surfaces with maximum 11 mm aggregate size or above (see chapter 12.1). In figure 4.64, the measured noise levels on the 6 DAC11/SMA11 surfaces of more than 1 year old are shown and compared to the ISO levels. Again, the ranking is different from the ISO surface. This is a clear indication that there is a lack of correlation between the ISO noise level of a tyre, and its actual noise performance on commonly used road surfaces in Norway (and presumably also in other Nordic countries, except perhaps Denmark). The range of noise levels is much smaller than on the ISO surface; in the order of 2 dB compared to 5 dB. The main reason for this is that on the more rough-textured surface, there is less noise difference between tyres, at least when tyres of the same main type (such as new car summer tyres) are compared.

According to table 4.10, the Shore A hardness of some of the tyres has changed quite much (4-5 units) between the measurements in 2009 and 2011. No "correction factor" due to this change has been applied to the results and this can obviously influence the comparison of these two studies.

In 2009, the Yokohama tyre was about 4 dB quieter on the ISO surface than the Pirelli P7 tyre. In the 2011 study, on the Norwegian road surfaces, we do not find such differences. On some surfaces, the Pirelli tyre is even quieter than the Yokohama. However, according to the hardness values from 2011 in table 4.10, there is now a difference of 10 units between the two tyres, which may explain some of this, even if the difference was of the same magnitude in 2009. The reason for this is that many of the measurements in 2011 were made at a temperature around +5 -10 °C, which may be more severe for a tyre with a harder rubber material, concerning the increase in noise levels at lower temperatures. Note that during these measurements, the Yokohama tyre is the oldest tyre, already 7 years old.

Air temperature during the measurements in 2009 was +19 °C.

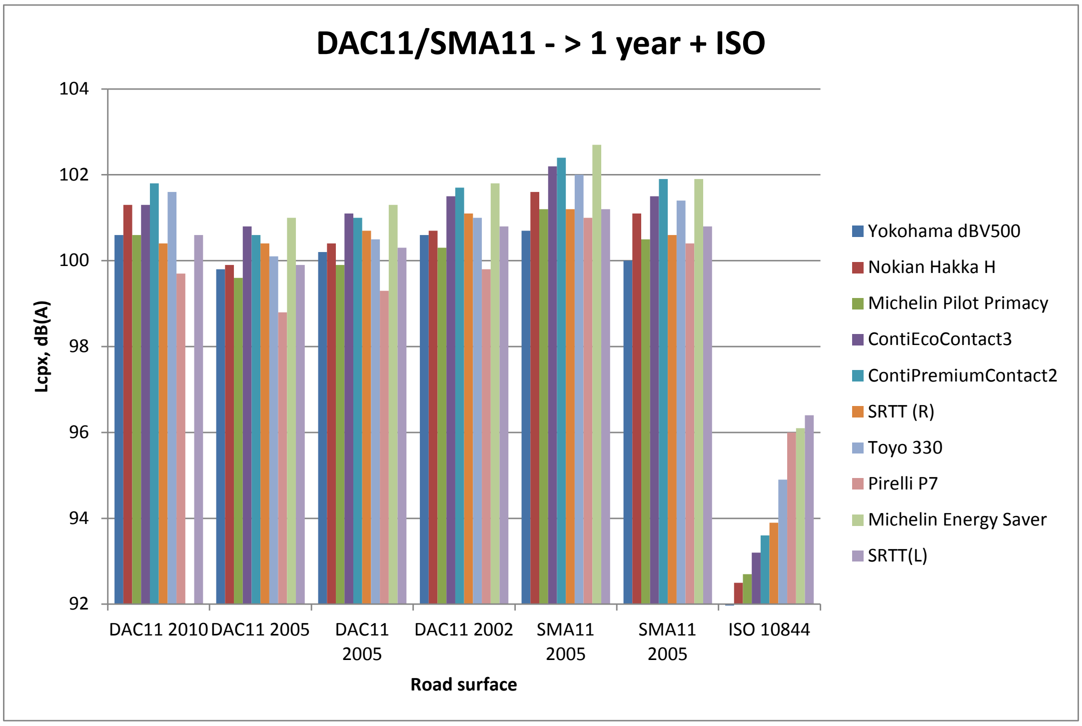


Figure 4.64 Measured CPX levels of 10 summer tyres for cars on DAC11/SMA11 surfaces > 1 year old. Speed: 80 km/h

General remark:
All these results are based on a small number of tyres, of different age (3-7 years old), and perhaps only one tyre that can be classified as a low noise tyre (Yokohama). In addition, some of the measurements were made at temperatures in the range of + 5 to +10 °C. These conditions can certainly influence the results, and the comparison with the ISO results. A further investigation, with new tyres and at temperatures closer to the reference temperature (20 °C) is recommended.

At one location outside Oslo, E18 Mastemyr, 5 different SMA surfaces were laid down as part of the project "Environmentally friendly roads" run by the Norwegian Public Roads Administration (2005-2008). The surfaces have maximum aggregate sizes from 6 to 16 mm. The measurement results are shown in figure 4.65, with the ISO levels included. For all the tested tyres, the correlation between maximum aggregate size and noise level is very high. It is interesting to see that the difference between the highest and the lowest noise levels (excluding the ISO surface) is 5.2 dB, where the highest noise level was obtained with the Michelin Energy Saver on the SMA16 and the lowest noise level was obtained with the Yokohama tyre on the SMA6. This is a good indication of the potential noise reduction of a combination of a smooth (and non-porous) road surface and a low noise tyre, compared to the use of 16 mm surfaces and tyres close to the noise limit for such tyres.

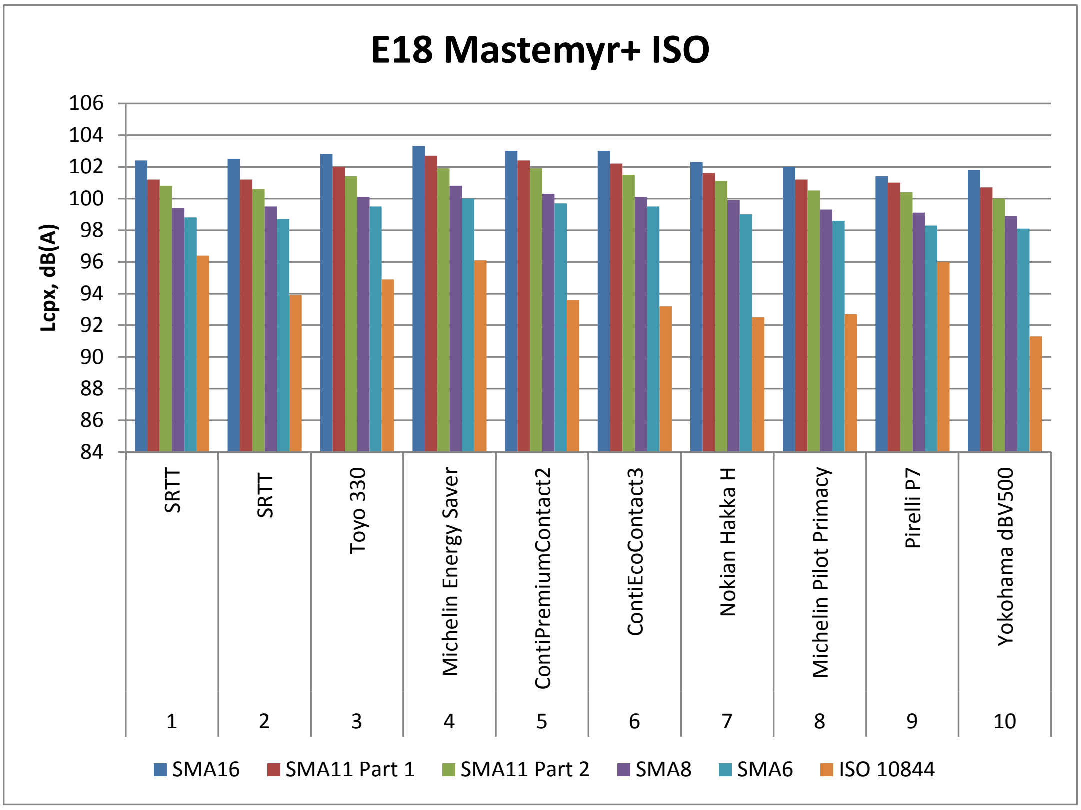


Figure 4.65 Measured noise levels (CPX) on 5 different SMA road surfaces at E18 Mastemyr and on the ISO surface at Kloosterzande. Speed: 80 km/h

4.3.5 Measurements in the Netherlands, 2007

As part of the selection of new reference test tyres for the CPX standard, M+P conducted a series of CPX measurements on 22 trafficked roads in the Netherlands [Schwanen, van Blokland, van Leeuwen, 2008]. The results for 5 different tyres are shown in figure 4.66.

Figure 4.66 CPX-measurements with 5 different car tyres on 22 different road surfaces in the Netherlands. Speed 80 km/h. [Schwanen, van Blokland, van Leeuwen, 2008]

From these results, it seems like the smooth two layered PAC and the thin layered asphalt are those who separate the different tyres best, with regards to sound levels. The noise ranking of the tyres on these surfaces is also almost the same.

4.3.6 Measurements in Sweden, 2007

SP Technical Research Institute of Sweden made a special study regarding sound levels of market tyres of various types [Jonasson, 2007]. In a report by Sandberg [Sandberg, 2008], the most important results have been processed. The measurements have been made with complete sets of tyres mounted on vehicles and measured on different road surfaces, including the ISO surface at Volvo Torslanda for C1 tyres and at the ISO surface at Volvo Hällered for C2 and C3 tyres.
Figure 4.67 show the results for 22 C1 tyres on the ISO surface and on an 8 year-old SMA11 surface. No truncation of levels has been made. The results for 20 C2 and 9 C3 tyres are shown in figures 4.68 and 4.69. The ISO levels for C2 and C3 tyres are compared with levels measured on a 7 year-old DAC16 surface.

The values are the measured values and have not been truncated. All data have been temperature corrected.
In the figures, Sandberg has indicated which tyres will meet the new limit (green colours), tyres that are less than 1 dB above the limit (blue) and more than 1 dB above the limit (red). Since the ISO values are sorted according to sound level, it seems that there is a somewhat better correlation of the ranking of C1 tyres than found in the results on the Norwegian pavements. However, for the C2 and C3 tyres, this correlation seems very weak. The range of sound levels for C1 tyres on the

SMA16 pavement seems also somewhat larger than measured in Norway. This could be due to the tyre samples included in the study (tyre size, age, etc.).

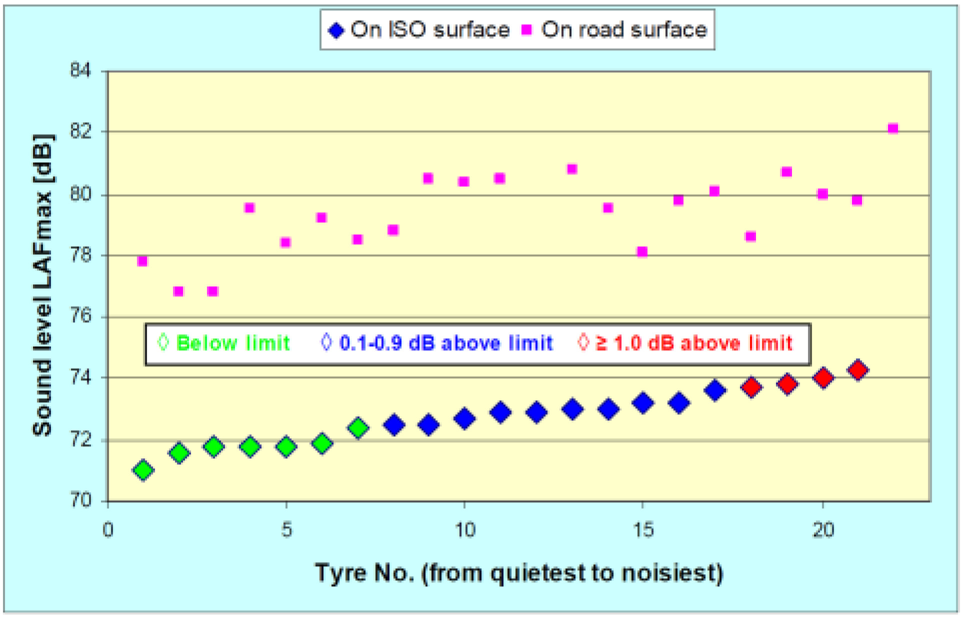


Figure 4.67 Average sound levels from 22 different C1 tyres. Data processed by Sandberg Speed: 80 km/h. No truncation of data. [Sandberg, 2008]

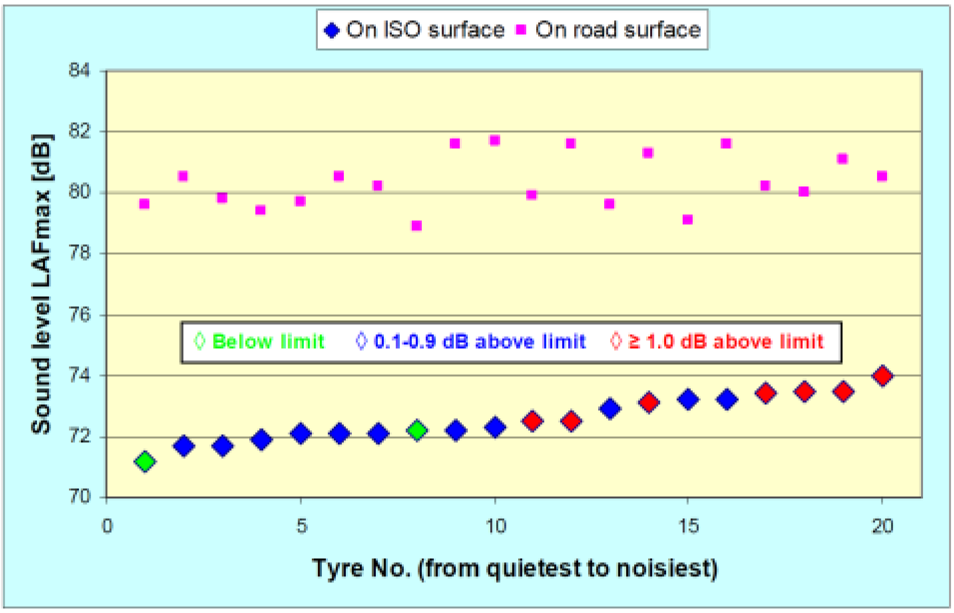


Figure 4.68 Average sound levels from 20 different C2 tyres. Data processed by [Sandberg. Speed: 80 km/h. No truncation of data. [Sandberg, 2008]

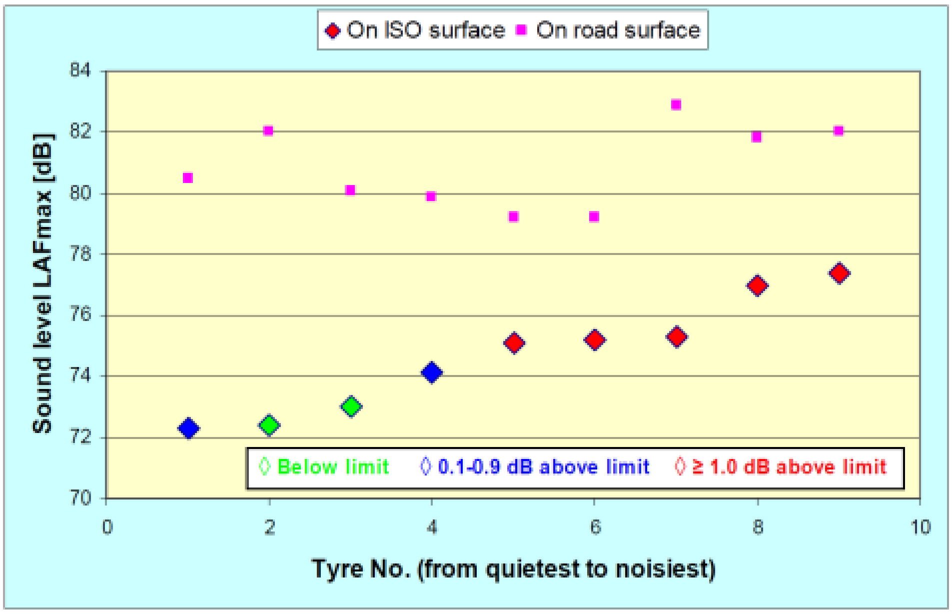


Figure 4.69 Average sound levels from 9diferent C3 tyres. Data processed by Sandberg. Speed: 70 km/h. No truncation of data. [Sandberg, 2008]

4.3.7 Measurements in Finland

In Finland, previously most of the reported measurements (modified CPX method) have been with slick tyres [Raitanen, 2006]. Direct comparison with results from the other Nordic countries is therefore not too relevant. However, a fairly good correlation between the modified CPX results and SPB measurements were found for light vehicles. Some of the pavements were measured over a 3 year period and an increase in the CPX levels of 3-8 dB was found for already after one year of construction.

In some newer investigations [Sainio, 2010], where the temperature influence on CPX measurements has been investigated, SRTT tyres are used, together with slicks. Table 4.12 presents results that can be compared with measurements in the other Nordic countries.

Table 4.12 CPX measurements in Finland at the speed of 50 km/h [Sainio, 2010]

	SRTT	std	E524 slick	std
SMA8	92,6	0,31	91,2	0,42
SMA11	93,4	0,18	92,1	0,39
Hiltti	91,7	0,58	90,3	1,21
Whisperfalt	91,9	0,28	90,4	0,66

A noise level of 93.4 dB(A) on the SMA11 surface indicates levels comparable to measured levels on Swedish pavements (see figure 4.70).

The reference pavement type in Finland is SMA16.

4.3.8 Norwegian road surfaces compared to Swedish surfaces.

In 2005, SINTEF did measurements with the Norwegian CPX trailer on dense surfaces (SMA and DAC, 11-16 mm) in both Sweden and Norway [Berge, 2006; Sandberg, 2007], using the Avon ZV1 tyre ("old" Tyre A in ISO/CD 11819-2: 2000). The Swedish pavements were 3-4 years old, and the Norwegian 1-14 years old.

The results at the two speeds 50 and 80 km/h are shown in figures 4.70 and 4.71.

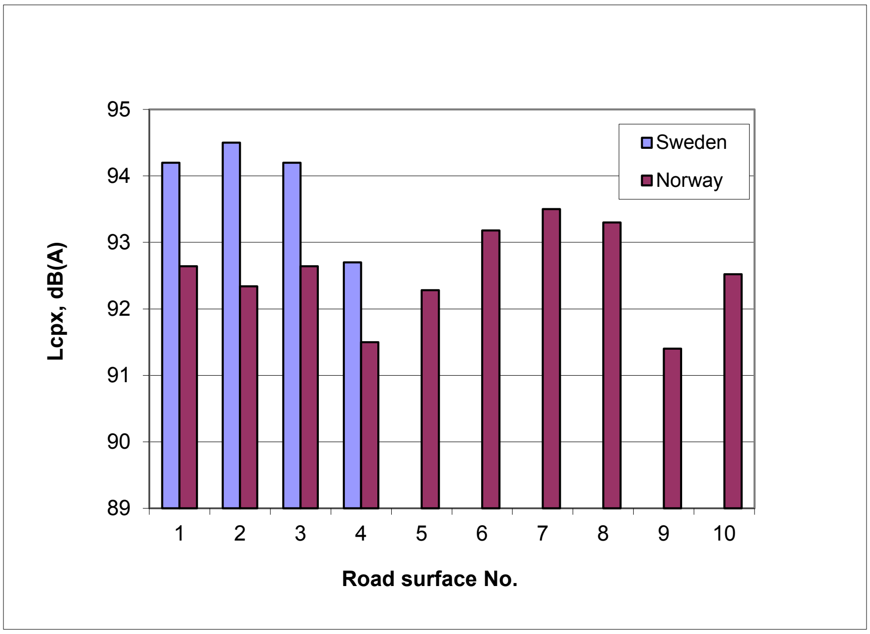


Figure 4.70 Comparison of CPX measurement results on dense Swedish and Norwegian pavements. Speed: 50 km/h [Berge, 2006; Sandberg, 2007]

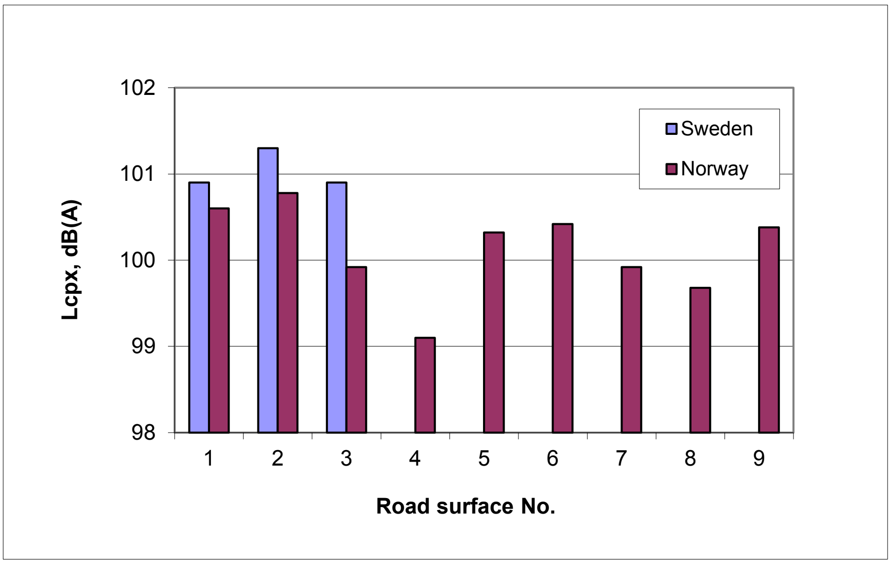


Figure 4.71 Comparison of CPX measurement results on dense Swedish and Norwegian pavements. Speed: 80 km/h [Berge, 2006: Sandberg, 2007]

These results indicate that Swedish pavements may give in the order of 1-2 dB *higher* tyre/road noise levels than the Norwegian. This is probably caused by a significantly higher number of vehicles with studded tyres in Sweden than in Norway. In the main cities of Norway, the percentage of cars with studded tyres is in the range of 15-30 %, while it is 70-80 % in Sweden (middle regions).

The reference surface in Sweden is SMA16.

4.4 Measurement of tyres on test track pavements

To our knowledge, there are only a limited number of studies available where different tyres have been tested on different pavement types on a test track. The main studies are summarised below.

4.4.1 Sperenberg, Germany

One major survey is the Sperenberg measurement campaign [Beckenbauer et al., 2001]. In total, 16 car tyres and four truck tyres were measured on 42 different road sections on a test track in Germany. The main objective for this survey, was to study the influence of different road surface characteristics (absorption, texture, etc.) on the generation mechanisms for tyre/road noise, and not necessarily for ranking tyres compared to the ISO track (one of the road surfaces included at Sperenberg). The development of the SPERoN model is very much based on measurement results from Sperenberg.

In figure 4.72, the results from the measurements of 12 of the passenger car tyres are shown. Note that this is coast-by results at 7.5 m.

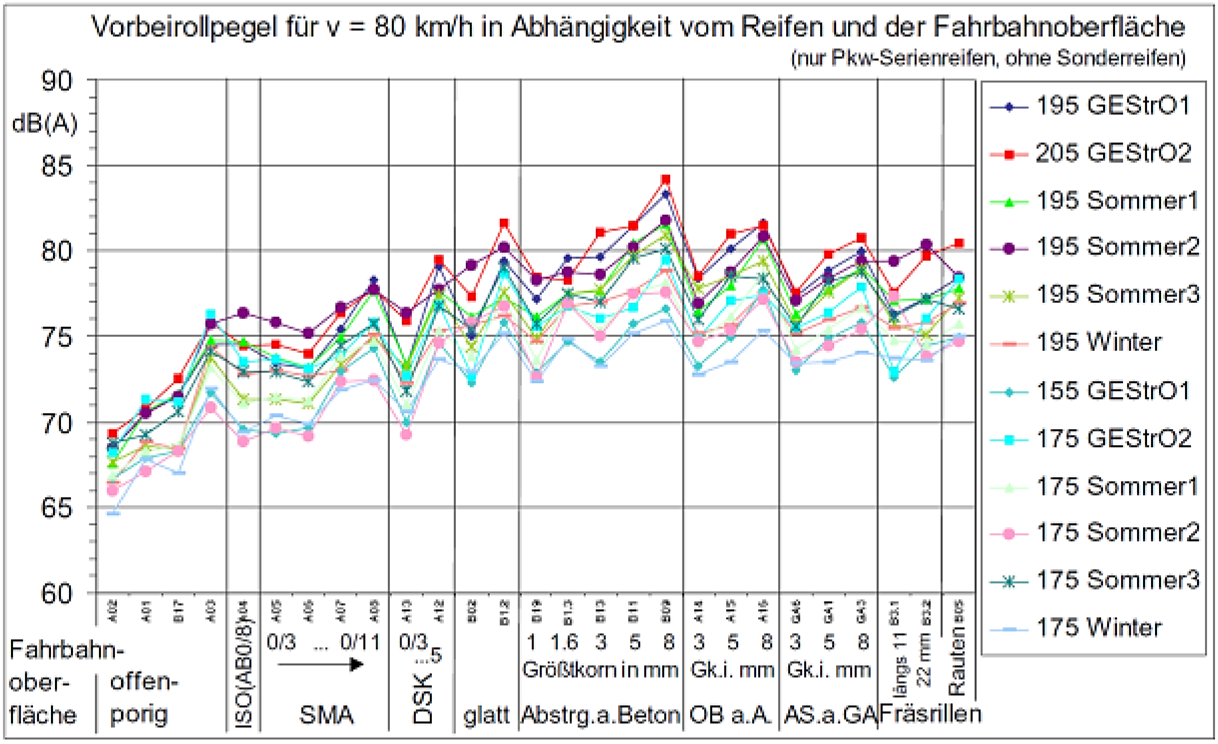


Figure 4.72 Coast-by sound levels for 12 car tyres, measured at Sperenberg. Speed: 80 km/h

The range of noise levels are about the same, 5-7 dB for the results on the ISO surface and on the SMA surfaces, and also the difference in level between the ISO and SMA11 is much smaller than found on the Norwegian and Swedish SMA pavements. The winter tyre (175 mm) seems to be the quietest tyre on most of the surfaces.

In figure 4.73, the noise levels from 3 truck tyres are shown on various road surfaces at Sperenberg [Silvia WP5, 2004].

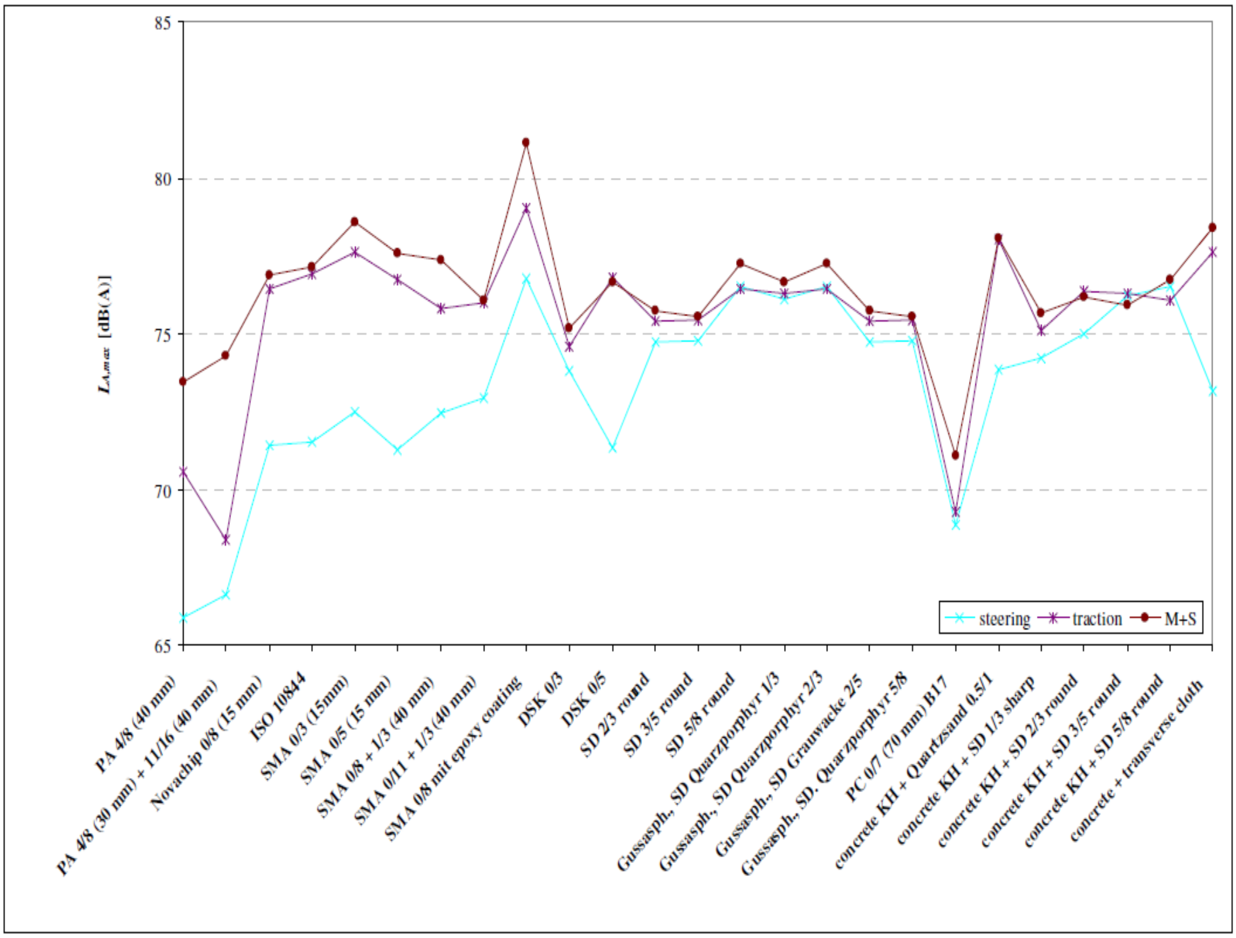


Figure 4.73 Tyre *noise levels of 3 truck tyres (Steering (blue), Traction (lilac) and Mud+Snow Profile (red)). [SILVIA, 2004]*

For truck tyres, the influence of the type of road surface is less clear than for passenger car tyres. Still, there is a difference of 4-7 dB going from the porous surfaces (far left in the figure) to the SMA surfaces (more than 10 dB difference for the extreme case, SMA with epoxy coating).

4.4.2 M+P measurements at Kloosterzande, 2007 and 2009

M+P has measured tyres at the Kloosterzande test area, with different types of tyres, both in 2007 and 2009.
In 2007, the measurements were part of the AOT project (Acoustical Optimization Tool) [Schwanen et al., 2007].
A total of 13 passenger car tyres were tested at speeds from 40 to 120 km/h using a special designed trailer with 22 microphones positions (including CPX positions). The tyre samples included a slick tyre and two winter tyres as well as the old CPX reference tyres A (Avon ZV1) and tyre D (Dunlop Artic SP). The report tables all the CPX results at 70 km/h. Excluding the slick tyre and tyre D (the "extreme" tyres), all levels on the ISO surface are within 2-3 dB of each other.

The study includes 7 truck tyres (slick, drive-, steering and trailer axle tyres), also measured with a special designed trailer. Speeds varied from 40 to 90 km/h. If the slick tyre is excluded, the variation between noise levels on the ISO surface is nearly 7 dB.

In figures 4.74 to 4.79, this author has made a linear regression analysis between the noise levels from the truck tyres measured on the ISO surface and on the thin layer (S2) and dense surfaces (S19-S23). The slick tyre is not included in the analysis.

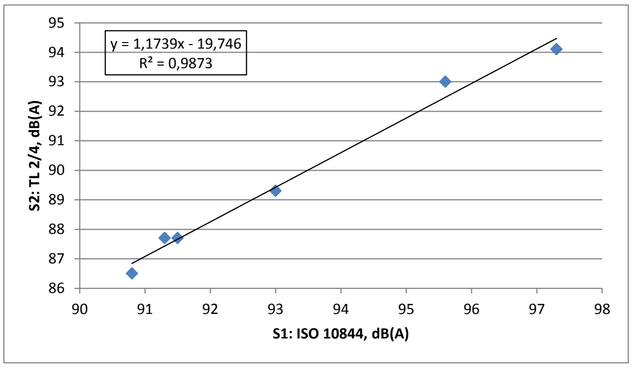


Figure 4.74 Truck tyres, linear regression S1 (ISO) and S2 (TL 2/4)

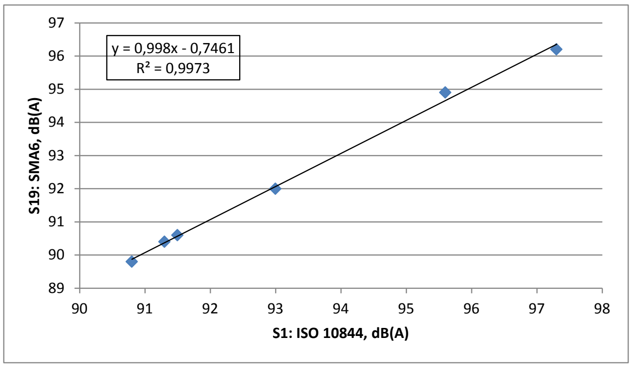


Figure 4.75 Truck tyres, linear regression S1 (ISO) and S19 (SMA6)

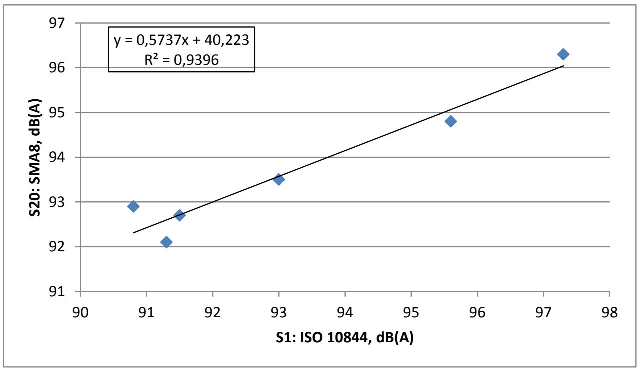


Figure 4.76 Truck tyres, linear regression S1 (ISO) and S20 (SMA8)

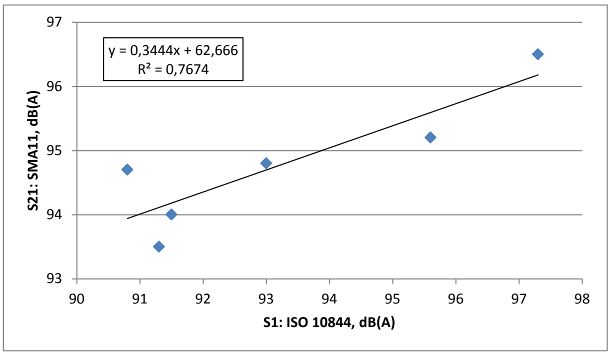


Figure 4.77 Truck tyres, linear regression S1 (ISO) and S21 (SMA11)

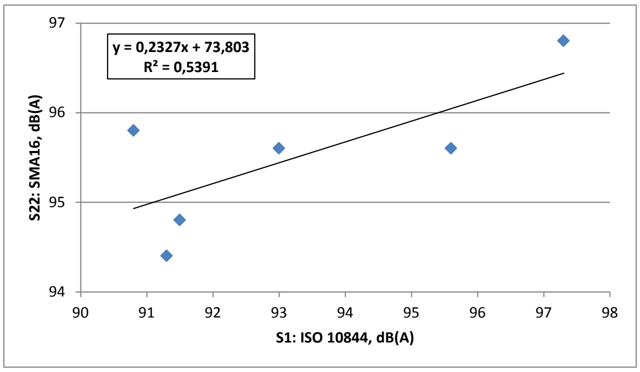


Figure 4.78 Truck tyres, linear regression S1 (ISO) and S22 (SMA16)

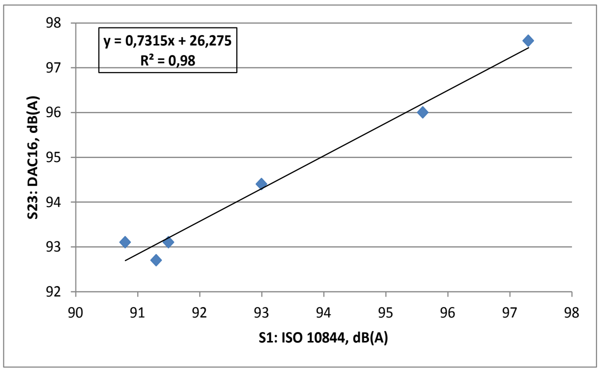


Figure 4.79 Truck tyres, linear regression S1 (ISO) and S23 (DAC16)

This analysis shows the same trend as for the passenger car tyres. The best correlation (and ranking) seems to be between the ISO surface and layers with maximum chipping size of 4-6 mm. However, the correlation is better for the DAC16 (S23), than for the SMA16 (S22).

The levels on all the other surfaces are found in the report [Schwanen et al., 2007].

In 2009, M+P did measurements with 10 passenger car tyres on the test sections at Kloosterzande [van Blokland et al., 2009a]. The tyres are listed in table 4.4, together with the SINTEF tyres also tested at this location in 2009. The results on the ISO surface are found in figure 4.26.
Of special interest is the noise variation on the SMA surfaces, and these are shown in figure 4.80.

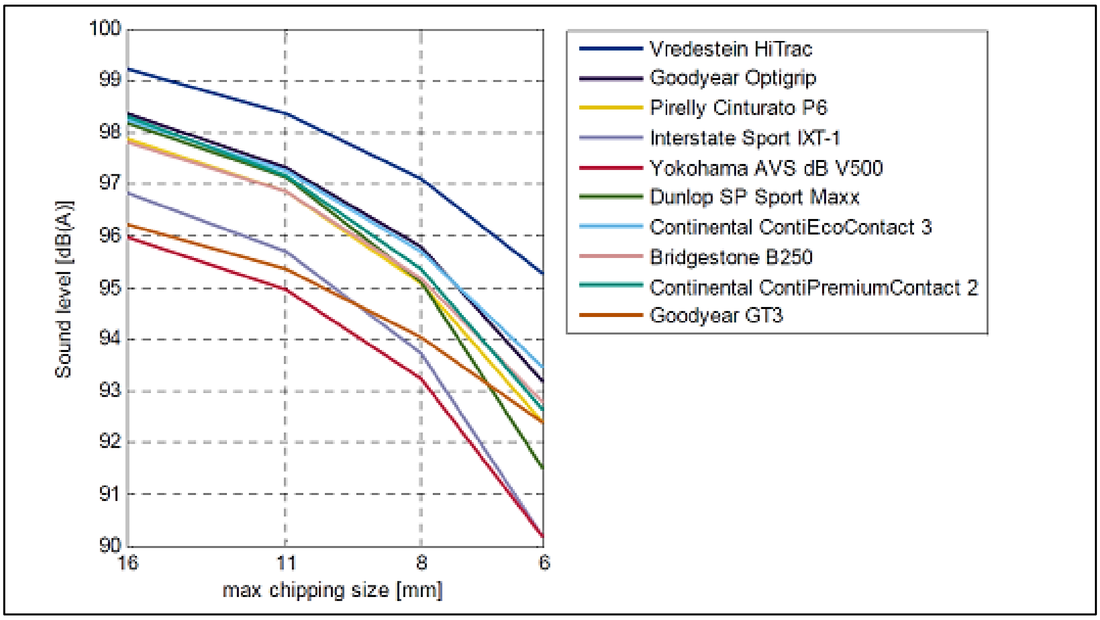


Figure 4.80 CPX measurements of 10 passenger car tyres on 4 SMA surfaces with different maximum chipping sizes. Speed: 80 km/h. [van Blokland et al., 2009a]

Except for one tyre on the 6 mm surface ((Goodyear GT3), the noise ranking is more or less the same on all the surfaces. As shown in the SINTEF study [Berge, 2011], the correlation with the ISO surface is best for the SMA6 surface (R^2 = 0.99), but fairly good also for the other SMA surfaces (R^2 variation between 0.7 and 0.9). See also figures 4.82 and 4.83.
The spread in levels on the SMA6 is approximately 5 dB, the same as found on the ISO surface.

4.4.3 Measurements by SINTEF, 2009

As described in chapter 4.2.4, SINTEF measured 22 tyres on 23 of the road sections at Kloosterzande in 2009.

The complete analysis can be found in [Berge, Haukland, Storeheier, 2011]. A summary of the results for 8 of the tyres included in the measurements on Norwegian roads (see table 4.10) is presented in figure 4.81.

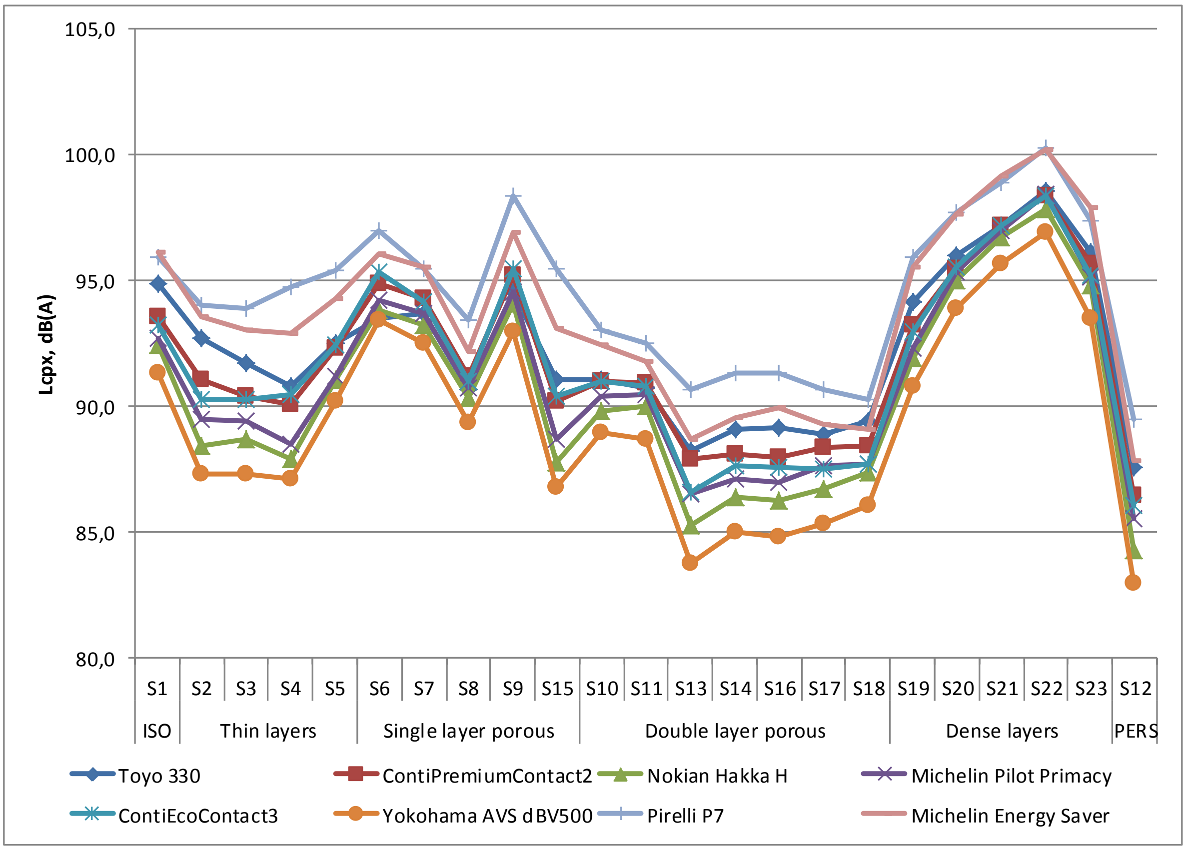


Figure 4.81 Measured CPX levels of 8 passenger car tyres on 23 road sections at Kloosterzande. Speed: 80 km/h. [Berge, Haukland, Storeheier, 2011]

Between the noise levels of the 25 tyres (SINTEF and M+P tyres) measured on the ISO surface and the 22 other surfaces a linear regression has been made, as shown in figure 4.82. The best correlation was found for the thin layer 2/4 (S2) and the SMA6 (S19), figures 4.82 and 4.83.

A complete list of the 23 road sections can be found in table 5.2 (p.84).

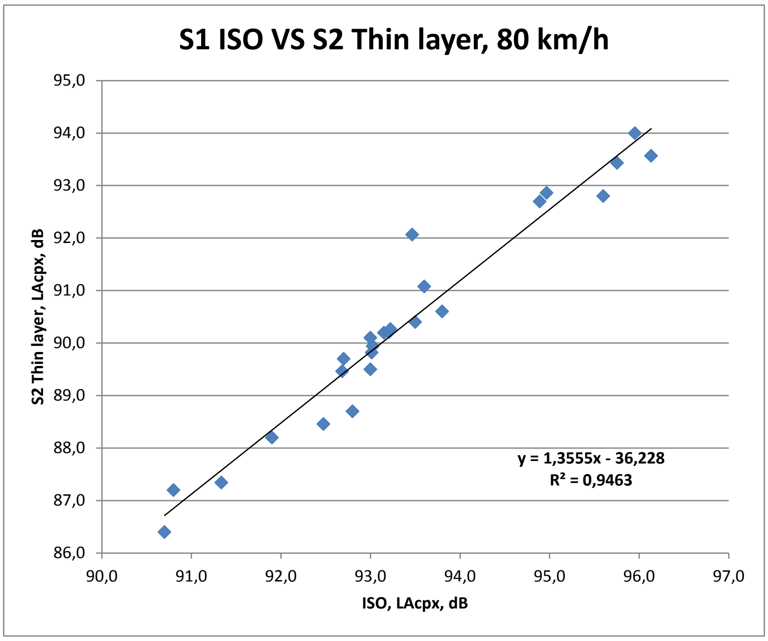


Figure 4.82 Linear regression of passenger car tyres, ISO (S1) and Thin layer 2/4 (S2)

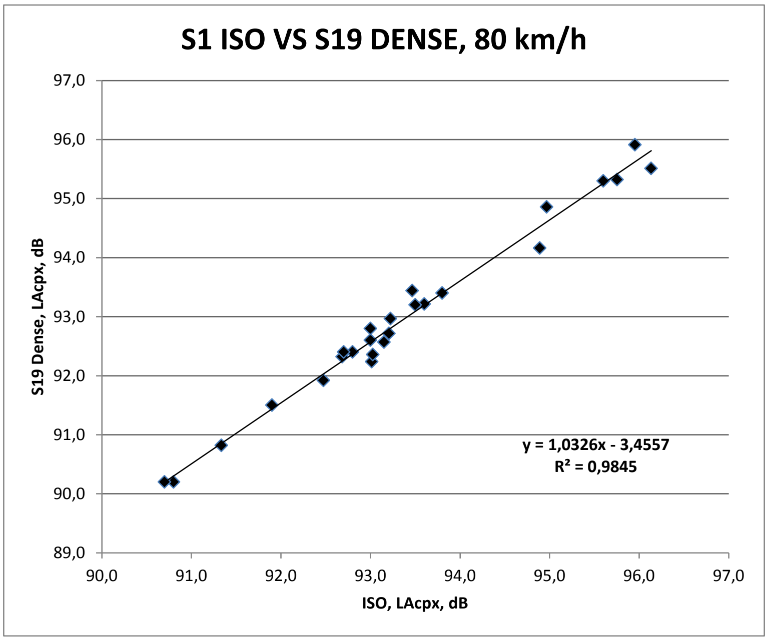


Figure 4.83 Linear regression of passenger car tyres, ISO (S1) and SMA6 (S19)

In chapter 5.3, the slopes and correlation coefficients from the linear regression analysis of the relationship between ISO levels and levels on the 22 other road sections are presented.

4.4.4 Measurements in the UK by TRL, 2004

In a project by Transport Research Laboratory (TRL), 23 passenger car tyres were measured on 7 different pavements [Watts et al., 2004]. The tyre width range was from 145 to 235 mm, with aspect ratios between 45 and 80. The measurements were carried out, using the TRITON tyre/road noise vehicle (CPX measurements).

The results of the regression analysis of the levels on the ISO surface and one of the pavements, the "Hot Rolled Asphalt" (HRA), are shown in figure 4.84. The HRA is one of the most common surfaces in the UK. Maximum chipping size is 14 mm.

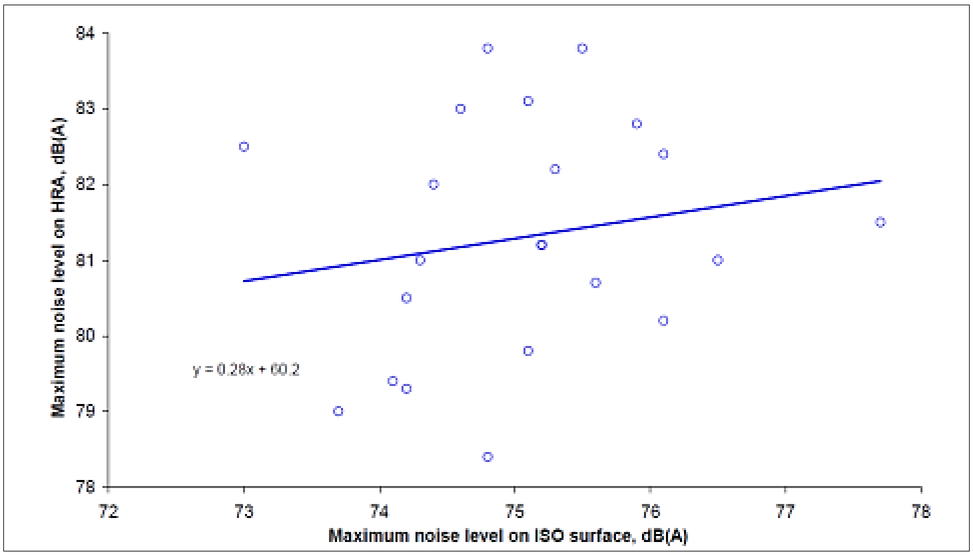


Figure 4.84 Regression analysis between A-weighted noise levels on ISO and HRA [Watts et al., 2004]

The correlation coefficient (r) was found to be 0.19 and not statistically significant. Also, the correlation with a SMA14 was found to be very weak, with a correlation coefficient of 0.32 and not statistically significant.
These results, especially for HRA and SMA, are very similar to what we found on typical Norwegian road surfaces.
If HRA still is widely used in the UK, they could face similar challenges with the new noise labelling system for tyres in 2012 as in Norway/Sweden.

4.4.5 Measurements of truck tyres in Germany

In the project Silent Traffic in Germany (Leiser Strassenverkehr, (http://www.fv-leiserverkehr.de/index.html)) some investigations have been made of the performance of truck tyres on ISO surface and other types of pavement.

In figure 4.85, the noise levels of 9 truck tyres are presented (including front axle (slick) tyres (Rfn 1 and 2) and rear axles (Rfn3-9)). They are measured according to ECE R117 on the Contidrom ISO track. If the two slick tyres are excluded, there is a variation in levels of about 5 dB [Schmidt, Leiser Strassenverkehr 2, 2010]

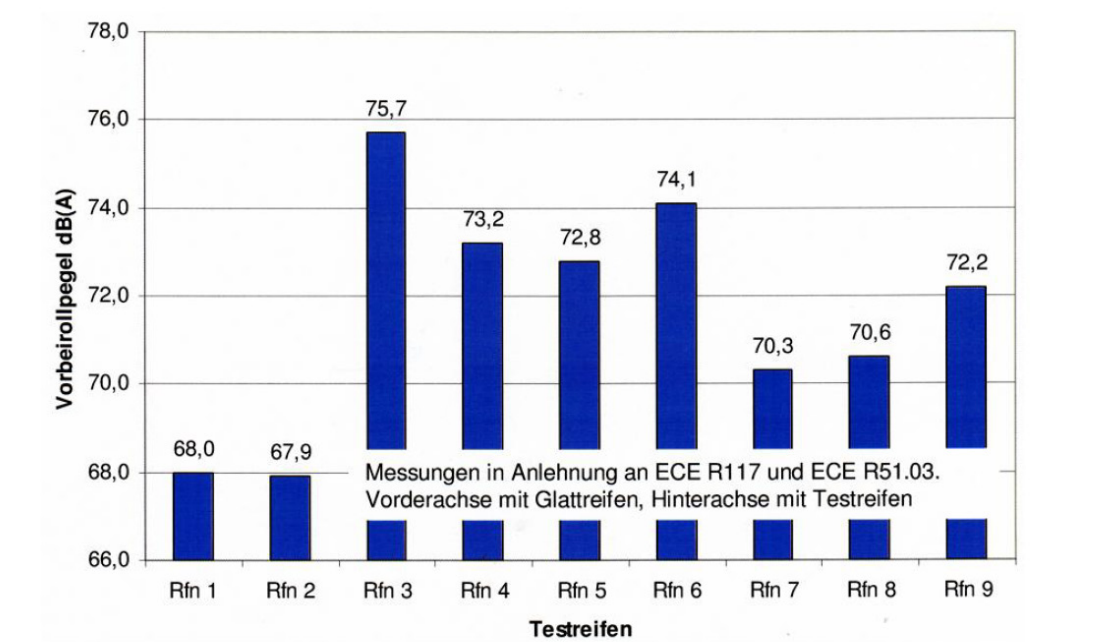


Figure 4.85 Truck tyres measured on an ISO track (Contidrom). Speed: 70 km/h No truncation of data. [Schmidt, 2010]

In figure 4.86, the measured ISO levels are compared to the levels measured on 4 surfaces on the Sperenberg test track; OPA (Open Porous Asphalt), AB (Asphalt Concrete), SMA and GA (Gussasphalt). Even if one again excludes the two slicks, there is a range of more than 10 dB in the combination of the best and worst combination of tyre and road (best: tyre 7 on OPA, worst: tyre 3 (block tyre) on ISO). Note that the noise levels on the AB surface are lower than on the ISO surface. It could be that this is one of the AC surfaces with maximum stone size below 8 mm.

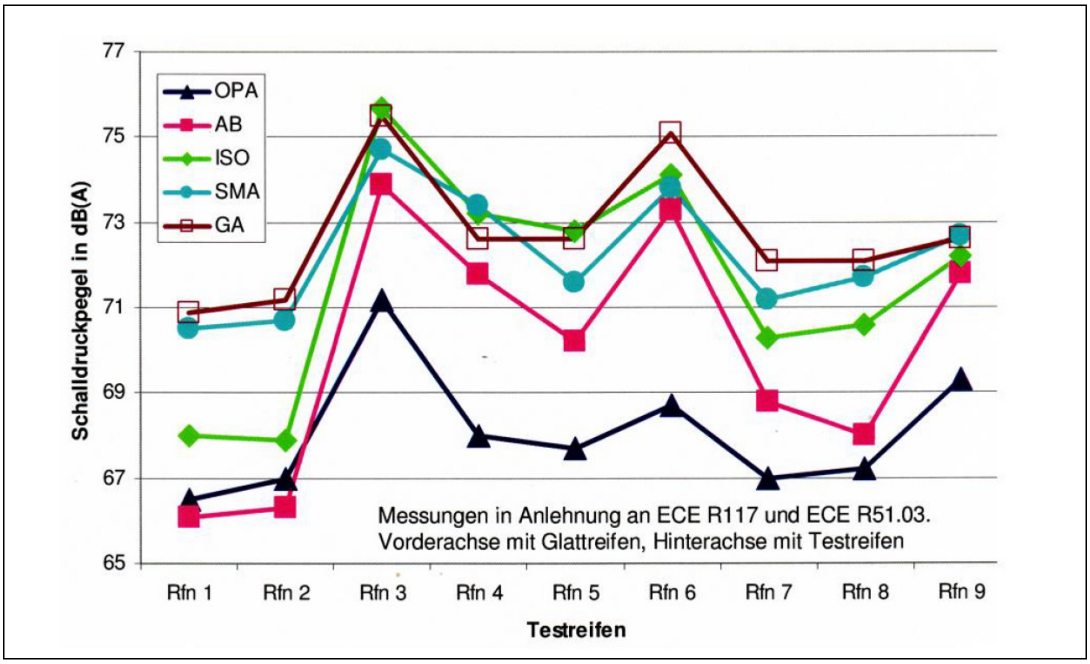


Figure 4.86 Nine truck tyres measured on ISO track and four other surfaces. Speed: 70 km/h. [Schmidt, 2010]

In figure 4.87, a ranking analysis is shown for the 9 tyres on the different road surfaces.

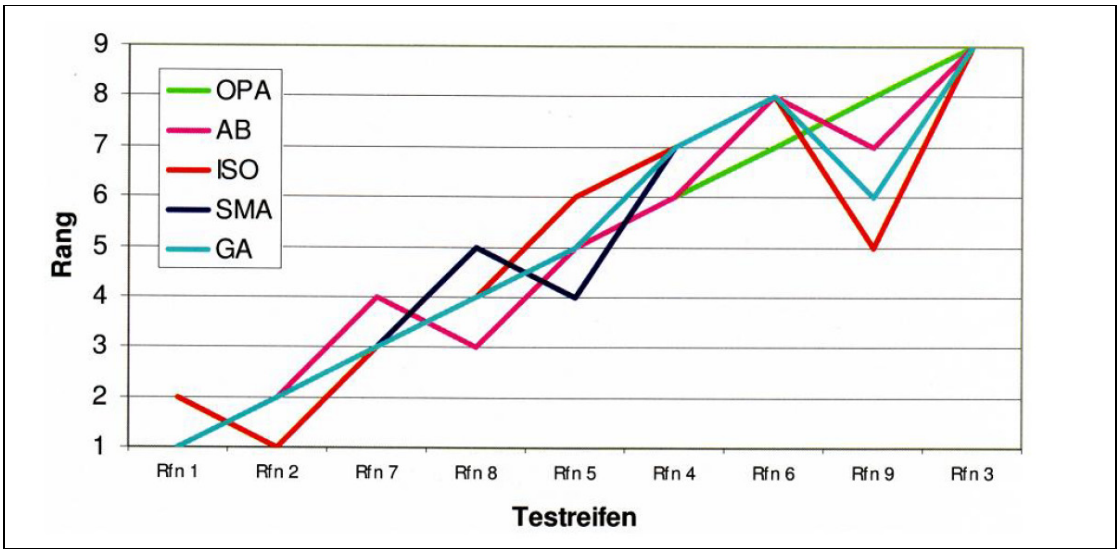
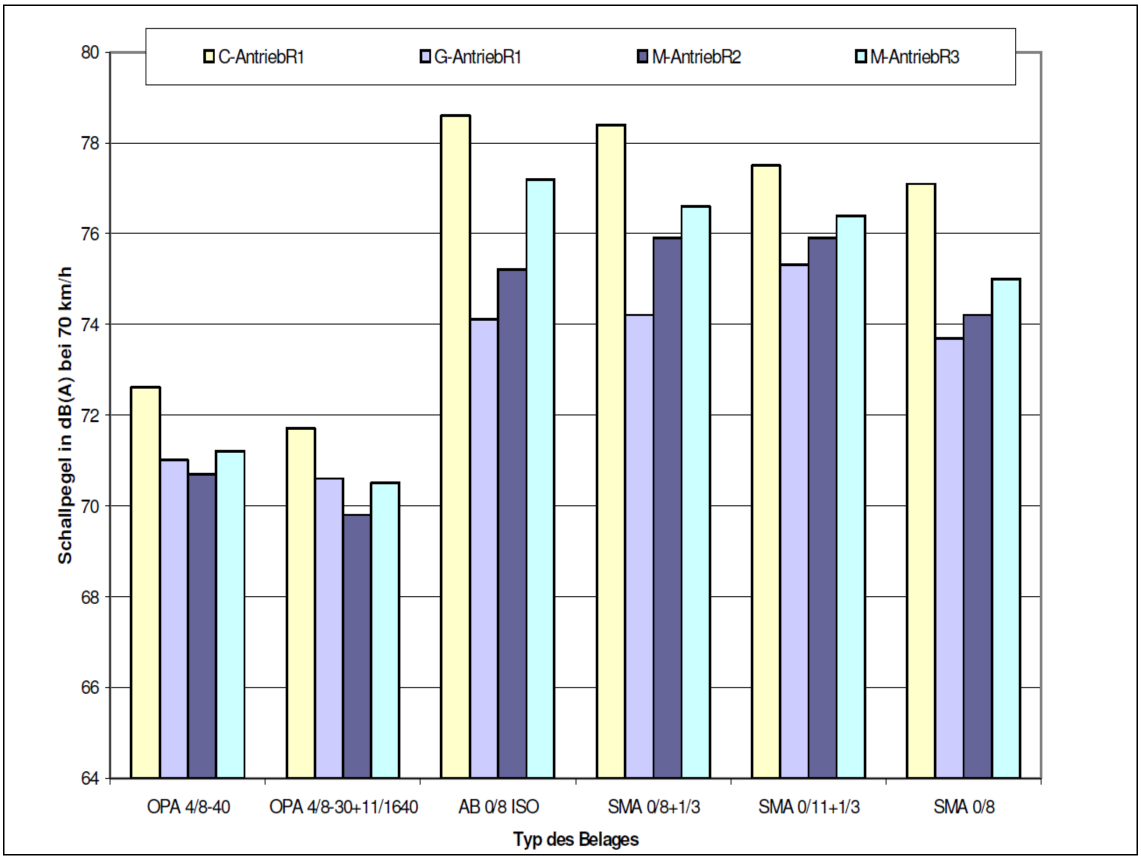


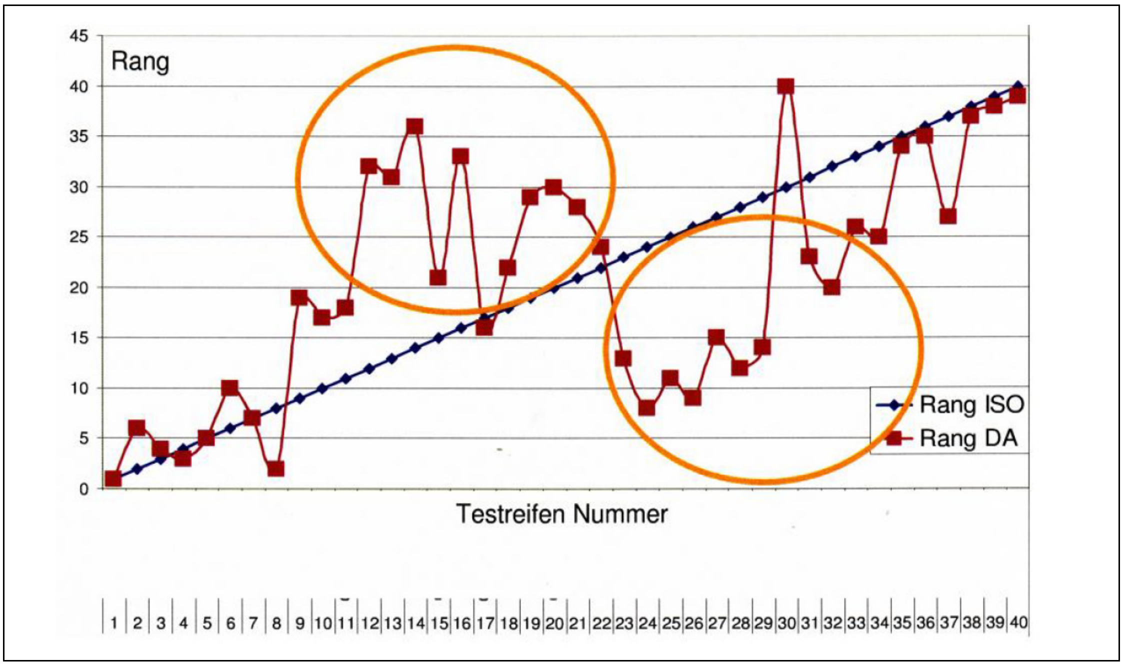
Figure 4.87 Ranking analysis between truck tyre noise levels on ISO and 4 other surfaces. [Schmidt, 2010]

Except for tyre Rfn 9 (on ISO and GA), the ranking on the ISO surface is more or less the same as on the other pavement types.
Another study of truck tyres within the Silent Traffic program, shows that the range of noise levels on the ISO surface can be 4.5 dB, while the range on an open porous surface is only 1.5 dB, see figure 4.88.
This figure is taken from the report from October 2010 [Schmidt, 2010], but is originally produced by M+P [de Graaff, Peeters, Peeters, 2004].



<u>Figure 4.88</u> Four truck tyres measured on ISO track and five other surfaces.
Speed: 70 km/h. [de Graaff, Peeters, Peeters, 2004]

In figure 4.89, a ranking analysis has been made between the levels on the ISO surface (Sperenberg?) and a porous surface (DA= drainage asphalt) for 40 truck tyres. This investigation is from Leiser Strassenverkehr 1 [Schmidt, 2010].



<u>Figure 4.89</u> Ranking analysis of 40 truck tyres measured on an ISO track and on a porous surface (DA).[From Leiser Strasseverkehr 1, Schmidt, 2010]

These results confirm that also for the truck tyres, the ISO surface may not be relevant for the noise behaviour of such tyres on surfaces normally used. However, more investigations are needed on this topic.

4.5 Laboratory measurements

Tyre noise properties are also measured in laboratories on a drum. Examples of laboratories with such facilities are The Federal Highway Institute (BASt), Germany (figure 4.90) , The Technical University of Gdansk (TUG) in Poland (figure 4.91) and Purdue University, USA (figure 4.92) (Photos from SILENCE, 2006).

<u>Figure 4.90</u> The drum facilities at BASt, called PFF (Prüfstand Fahrzeug-Fahrbahn)

Figure 4.91 TUG drum

Figure 4.92 The Tire-Pavement Test Apparatus at Purdue University

Many tyre manufacturers also have such facilities at their technical development centres. Laboratory measurements are well suited for study of tyre generation mechanism on different replica of road surfaces, under well controlled conditions. Since they can differ quite much from "real" road conditions, it can be difficult to compare results from a drum to outdoor road measurements.

Laboratory measurements can be useful to compare the noise levels from different types of tyres, as shown in figure 4.93 [Sandberg, Ejsmont, 2002]. These are measurements of about 100 passenger car tyres done on the TUG drum in the period 1997-1999.

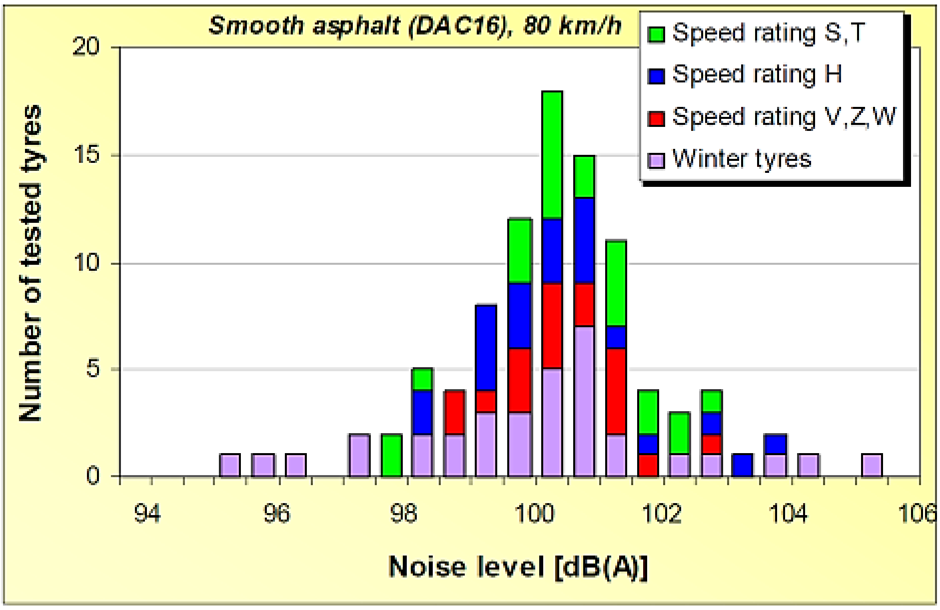


Figure 4.93 CPX results of TUG drum measurements of approximately 100 passenger car tyres on a DAC16 replica surface [Sandberg, Ejsmont, 2002]

As figure 4.93 shows, there seems to be no relationship between the noise level and the speed rating. This is confirmed by the analysis done by M+P [de Graaff, van Blokland, 2007], shown in figure 4.94.

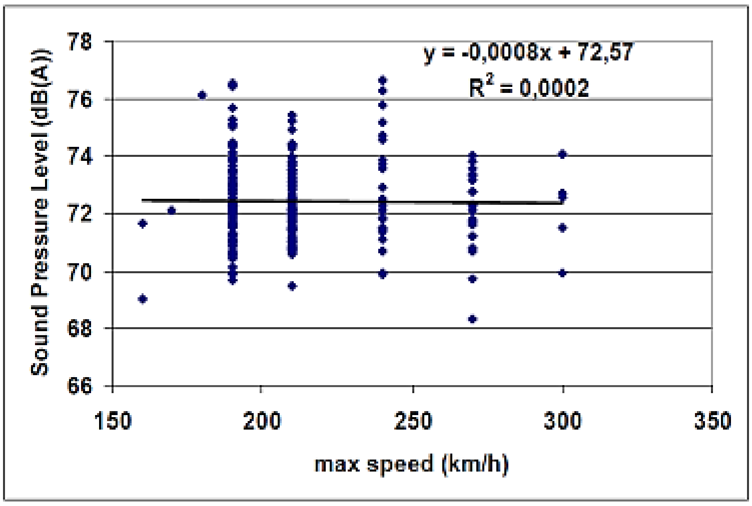


Figure 4.94 Noise levels of C1 tyres as a function of speed index [de Graaff, van Blokland, 2007]

In a SINTEF project [Berge, Haukland, Ustad, 2009b] 15 passenger car tyres were measured on different road surfaces in Norway (CPX measurements) as well as measured on the drum at the TUG. In addition, 10 of the tyres were also modelled using the SPERoN model.
A linear regression analysis has been made between the results from the drum measurements and CPX measurements.

Figure 4.95 show the correlation between the drum measurement results on a replica of an ISO surface and CPX measurement results on a new SMA11 (not having been exposed to winter conditions).
As can be seen, the correlation is very weak. Between a rougher textured surface on the drum (GRB-S) and a 3 year old SMA11, the correlation is somewhat better.

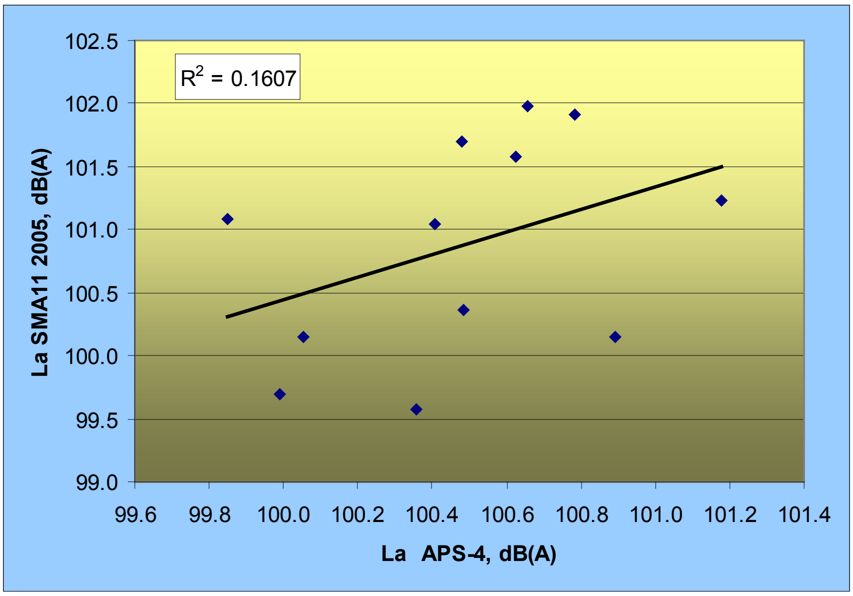


Figure 4.95 Correlation between CPX measurements on SMA11 2005 and drum measurements on the APS-4 surface, 80 km/h. [Berge, Haukland, Ustad, 2009b]

A regression analysis between the measured CPX noise levels and the modelled noise levels showed that no significant correlation was found.

The correlation of linear regression of the overall A-weighted dB levels between the different modes of operation is based on an assumption that there exists such a linear dependency. All the results above show that such a linear correlation for tyre/road noise does not exist, where different tyres, road surfaces and modes of excitations (CPX, drum, and model) are compared.

One single tyre on one single surface can have a linear correlation between the coast-by noise level and with speed in a certain speed range, while the same tyre on an ISO surface has a non-linear relationship in the same speed range. This demonstrates the non-linearity of the noise generation mechanisms.

When comparing for instance CPX measurements and drum measurements, it is clear that the generation mechanisms are strongly dependent on the testing facilities. On the drum, with a relative small curvature, the shape of the horn will be different from the road, and this changes the radiation conditions severely. Also on a small-diameter drum, the shape of the footprint on a tyre is different from a tyre tested on a flat road. This means that the angle of attack of the rubber blocks of the tyre is different on these two conditions, and this influences the generation of noise.

In general, the correlation procedure used is not able to distinguish where the differences of the two variables (overall A-weighted dB levels) come from.

When studying the noise ranking of tyres on different road surfaces and comparing this to the noise labelling system, one should only base this on measurements on representative and trafficked roads (coast-by/CPX), and on a representative ISO track.

5 The effectiveness of tyre noise limit reduction on ISO surface

Since the ISO surface is not used as a pavement type on regular roads, it is important to compare the noise behaviour on regular road surfaces with the ISO noise levels. If there is a strong correlation between the measured ISO noise levels and noise levels on normally used surfaces, this will indicate that a reduction of the tyre noise limit will also be effective on these surfaces.

It is therefore useful to perform a linear regression analysis of a set of tyre measurements on an ISO track and a representative pavement type.

The equation for a linear correlation is given on the format of

$$L_A(y) = a + b \cdot L_B(x) \qquad (1)$$

Where
$L_A(y)$: the noise level on surface A
$L_B(x)$: the noise level on surface B
a: interception at $L_B(x)=0$
b: slope

The slope shows in average how much a reduction of the ISO noise level (if ISO= $L_B(x)$) will give on the other surface.
As an example, if the slope of the regression is 0.8, it means that a reduction of 1.0 dB on the ISO surface gives a reduction of 0.8 dB on the other surface.
This would be the most important parameter for evaluating the efficiency of the EU directive for noise reduction (type approval and labelling).

The regression coefficient R^2 gives the explained fraction of variance of the relation. It is then a measure on the quality of the relation. The correlation coefficient, r, is the square root of R and is often used as a parameter comparing the relationship between two variables. A high correlation means that low noise tyres also will perform as low noise tyres on the other surface. A perfect linear correlation would also show that the relationship between the noise levels of the tyres on the two compared road surfaces is explained by the overall A-weighted noise level only.

5.1 FEHRL analysis

In the FERHL-report [FEHRL, 2006-1] there is a presentation of the slope and the correlation coefficient, r, from 3 independent investigations (TRL, M+P and SINTEF). Data for 6 SMA surfaces and 1 Hot Rolled Asphalt (HRA) are presented, see figure 5.1 and 5.2.

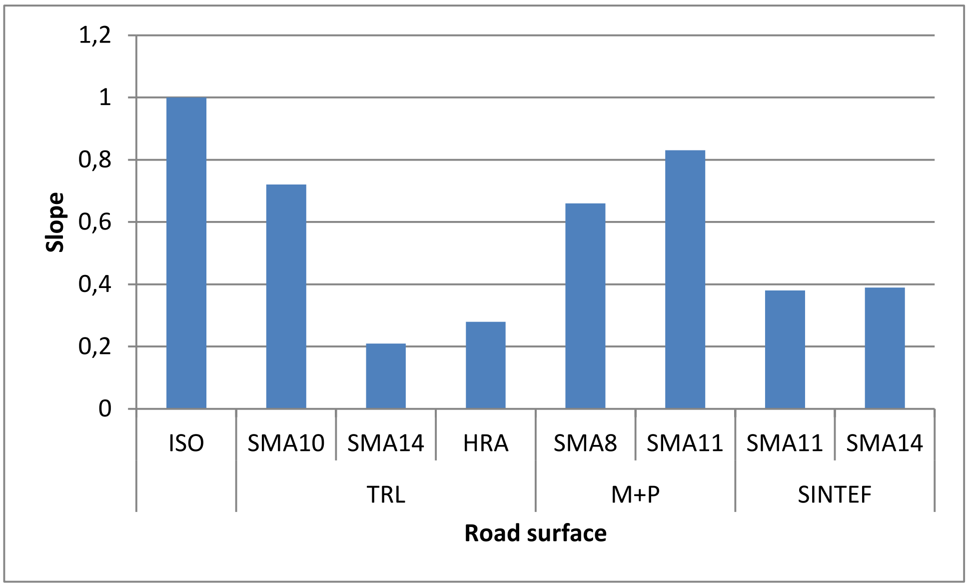


Figure 5.1 Slope from regression analysis between measurements of car tyres on ISO and SMA/HRA road surfaces [FEHRL, 2006-1]

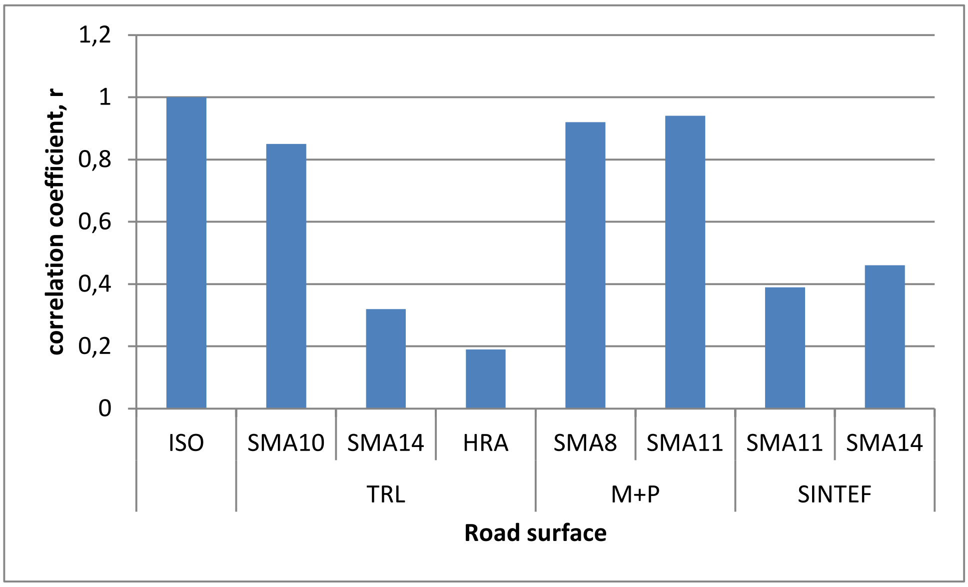


Figure 5.2 Correlation coefficient, r, from regression analysis between measurements of car tyres on ISO and SMA/HRA road surfaces [FEHRL, 2006-1]

The conclusion of the FEHRL authors was that “a reduction of 1 dB on the ISO-surface produces an average reduction of 0.65 dB on SMA 8 to 11. For the rougher surfaces, SMA 14 and HRA, the corresponding reduction was found to be less at 0.29 dB”.

These estimates were used for the impact assessment of the new EU noise limits for tyres, and they were employed as well when it was decided to include noise in the EU tyre labelling.

5.2 M+P analysis from 2009

In 2009, M+P did an analysis on available measurement data of tyres measured on different regular road surfaces, and on the ISO 10844 test surface [van Blokland, van Leeuwen, 2009a].

The motivation for the project was primarily to study the acoustic performance of tyres, especially low noise tyres on regular road surfaces in relation with the performance under the ISO 10844 and ISO 13225 test track conditions.

In addition, the following questions were addressed:

- Can, on base of available data, a relation be established between the performance of low noise tyres on different types of road surfaces and the road surface type?
- If such a relation exists, what is the nature of that relation?
- Is the available data representative for the present situation? Many data is coming from studies performed 10-15 years ago (author's comment: 13-18 years today).

The database for the analysis was based on the following studies, see table 5.1:

Table 5.1 Overview of 4 studies included in the analysis by M+P, 2009

Study	No. of test surfaces	No. of car tyres	No. of truck tyres	Test speeds km/h
Welschap	9	25	10	40-90
Sperenberg 1e tranche	44	16	-	50-120
Sperenberg 2e tranche	16	-	15	40-90
Kloosterzande	40	10	15	50-110

At all locations, an ISO track was part of the test surfaces. All results were normalised to 80 and 110 km/h for passenger car tyres and to 80 km/h for truck tyres.

The Welschap data is from the period 1990-1993, the Sperenberg is from period 2000-2003 and the Kloosterzande from the period 2006-2007.

For all 4 studies a linear regression analysis has been performed to establish the slope and the correlation coefficient, r, between the ISO levels and levels on the other surfaces.

Only the results from the Kloosterzande measurements are included here, since they can be directly compared with the measurements SINTEF did in 2009 (chapter 4.4.3).
The slope and correlation from the Kloosterzande measurements are shown in figures 5.3 and 5.4 (figures from van Blokland, van Leeuwen, 2009a).

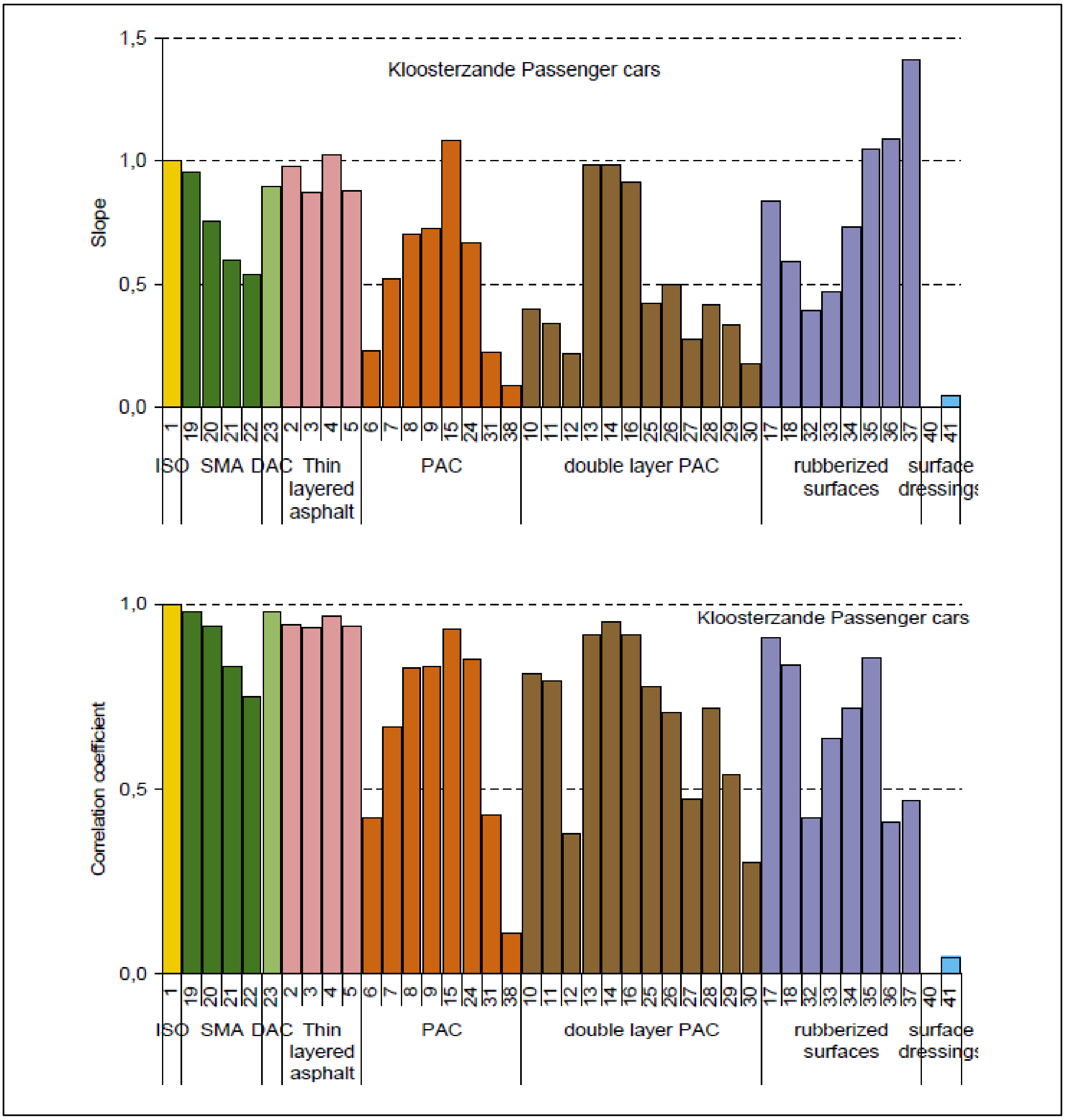


Figure 5.3 Kloosterzande study 2006-07: Slope and correlation (coefficient r) between ISO and other road surfaces.10 passenger car tyres [van Blokland, van Leeuwen, 2009a]

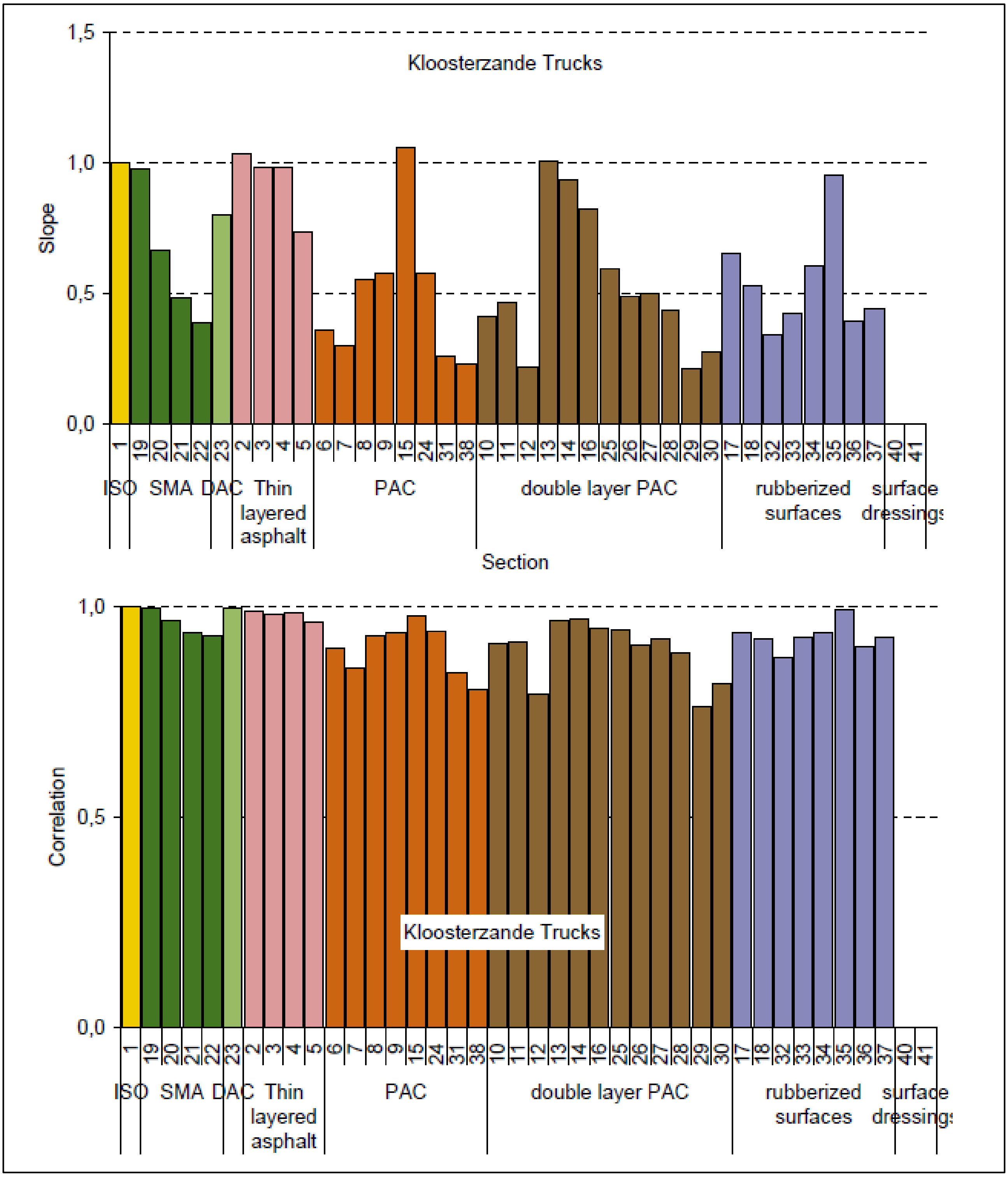


Figure 5.4 Kloosterzande study 2006-07: Slope and correlation (coefficient r) between ISO and other road surfaces. 15 Truck tyres [van Blokland, van Leeuwen, 2009a]

Some of the data in the study represent a tyre generation nearly 20 years ago (Welschap study). Still, M+P regards that some general trends can be found from these measurements and analysis.

In general, M+P concluded that the findings showed that to reduce tyre/road noise, an integrated approach of both tyres and road surfaces are needed.

Summarizing the main conclusions from the report:

- In the majority of the cases, the differences in noise levels are higher on the ISO surface, than on regular roads (the slope is less than 1.0). This is found for both car and truck tyres. There is a strong indication that the most important factor influencing these findings is the surface texture in the middle wavelength range around 40-80 mm.
- Porosity in general is not so important, even though some texture optimised porous surfaces (smoother texture, possible due to smaller maximum aggregate) can give a better correlation with the ISO surfaces than non-optimised.
- With some thin layers and smooth textured rubberized surfaces, a high slope and correlation was found.
- Many of the tyres included in this study are rather old and has been replaced by tyres with more modern tread pattern and rubber compound design. The report makes a proposal for a measurement program of car tyres. This program with 10 passenger car tyres was completed in 2009 [van Blokland, van Leeuwen, 2009b].

In figures 5.5 and 5.6, the slope and correlation coefficient from this measurement program are shown. The surface type and aggregate size for the first 23 sections are given in table 5.2.

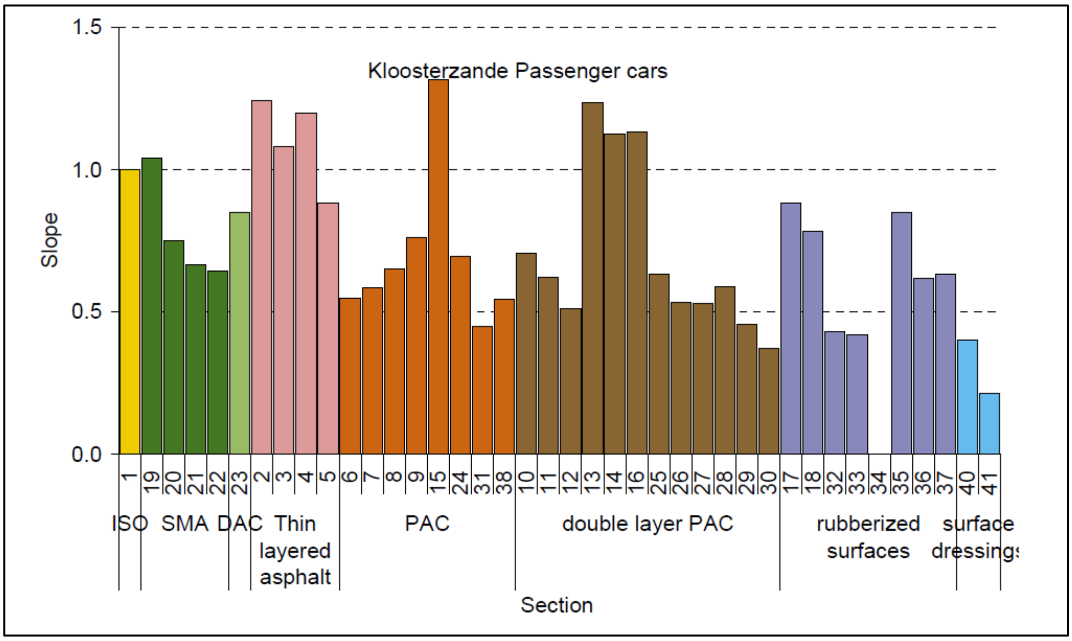


Figure 5.5 Kloosterzande study 2009: Slope between ISO and other road surfaces, 10 passenger car tyres [van Blokland, van Leeuwen, 2009b]

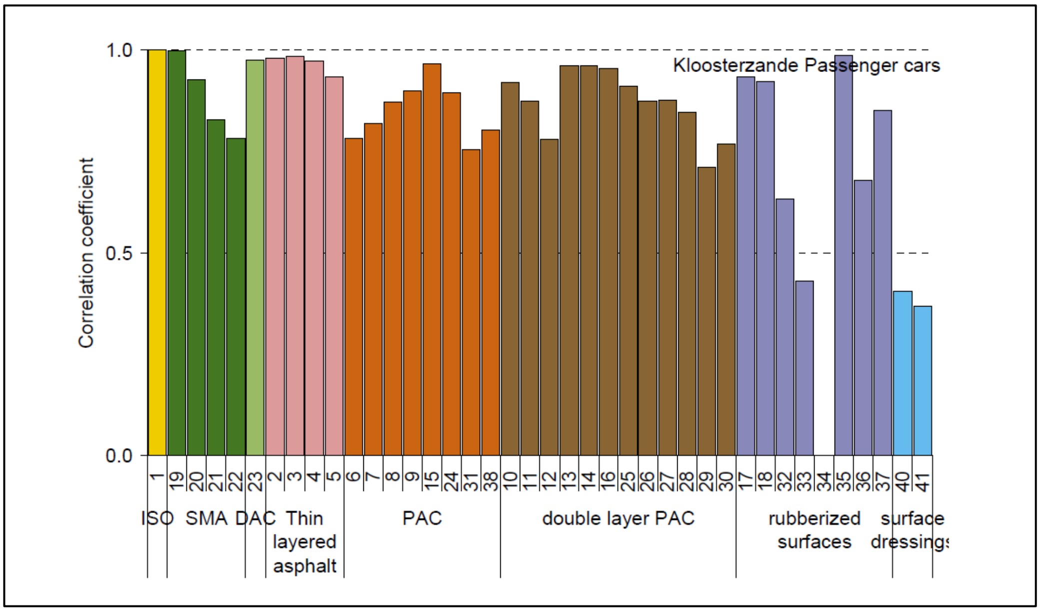


Figure 5.6 Kloosterzande study 2009: Correlation coefficient r, between ISO and other road surfaces, 10 passenger car tyres [van Blokland, van Leeuwen, 2009b]

Table 5.2 Kloosterzande: section numbers 1-23, surface type and chipping sizes

Surface no	Surface type, aggregate size
S1	ISO-surface (DAC 8)
S2	Thin layered 2/4, 12%
S3	Thin layered 2/6, 8%
S4	Thin layered 2/6, 12%
S5	Thin layered 4/8, 12%
S6	Porous 0/11
S7	Porous 0/16
S8	Porous 4/8
S9	Porous 4/8
S10	Porous 4/8 +11/16
S11	Porous 4/8 +11/16
S12	Rollpave PERS
S13	Porous 2/4 + 8/11
S14	Porous 2/6 + 8/11
S15	Porous 2/6
S16	Porous 2/6 + 11/16
S17	Porous 2/6 +EPAC 0/16
S18	Porous 2/6 +EPAC 0/16
S19	SMA 0/6
S20	SMA 0/8
S21	SMA 0/11
S22	SMA 0/16
S23	DAC 0/16

Comparing the two measurement campaigns at Kloosterzande (figures 5.3 and 5.5/5.6 - passenger car tyres), the results show that, except for some of the rubberized surfaces, the two fleets of tyres have more or less the same relationship between the noise levels on the ISO surface and the noise levels on the other surfaces.

The surfaces with the smallest maximum chipping size have the highest slope and the best correlation coefficient. However, the results are rather satisfactory even for the SMA11 and SMA16 surfaces, the slopes are 0.5 or higher (section numbers 21 and 22). The results for the DAC surface - it is a 0/16 surface – are very good (section number 23).

5.3 Analysis of SINTEF measurements at Kloosterzande, 2009

As presented in chapter 4.2.4, SINTEF measured 22 tyres on 23 different road surfaces in 2009, including the ISO surface at Kloosterzande. A linear regression analysis was made on the 22 tyres (listed in table 4.3). Table 5.2 give an overview of the 23 road sections used for the analysis.

The results for the slope and the correlation coefficient, r, are given in figures 5.7 and 5.8. (The colours used in the figures correspond to the colours used by M+P).

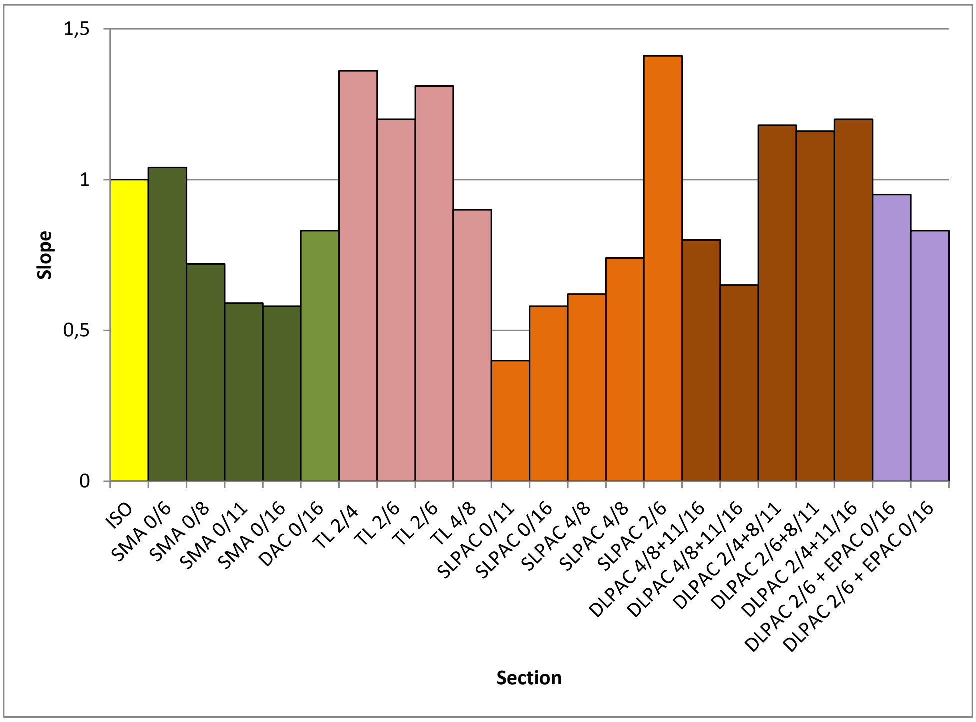


Figure 5.7 SINTEF measurements at Kloosterzande in 2009. Slope for 22 car tyres

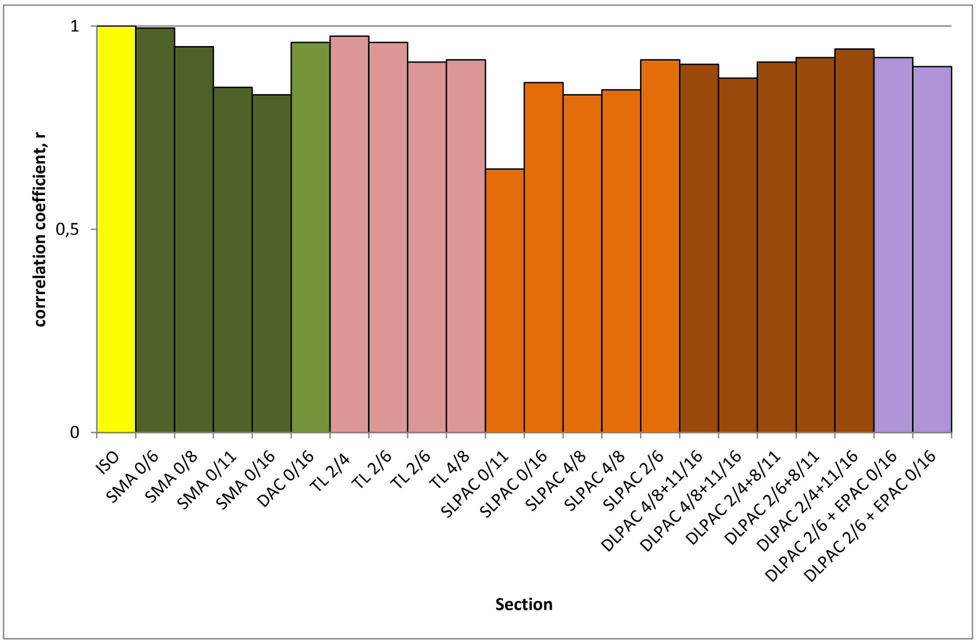


Figure 5.8 SINTEF measurements at Kloosterzande in 2009. Correlation coefficient for 22 car tyres

The results of the analysis gave fairly the same result for these two parameters as the M+P study. It shows that the two tyre fleets chosen for measurements are not critical for the results of the analysis.

5.4 Analysis of SINTEF measurement results in 2011

As presented in chapter 4.3.4, SINTEF measured 10 summer tyres for cars on 6 new DAC pavements (not exposed to winter conditions/studded tyres) and 15 older DAC/SMA pavement types. All tyres have previously been measured on the ISO surface at Kloosterzande, so a similar regression analysis with the ISO levels and the other levels could be made (see also figure 4.62).

The slope and the correlation coefficient are presented in figures 5.9 and 5.10 for the new pavements and in figures 5.11 and 5.12 for the older pavements.
In all figures, several road surfaces of the same types are included (like DAC8, DAC11, SMA11, etc.). The differences between these surfaces may be related to:

- differences in age
- differences in location and traffic load
- differences in laying process and material

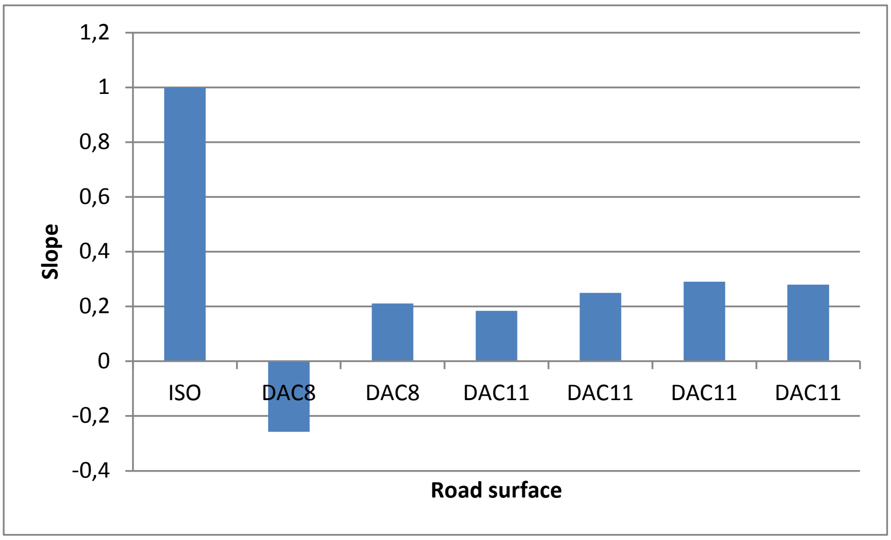


Figure 5.9 Slope from regression analysis 2011, between measurements of 10 car tyres on ISO surface and newly laid Norwegian road surfaces

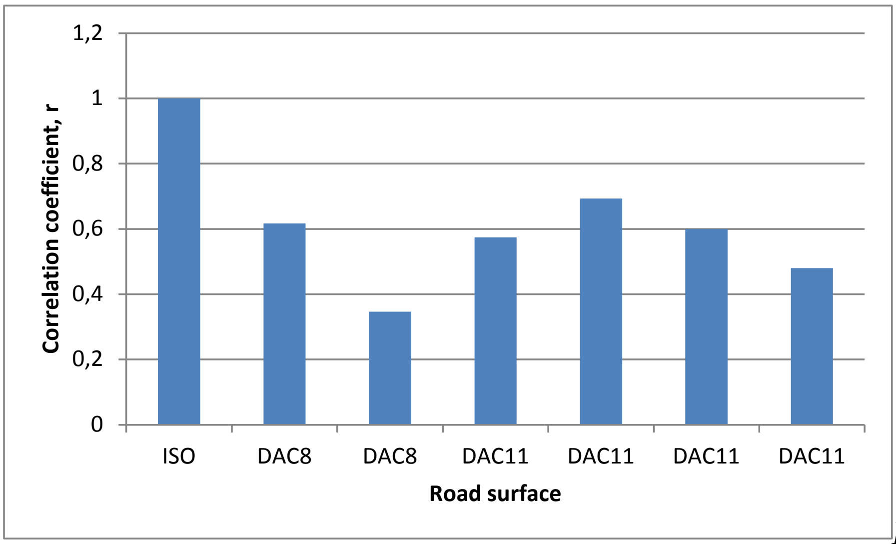


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Figure 5.10 Correlation coefficient from regression analysis 2011, between measurements of 10 car tyres on ISO surface and newly laid Norwegian road surfaces

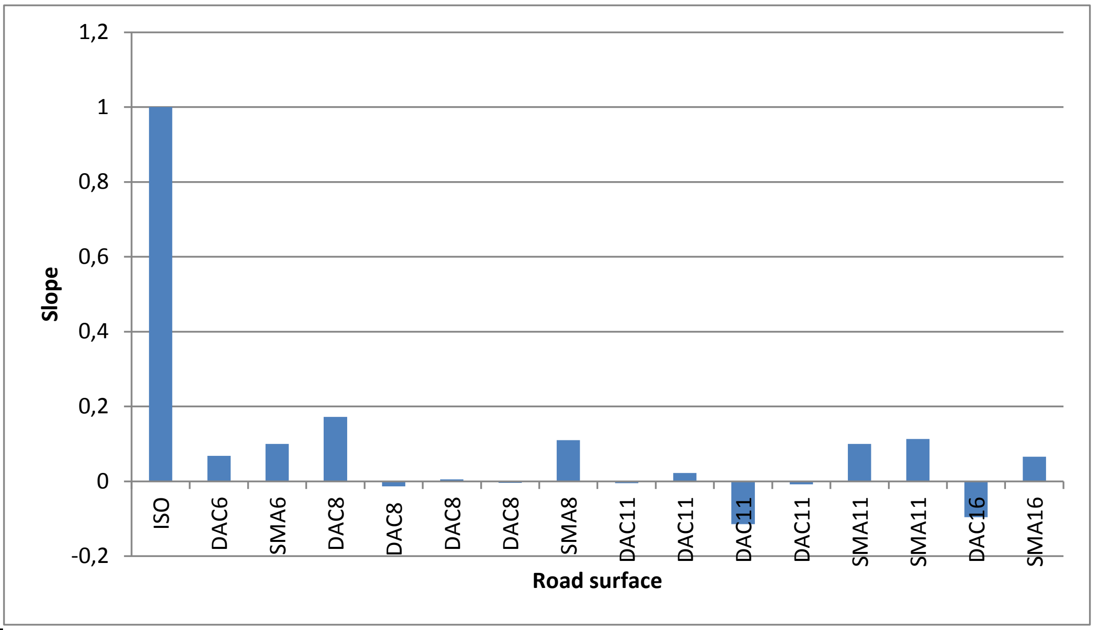

Figure 5.11 Slope from regression analysis 2011, between measurements of 10 car tyres on ISO surface and older Norwegian road surfaces

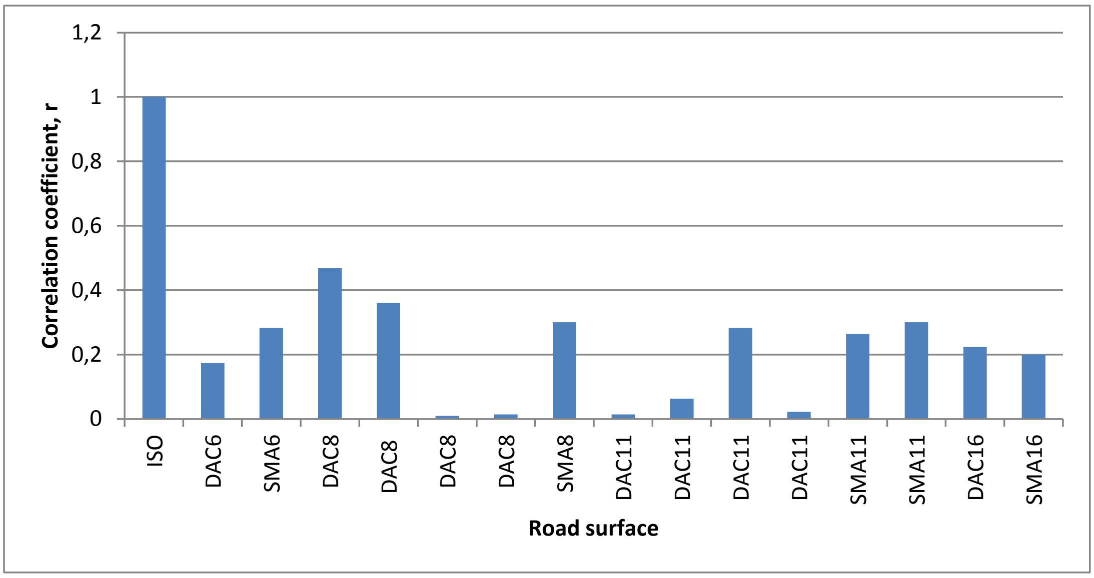

Figure 5.12 Correlation coefficient from regression analysis 2011, between measurements of 10 car tyres on ISO surface and older Norwegian road surfaces

The analysis of the results of measurements made in 2011 on the Norwegian surfaces clearly shows a much poorer correlation with the ISO surface, than found in the 2009 results from the Kloosterzande test track. However, it is likely that the results from the analysis of the Norwegian measurements are influenced by the fact that the measurements on the ISO track was made 3 years earlier than the measurements on the other surfaces. Measurements of the shore hardness (see table 4.10 p.55) showed that several of the tyres had changed hardness levels over this period, and this could increase the uncertainty in this analysis.
The differences in slope and correlation coefficients between the Kloosterzande DAC 16 and the newly laid Norwegian DAC 8-11 surfaces are very large. It seems probable that there have been

important differences in laying process and material between Kloosterzande and these Norwegian surfaces.

A general conclusion from this analysis of SINTEF's 2011 measurement series is that the effectiveness of lowering the tyre noise limits based on the existing ISO surface is strongly dependent on the type of surface used on a regular road.

6 Studded tyres and winter tyres

In general, studded tyres are not part of the NordTyre project. However, some general information about the use of such tyres in Norway, Sweden and Finland are included, as these tyres make a significant contribution to the wear of road surfaces in these countries.

In Norway, in the recent years, focus has been to motivate more car owners to change to non-studded winter tyres. This is mostly motivated by the desire to reduce the dust created by the studs on dry roads and on cold days. Incentives have been taxing of studded tyres in the main cities (Oslo, Bergen, Trondheim), as well as economic benefits, when changing from studded to non-studded tyres. These incentives have reduced the number of studded tyres in these cities to around 15-25 %.

In Sweden, the figures are much higher, from 73 to 94 % are using studded tyres, depending on the Road Administration region.

In Finland, it is estimated that approximately 85 % of the vehicles use studded tyres during the winter season.

Measurements results of pass-by levels as a function of vehicle speed of passenger cars with studded winter tyres and non-studded winter tyres under real traffic conditions are shown in figure 6.1 [Berge, 2007]. An average difference of about 2-4 dB can be observed over the speed range of 50-80 km/h.
These measurements are now about 10 years old, and should be repeated to check for the current fleet of studded-/non-studded tyres (not as part of the NordTyre project, though).

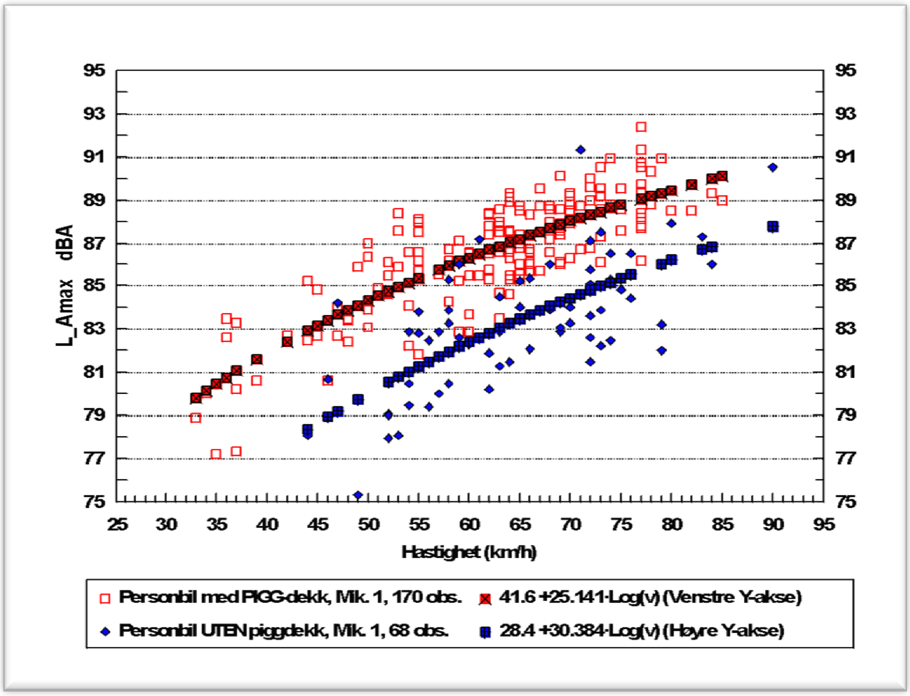

Figure 6.1 Coast-by levels (LAmaks, dB(A)) of passenger cars with studded and non-studded winter tyres as a function of vehicle speed [Berge, 2007]

As part of the tyre/road noise measurements in Denmark 2010 (see chapter 4.3.3) one non-studded winter tyre, ContiVikingContact5, was included in the study. On all the tested surfaces at Kastrupvej, this tyre was about 1 dB quieter than the quietest of the summer tyres (Michelin Primacy LC) and about 4 dB quieter than the other tyres. In figure 6.2, these results are shown for the reference surface in Denmark, AC11d. It should be noted that these measurements were done at an air temperature of + 13 °C. Non-studded tyres have a softer rubber compound than summer tyres, and this may influence the noise levels (giving lower noise levels at higher temperatures).

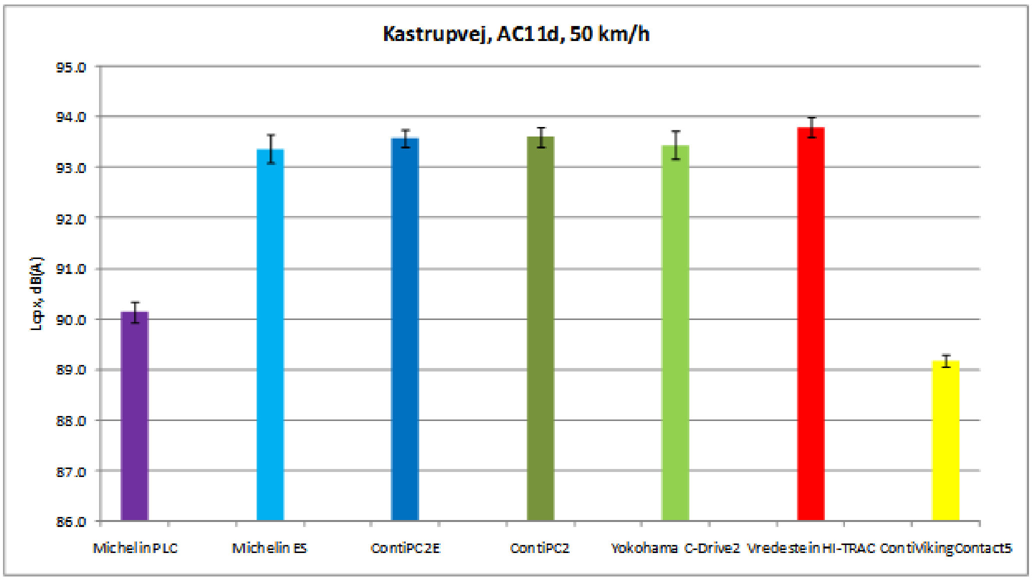

Figure 6.2 Comparison of tyre/road noise levels (CPX) at 50 km/h between a non-studded winter tyre (yellow column) and summer tyres [Berge, Haukland, 2011]

7 Effect of wear of tyres

The effect of wear of tyres is not part of the on-going NordTyre project, but may be so at a later stage.

The influence of wear of tyres was investigated as part of the SILENCE project. A very comprehensive summary of the project can be found in [Sandberg, Ejsmont, 2007; Sandberg, Glaeser, 2008].

5 summer tyres and 1 winter tyre for cars were used for the test, where the material ageing was artificially accelerated, using a climate chamber at VTI. The tyre wear was accelerated by using a special drum machine at Continental.

The main conclusions from the experiments were:

Rolling resistance:

- Rolling resistance was found to be substantially reduced with tyre wear; appr. linearly related to the remaining tread depth, except that between 4 mm and 2 mm the decrease was faster.
- An average reduction from new conditions of 20 % on a smooth surface and 17 % on a rough-textured surface was found, when the thread depth was down to 2 mm

Noise:

For the individual tyre, the noise level clearly depends on the Shore A hardness. As noted on chapter 4.2.4, one tyre with a certain Shore A value can have a lower measured noise level, than another softer tyre.

On a smooth ISO surface, the average increase in noise level was found to be 0.7 dB between new and aged condition of a tyre. The increase was found to be 0.10 dB per unit Shore A hardness. On a rough-textured surface, the average increase between new and aged conditions was 1.8 dB, and 0.22 dB per unit Shore A hardness.

8 Rolling resistance

8.1 General remarks

Rolling resistance (RR) in the interaction of a tyre with a road surface is a physical phenomenon resulting in energy losses. 3 main mechanisms have been identified through which the energy is lost:

1. Losses due to the bending/deformation of the tyre sidewalls
2. Losses due to micro-deformation of the tyre tread in the contact area
3. Losses due to slippage friction in the contact area between the tyre and the surface

In addition, the inflation pressure, tyre rubber compound, tread pattern and the road surface texture could influence the rolling resistance.

More focus has been on the rolling resistance related to tyres than to road surfaces, as it is directly linked to the fuel consumption of a vehicle, and by this also the CO_2 emissions. It is assumed that the contribution of the rolling resistance to the fuel consumption of a car is approximately 20 %. It has been estimated that 10 % reduction in rolling resistance could lead to 2-3 % reduction in fuel consumption. However, no single and universal conversion exists. Clearly, the road texture, among many other parameters plays an important role for the rolling resistance of a tyre.

Rolling resistance has been decided to be an integral part of the NordTyre project and some basic information about this topic is therefore included in this report.

Two international projects deal with this topic:

- TYROSAFE (http://tyrosafe.fehrl.org/)
- MIRIAM (http://miriam-co2.net/index.htm)

The TYROSAFE project (Tyre and Road Surface Optimisation for Skid Resistance and Further Effects) was running from 2008 to 2010.

TYROSAFE project report D10 [Kane, Scharnigg, 2009] is a comprehensive study on the parameters influencing skid resistance, rolling resistance and noise emission.

TYROSAFE project report D15 [Scharnigg, Schwalbe, 2010] gives specified proposals to reduce the knowledge gaps of rolling resistance, both related to the tyres and the road surfaces.

MIRIAM (Models for rolling resistance in Road Infrastructure Asset Management system) has 12 partners from Europe and USA. It started in 2010, with internal funding for 2010 and 2011. The project is managed by DRI in Denmark.

In June 2011, a state-of-the-art report on rolling resistance was published by MIRIAM, SP1 [Sandberg, 2011].
This report covers in detail variables and parameters affecting the rolling resistance, the contribution to vehicle energy consumption, measuring method for rolling resistance (both laboratory and trailer methods), as well as a comprehensive reference and literature list.

Some of the conclusions are:

- Tyre RR test methods lack consideration of realistic road surfaces
- Standard test methods are available only for testing tyre RR in laboratories (SAE and ISO methods)
- Road parameters that clearly affect RR include macrotexture (represented by MPD), megatexture, and unevenness.

It should be investigated if the use of a trailer or a coast-down method could be used to compare RR on different Nordic pavements, using selected tyres.

For further reading, this report from MIRIAM [Sandberg, 2011] is recommended.

8.2 Measuring methods

International standards for measuring the rolling resistance only exist for tyres and not for road surfaces.

All present (and earlier) methods are based on laboratory measurements. Institutes like the TUG in Gdansk and BASt in Bergisch-Gladbach, have facilities to perform such standardised measurements. In addition, several trailers have been developed to perform measurements on roads (e.g. TUG, BASt, BRRC (Belgian Road Research Centre)). Both laboratory equipment and trailers are well described in [Sandberg, 2011].

Table 8.1 gives a summary of present international standards for measuring rolling resistance.

<u>Table 8.1</u> SAE and ISO standards for measuring of rolling resistance [Sandberg, 2011]

Method	SAE J1269		SAE J2452	ISO 18164:2005	ISO 28580:2009
Test point	Single-point	Multi-point	Multi-point	Multi-point	Single-point
Measurement methods	Force, torque, power	Force, torque, power	Force, torque	Force, torque, power, deceleration	Force, torque, power, deceleration
Rolling resistance	Force	Force	Energy loss per distance	Energy loss per distance	Energy loss per distance
Roadwheel diameter	1.7 m	1.7 m	1.219 m or greater	1.5 m or greater	2.0 m or >1.7 m corrected to 2.0 m
Roadwheel surface	Medium-coarse texture	Medium-coarse texture	Medium-coarse texture	Smooth (texture optional)	Smooth (texture optional)
Temperature range	20 to 28 °C	20 to 28 °C	20 to 28 °C	20 to 30 °C	20 to 30 °C
Reference temperature	24 °C	24 °C	24 °C	24 °C	24 °C
Speed	80 km/h	80 km/h	Coastdown; 115 km/h to 15 km/h	80 km/h	80 km/h

8.3 Legislation and official requirements

Requirements for rolling resistance is defined in two EU directives, one regulating the limits for the rolling resistance coefficient (RRC); Regulation (EC) 661/2009 and the other one on the labelling of tyres; Regulation (EC) 1222/2009.
The rolling resistance shall be measured according to ISO 28580 [ISO, 2009].
The UNECE R117 [ECE, 2007] includes similar requirements for rolling resistance.

The limits according to (EC) 661/2009 are shown in table 8.2.

Table 8.2 Maximum allowed rolling resistance coefficient (RRC) expressed in kg/tonne, which is identical with unitless RRC multiplied with 1000. For snow tyres, the limits are increased with 1 kg/tonne

Tyre class	First stage 1.11.2012 Max value [kg/tonne]	Second stage 1.12.2016 Max value [kg/tonne]
C1	12.0	10.5
C2	10.5	9.0
C3	8.0	6.5

The labelling classes of rolling resistance according to (EC) 1222/2009 are shown in table 8.3.

Table 8.3 The energy efficiency classes A-G and the corresponding limits for RRC, according to (EC) 1222/2009

C1 tyres		C2 tyres		C3 tyres	
RRC in kg/t	Energy efficiency class	RRC in kg/t	Energy efficiency class	RRC in kg/t	Energy efficiency class
RRC ≤ 6,5	A	RRC ≤ 5,5	A	RRC ≤ 4,0	A
6,6 ≤ RRC ≤ 7,7	B	5,6 ≤ RRC ≤ 6,7	B	4,1 ≤ RRC ≤ 5,0	B
7,8 ≤ RRC ≤ 9,0	C	6,8 ≤ RRC ≤ 8,0	C	5,1 ≤ RRC ≤ 6,0	C
Empty	D	Empty	D	6,1 ≤ RRC ≤ 7,0	D
9,1 ≤ RRC ≤ 10,5	E	8,1 ≤ RRC ≤ 9,2	E	7,1 ≤ RRC ≤ 8,0	E
10,6 ≤ RRC ≤ 12,0	F	9,3 ≤ RRC ≤ 10,5	F	RRC ≥ 8,1	F
RRC ≥ 12,1	G	RRC ≥ 10,6	G	Empty	G

8.4 Measurements on Nordic Pavements

Of special interest for the NordTyre project will be to implement relevant measurements of RRC on Nordic pavements.
To our knowledge, such measurements have only been made in Sweden and Denmark.

TUG, in cooperation with VTI in Sweden has made measurements on roads in Sweden, using their TUG "R^2 trailer".
In figure 8.1, the measured relationship between the RRC and the macrotexture (MPD) for different roads in Sweden and Denmark is shown. The data have been collected over a 5 year period [Sandberg, 2011]. As part of the Nordic project on the relationship between tyre/road noise and texture, NordTex, measurements of rolling resistance have been made in Denmark in 2009, with the TUG trailer [Kragh, 2010a]. The results of these measurements are included in Figure 8.1. The Danish road surfaces include the 7 test sections at M10, Solrød and 6 sections at Kongelundsvej:

Kastrup
M10:
- HRA 11/16
- AC11d
- SMA 8
- AC 8o/Microville 8
- UTLAC 8/TB 8k/Combifelt 8
- SMA 6P
- AC 11o

Kongelundsvej:
- AC 11d
- AC 6o
- UTLAC 8/TB 6k
- SMA 6+
- AC 8t
- AC 11d

Data for the Swedish surfaces are not given in the report [Sandberg, 2011].

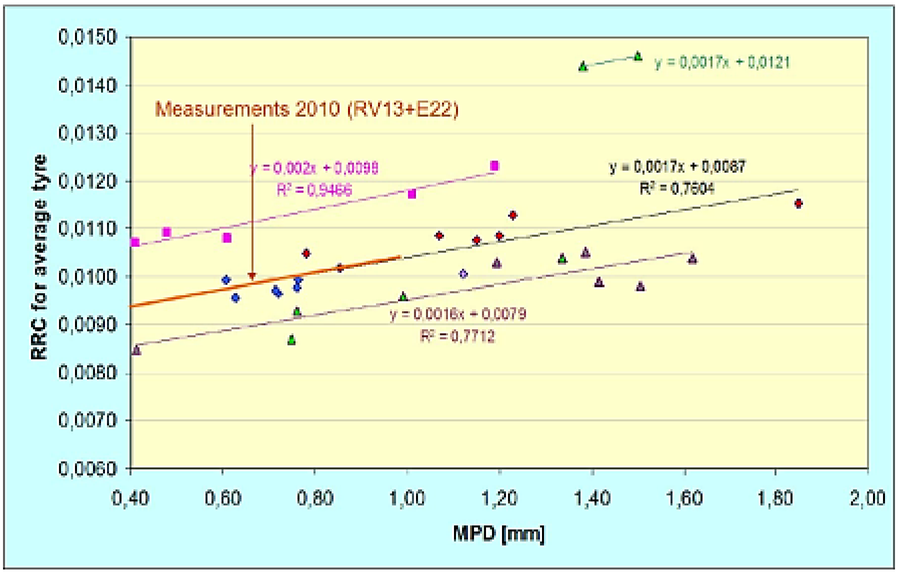

Figure 8.1 Results from TUG measurements in Sweden and Denmark 2009-2010. A certain cluster of points and associated regression line belongs to the same data set measured within a few days [Sandberg, 2011]

The data shows that the slopes are fairly constant, for all surfaces, indicating the sensitivity of RRC to a change in MPD. The figure does not separate results from Sweden and Denmark.

In chapter 4.2.5 (the Dutch list of tyres), the relationship between measured RRC and wet grip (figures 4.27 and 4.34) and between RRC and noise levels (figures 4.27, 4.29-4.33 and 4.36) is presented for summer tyres. No positive or negative correlation was found. This was also the case for the winter tyres.

8.5 Recommendations for further work

Both in the TYROSAFE and the MIRIAM project, a long list of recommendations are given to improve the knowledge between rolling resistance of tyres and the influence of the road texture.

For the NordTyre project, a measurement program of tyre performance on Nordic pavement types, rolling resistance measurement should also be made on Norwegian pavements, in addition to the Danish and Swedish data. It is recommended to:

- Measure the RRC on a selected number of Nordic road surfaces with some of the tyres in the measurement program, or using SRTT /Avon AV4. Measurements are made with a trailer
- Measure the RRC of all the selected test tyres on drum facilities to check against labelling figures

9 Representative tyre populations in the Nordic countries

9.1 Norway

In Norway, approximately 2 600 000 tyres are sold per year, including roughly 150 000 truck tyres. There is no official list available of the most popular tyres on the after market. However, according to the organization of tyre importers in Norway, the tyre manufactures Continental, Michelin, Nokian and Goodyear have the biggest market shares (~80 %?).

In table 9.1, the 10 most sold car models in Norway by end of November 2011 are listed, together with the most frequently used tyre widths. As can be seen from this table, the most sold vehicles are dominated by relatively large family cars/medium SUV's. The most frequent OEM tyre dimensions would then be in the range 195-215 mm in Norway. According to Continental Norway (Frank Larsen), the most sold tyre dimension in Norway is 205/55 R16. The most common rim sizes are 15-16 inches.

Table 9.1 The most sold cars in Norway, 2011 and normal tyre widths (Source: Adresseavisen 3.12.2011)

No.	Car model	Tyre widths, mm
1	VW Golf	195-205
2	VW Passat	205-215
3	Ford Focus	195-205
4	Mitsubishi ASX	215
5	Volvo V70	225
6	Toyota Avensis	205-215
7	Nissan Qashqai	215-225
8	Toyota Auris	205
9	Skoda Octavia	195-225
10	Ford Mondeo	205-215

9.2 Sweden

The vehicle fleet in Sweden is not too different from Norway, concerning the most sold vehicles and tyre dimensions. The 10 most sold vehicles in Sweden per November 2011 are listed in table 9.2. Again, the indication is that tyres in range 195-215 mm are the most frequent widths, with 205 mm probably the most common.

Table 9.2 The most sold cars in Sweden, 2011 and normal tyre widths (Source: Bil Sweden)

No.	Car model	Tyre widths, mm
1	Volvo V70	225
2	VW Passat	205-215
3	VW Golf	195-205
4	Volvo V60	215
5	Volvo S50	195-205
6	Kia Cee'd	195-205
7	Audi A4	215
8	Volvo XC60	205
9	Renault Megane	195-225
10	Ford Focus	195-205

9.3 Finland

The 10 most sold cars in Finland in 2010 are shown in table 9.3.
(http://194.157.221.15/markkinointijarjestelma/taulujulkaisu/92_taulu_katso_uusi.asp?tjid=532&kieli)

Table 9.3 The 10 most sold passenger cars in Finland, 2010 and tyre widths

No.	Car model	Tyre widths, mm
1	VW Golf	195-205
2	Skoda Octavia	195-225
3	Toyota Avensis	205-215
4	Nissan Qashqai	215-225
5	Kia Cee'd	195-205
6	Opel Astra	205-215
7	Ford Focus	195-205
8	Toyota Yaris	165-185
9	Toyota Auris	195-205
10	Volvo V70	225

According to [Sainio, 2011], 80 % of the tyre fleet are covered with 20 % of the tyre sizes.

If 8-10 different tyre sizes are chosen for a measurement program, this could cover 80 % of the fleet.

The trend today is that the typical tyre size for summer tyres for cars is now moving to 215/55 R17 for middle class cars and 205/55 R16 is for smaller and/or older cars. Due to the amount of older cars still in the traffic (valid for all the Nordic countries) there is many cars still running with tyres of 175-185 mm width.

9.4 Denmark

No statistics have been available at the time of writing the report.
Due to the vehicle taxing system in Denmark, the most frequent sold models are much more dominated by smaller cars like the VW Polo, Ford Fiesta, Skoda Fabia, etc. Thus, the tyre dimensions are probably more likely to be in the range from 175-195 mm.

10 Low noise tyres

A general definition of a low noise tyre is difficult. Is it a tyre with a certain maximum level under type testing conditions (80 km/h, ISO surface)? Or is it a tyre which, in addition have a low noise level, more or less independent of road surface, as the Michelin Primacy LC (figure 4.54), seems to be?
Or should one just refer to a manufacturer description of the tyre as low noise tyre in a commercial "fact sheet"?
It is evident that the noise level of a tyre would depend on a range of parameters, as shown in this report. Even the coming "labelling" level, will depend on which ISO surface has been used during type approval (see figure 4.1, showing the variation in noise levels for different tyres on different ISO tracks). The measuring conditions, and any use of temperature corrections also has an influence. The normal spread in production of tyres, even from the same batch also has an influence. This has been demonstrated in a comparison of noise levels from different SRTT tyres, where tyres from the same batch can have a different "ISO" level of about 1 dB [Kragh, 2010b].

There are several lists of so-called "low noise" tyres, as for example the Dutch list from 2005.

(http://www.innovatieprogrammageluid.nl/GBpage.asp?id=931)

In the list a total of 34 passenger car tyres (of 105) were found with a noise level 5 dB or more below the present limit.

Since the new noise limits will be introduced from November 2012, it may be more correct to look at the present fleet of car tyres, as listed in the Dutch list from 2010 (see chapter 4.2.5). This list consists of 223 summer tyres for cars of the classes C1A, C1B and C1C. If all tyres 1 dB or more already below the coming limits are defined as "low noise" tyres, the following number of tyres in each class can be found; table 10.1.

Table 10.1 Number of passenger car tyres 1 dB or more below the coming noise limit, based on the Dutch list of 2010

Tyre class	Number of tyres in the list	Number of tyres 1 dB below new noise limit	Percentage %
C1A	67	4	6
C1B	101	28	28
C1C	55	1	2
Total	223	33	15

Based on these statistics, already about 15 % of the tyres in these categories can be classified as "low noise" tyres. In class C1B, the figure is even higher, about 28 %.

If the definition would be "at least 2 dB" below this new limit, only 7 tyres of class C1B (7 %) would be classified as "low noise" tyres.

In addition, when new type approval levels will be reported later this year, as part of the labelling system, this list can be expanded.

This definition is based on type approval levels. Other definitions of "low noise" tyres can be based on actual measurements on different road surfaces or on the manufactures own "definitions", such as in advertisements /brochures.

11 Future trends for tyres

The present tyre fleet technology is more or less based on a continuous development due to customer and vehicle manufacturer demand. Focus in recent years has been more on issues like rolling resistance, wet grip/safety and mileage, than on issues like noise. The new labelling system and new noise limits may change this somewhat, to make the customers more aware of the possibilities to choose more low noise tyres.

There have been a few new ideas for a more radical change of tyre design to achieve a significant noise reduction, like the Composite Wheel in Sweden. A similar tyre has been developed by Michelin, named the TWEEL [Sandberg, 2009].
However, so far, none of these concepts have led to commercial available low noise tyres.

Continental has presented a paper on improvement of noise performance with sealed tyre and cavity absorber technology [Saemann et al, 2011] They modified 2 standard Conti tyres in order to reduce interior noise. The seal technology is reducing the low frequency, vertical tyre modes and the high frequency tyre pattern noise. The foam absorber technology is reducing tyre cavity noise. Figure 11.1 shows a cross section of a tyre mounted on a rim, with this technology applied. The interior noise has been reduced with up to 7.5 dB on a smooth road surface. No indication on the impact on exterior noise is given, but should be investigated.

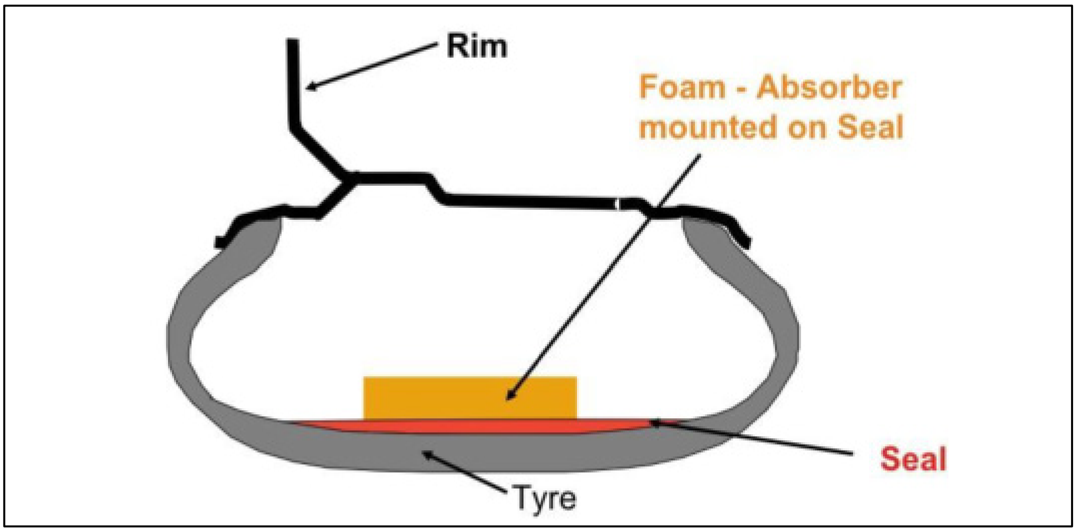

Figure 11.1 Tyre cross section with seal and foam absorber, mounted on a rim [Saemann et al., 2011]

Bridgestone has demonstrated a reduction of interior noise by changing the tyre surface geometry and the introduction of Helmholtz resonators on tread pattern [Kithara et al., 2011].
To supress a vibrational mode around 400 Hz, a modified surface geometry was tested on a 225/45 R17 tyre, as shown in figure 11.2.
In addition, to reduce pipe resonances in the contact patch, Helmholtz resonators were implemented in the tread pattern, as shown in figure 11.3.

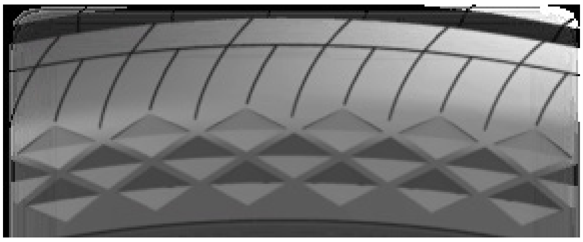

Figure 11.2 Dedicated surface geometry of Bridgestone tyre [Kithara et al., 2011]

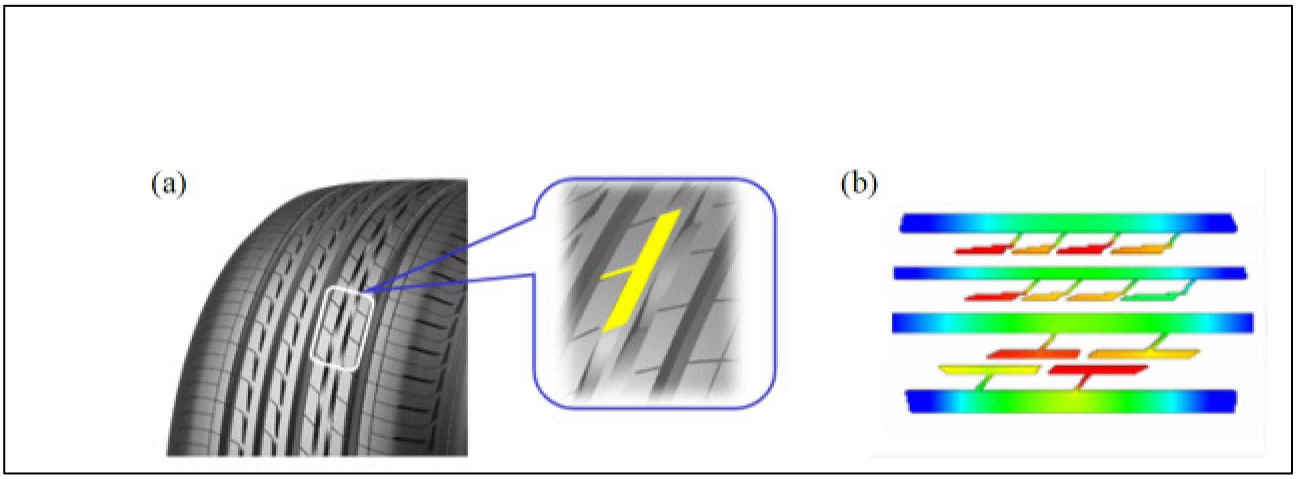

Figure 11.3 Application of Helmholtz resonators: (a) resonators on tread pattern; (b) illustrative explanation of acoustical resonance of the pattern [Kithara et al., 2011]

The results for the interior noise are shown in figure 11.4. Again, only the interior noise has been monitored, but the technology should also have a potential to reduce external noise and should be investigated.

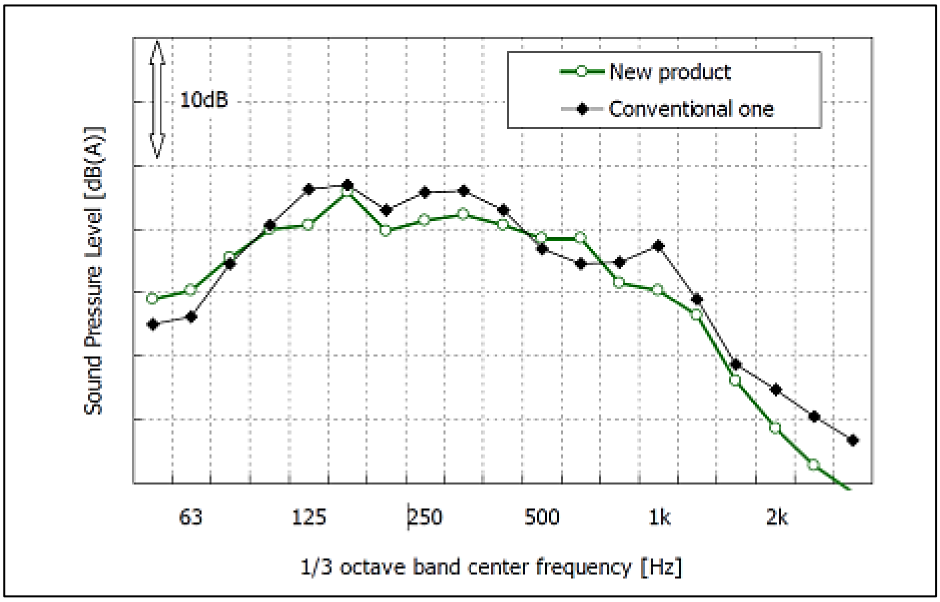

Figure 11.4 Measured interior noise in modified Bridgestone tyre [Kithara et al., 2011]

Bridgestone has also developed an airless tyre, and a description can be found in:
http://www.tiretechnologyinternational.com/news.php?NewsID=35276

No indications on noise behaviour, but optimized design could possibly influence radiation efficiency and then the noise generation.

The EU project "Green City Car" has motivated tyre manufacturers to develop new types of tyres design to meet the goals of this project (http://fp7-co2ntrol.eu/?About_Green_City_Car). This project started in 2009 and will finish in 2012.

One of the goals is to reduce the total noise emitted by a vehicle with 10 dB, having identical weight and energy consumption as normal today.
For such vehicles (can be electric or hydrogen vehicles), there is obviously a need for special low noise tyres, which at the same time meet the requirements for low rolling resistance and safety.

All the main tyre companies are working on new solutions to meet such requirements.
Continental is an active partner in the EU project and has studied several possibilities for design changes, which can lower the noise emission. Such tyres could be made to meet a significant lower maximum vehicle speed (since it shall fit a "city" car). By reducing the profile depth (without scarifying the wet grip) and a reduction of the negative part of the tread, a 6 dB noise reduction has been measured [Saemann, 2010].

Michelin has presented two tyre concepts, which can be commercial available tyres for "green" cars in the future. One is the Michelin Small Tyre/Wheel Assembly. This tyre has the dimension 175/70 R10 and has the same road performance as a 14in tyre (175/65 R14). Figure 11.5 show this tyre mounted on a Citroen C2 car under a demonstration at the conference "Challenge Bibendium" in 2010 [BIL, 2010].

Figure 11.5 Citroen C2 fitted with new small tyres from Michelin [BIL, 2011]

Instead of reducing the tyre size from a normal 14-16in, Michelin has also developed a prototype tyre for EV (Electric Vehicle) with a significant increase in rim size, called the "Tall and Narrow" tyre with dimensions 155/70 R19, as shown in figure 11.6. Since the noise level is related to the width of the tyre, a 155 mm tyre would certainly have a potential for reduced noise level, compared to "normal" widths of 195-205 mm.
The tyre was presented at the "Challenge Bibendium 2011" in Berlin [Tire Tech. Int., 2011].

Figure 11.6 The new prototype 19 in tyre from Michelin [Tire Tech. Int. 2011]

Hankook has designed a new tyre range "the Kinergy Eco EV", which claims to combine state-of-the-art safety, handling and comfort technology, with eco friendliness and efficiency. Like the Michelin tyre (figure 11.6), this tyre has a size of 155/70 R19. The tyre is Hankook's interpretation of the tyre of the near future and could be fitted on EV and hybrids [Tire Tech. Int., Nov/Dec.2011]. No noise information has been given.

A common feature for all the "green city cars" is that they will have a maximum speed limitation, probably around 140 km/h. Tyres developed for such vehicles should not have to be type approved for speeds up to and above 200 km/h. This gives a much larger potential to develop more quiet tyres and could possibly also benefit "normal" cars fitted with speed limitations, say around 150-160 km/h.

12 Road surfaces representative for the Nordic countries

12.1 Norway

In Norway, the normally used road surfaces on the main roads (Ev (European) and Rv (highways)) are dense asphalt concrete surfaces (DAC) or Stone Mastic Asphalt (SMA). The same is the situation for the secondary county roads (Fv).

Table 12.1 shows the common percentage of existing pavement types on Ev/Rv/Fv for 2 of the Road Administration regions (Middle and East), depending on the maximum chipping size. The road network with the highest traffic volumes is totally dominated by 11 and 16 mm pavements.

Table 12.1 Percentage of pavement types on the Ev/Rv/Fv road network in two regions in Norway

Max chipping size	Ev/Rv, %	Fv, %
8 mm	1	4
11 mm	40	62
16 mm	58	32
18-22 mm	1	2

The secondary network has a larger amount of roads with 8-11 mm maximum chipping size, than the highways.

For recently paved roads, the common distribution for new surfaces (laid in 2010) for the same two regions is given in table 12.2.The trend is to use more 8-11 mm maximum stone sizes in these two regions.

Table 12.2 Percentage of pavement types on the main road network laid in 2010

Max chipping size	New surfaces 2010, %
8 mm	7
11 mm	66
16 mm	27

In figure 12.1, a comparison of CPX measurements in Norway (from 2005) and similar measurements in the Netherlands and in UK (using different measurement equipment, but same type of tyre) has been made.
It shows that the Norwegian road surfaces are 2-4 dB noisier than similar types of road surfaces in these two countries. The reason for this must be related to the use of studded tyres/winter conditions in Norway. The differences are comparable to what was found between Norwegian and Danish pavements (chapter 4.3.3).

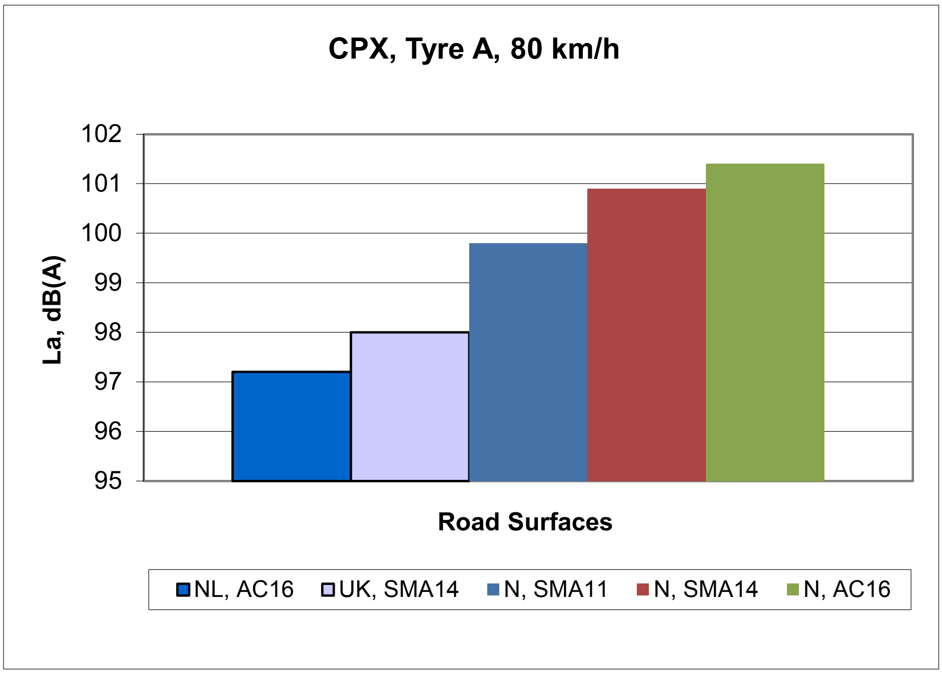

Figure 12.1 Comparison of CPX-levels measured in Norway (N), the Netherlands (NL) and the UK Tyre: Avon ZV1. Speed: 80 km/h

12.2 Denmark

From the Danish Road Institute [Bendtsen, 2011], the following statistics are available:

Table 12.3 Percentage of road network in Denmark, Motorways and Highways

Max chipping size	Motorways/Highways, %
6 mm	5
8 mm	20
11 mm	75

Table 12.4 Percentage of surfaces used in 2011 (main road network in Denmark)

Max chipping size	New surfaces, 2011, %
6 mm	5
8 mm	20
11 mm	75

Compared to surfaces in Norway, there is more use of 6-8 mm surfaces, but still, the majority of the network is dense surfaces with 11 mm maximum chipping size.

12.3 Sweden

No statistics has so far been available, but SMA16 is considered the most common surface on the highway network.

12.4 Finland

No statistics have been available, but SMA16 is the most commonly used pavement type [Sainio, 2011].

13 Evaluation of measuring methods of tyre noise and measurement uncertainty

13.1 General considerations

Any measurements of noise are influenced by uncertainties. Uncertainty can be due to
- Uncertainty in reproducibility
- Uncertainty in repeatability

For measurements of noise levels of tyres, reproducibility can be related to:
- Variability due to site-to-site (from one ISO track to another)
- Variability due to tyre-to-tyre (within the same tyre type)
- Influence of measurement equipment and personnel
- Meteorological conditions (mainly temperature)
- Influence of measurement device (vehicle/trailer)

Repeatability uncertainty can be influenced by
- Day-to-day variations on the same ISO track
- Variability of tyre (variation in rubber hardness)
- Instrumentation uncertainty

In the ISO standards used for measurements of tyre/road noise, this issue is discussed in more detailed and indications on the expanded uncertainty are presented.

13.2 Type approval measurements

Type approval measurements according to ECE Reg. 117 are made as coast-by measurements with tyres fitted on a vehicle. The method itself is relevant concerning the measurement conditions; reference speeds of 70 km/h (trucks) and 80 km/h (cars), microphone positions (1.2 m height and 7.5 m distance).

The coast-by method has some positive and negative characteristics [Sandberg, 2006]:

Positive:
- Representative of actual noise emission
- Accounts very well for the road surface influence

Negative:
- Requires 4 or more test tyres
- Sensitive to background noise

- Sensitive to meteorological conditions
- Test vehicle may influence the results
- Many vehicles needed to test all tyre sizes
- Usually difficult and expensive to perform
-

In addition, there is another element of concern in the method. The measurements shall be made on the ISO 10844 road surface, which was developed in the early nineties for type approval measurements of accelerating road vehicles (ISO 362). It was designed to be a smooth surface with minimum contribution of tyre/road noise. It was never designed for type approval of the noise levels of tyres. However, it is understandable that it was chosen to be implemented in the tyre noise regulations, since it was the only "standardised" road surface. The specifications of the ISO surface were given to make it close to non-absorptive and with a minimum requirement for texture depth (MPD). Experiences with this surface over the last 15 years have shown that the variation from one ISO track to another has been much larger than foreseen. As presented in chapter 4.2, M+P did a survey in 2006, comparing the noise levels from 4 tyres measured on 7 different ISO tracks in Europe [van Blokland, Peeters, 2006]. The average noise level of the 4 tyres varied from 70.2 dB(A) to 75.5 dB(A), i.e. more than 5 dB. This fact makes it very difficult to compare noise levels from tyres collected from different ISO tracks. Over the last years, ISO WG42 (TT) (Test Track) has worked on revising the standard and recently a new, improved version of ISO 10844 has been issued. Among several changes, the tolerances for absorption and texture have been tightened, in order to reduce the variance from one track to another.

Still, the representativity of the ISO surface for normally used road surfaces is an open issue. As shown previously in this report, this is definitely not the case for the Norwegian situation (and presumably also Swedish and Finnish). After the revision of ISO 10844, the subgroup of ISO WG42 (TT) will have to decide if a second and more rough-textured surface should be implemented, either as a supplement to ISO 10844 or as a replacement surface for tyre measurements.

As stated in the list of negative characteristics above, the method is sensitive to meteorological conditions. In order to compensate for some of this influence a temperature correction has been introduced (for passenger car tyres only) as given in Chapter 3.2.1. This correction is not linear as it has a different slope for corrections below or above the reference temperature of + 20 °C. This generic correction can vary from tyre to tyre and may have a significant influence on the results. Often temperature coefficients are between -0.02 dB/°C and sometimes up to -0.12 dB/°C. Within an allowed temperature range of 35 °C, this can mean a variation from 0.7 to 4.2 dB, depending on the tyre and road surface.

There are recent investigations [Anfosso-Lédée, Pichaud, 2007; Bueno et al., 2011; Bendtsen et al., 2009] where the influence of temperature on tyre/road measurements has been investigated. Even if there are some differences in the findings, the main conclusion is that there seems to be a linear (negative) correlation between the air temperature and the measured noise levels. This should indicate that the temperature correction given in the tyre noise directive should be revised to have a linear correction over the whole temperature range allowed for measurements.

13.3 The CPX method

The tyre noise can also be measured using a CPX trailer. The CPX method (ISO/WD 11819-2, 2011) is primarily developed to measure the influence of the tyre/road noise component to the overall traffic noise, but is also suitable for the measurements of different tyres on the same road surface, as presented in previous chapters in this report.

The major characteristics of the CPX method:

Positive:

- Accounts well for road surface influence
- Not very sensitive for background noise
- Requires only one or two test tyres
- Fairly representative
- Measurements rather easy and inexpensive

Negative:

- Not useful under wet conditions
- Equipment rather expensive

Concerning measurement uncertainties, several investigations have studied this topic. In [de Roo et al., 2009] a presentation is given with the results from a round-robin test with 4 different CPX trailers measured on 8 different road sections in the Netherlands. The tests were done with different test tyres, but also a set of SRTT were tested with all trailers.

The tables in figure 13.1 summarise the findings

	A	Avon AV4	D	SRTT	SRTTR
Trailer	0,16 / 0,16	0,32 / 0,32	1,02	0,39 / 0,39	0,25 / 0,25
Mounting side	0,95 / -	0,83 / -		0,68 / -	0,47 / -
Residue	0,24 / 0,17	0,32 / 0,23	0,19	0,41 / 0,29	0,29 / 0,21
Total	1,00 / 0,23	0,94 / 0,39	1,03	0,88 / 0,49	0,60 / 0,32

	Preliminary estimation of uncertainty budget according to ISO-methodology
Trailer	0,44
Mounting side	0,10
Residue	0,27
Total	0,52

Figure 13.1 Standard deviation and respective uncertainties (blue= single and red= double mounting) [de Roo et al., 2009]

A new round-robin test of CPX trailers was conducted in 2011, by DWW/NL. In this test, not only Dutch trailers were participating, but also the Danish (DRI) trailer and a Belgian trailer. The trailers were again measured on a selection of different road surfaces, using their own reference tyres (SRTT + Avon AV4). One set of the SRTT was measured by all participants. Results from these measurements will be available later.

In the AOT project, M+P measured 12 car tyres on the Kloosterzande test area [Schwanen et al. 2007]. The CPX measurements were repeated several times, and even repeated both in 2006 and 2007. From the measurements on each of the 41 road sections, the 95 % expanded uncertainty for the LAeq levels at the speed was calculated for all the tyres. This uncertainty was for most of the combinations 0.1 dB and up to 0.3 dB for a few tyre/road combinations.
To investigate the run-to-run variations, several runs were repeated with different tyres at different speeds. The histogram of the difference in CPX levels is shown in figure 13.2. The average difference equals 0.0 dB, with standard deviation of 0.35 dB.

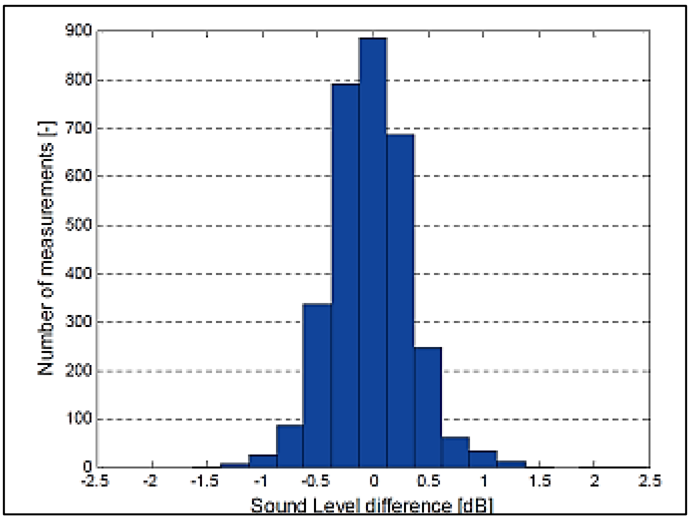

Figure 13,2 Histogram of the difference between repeated measurements on the same day

The year-to-year variation was also investigated. The difference in sound levels for some of the tyres is shown in figure 13.3. The value for each tyre is the average from 31 test sections. Most of the variation is less than 1 dB, except for some of the tyres, where the difference is 1.1 dB. For tyre 9 (Goodyear Ultragrip winter tyre), the difference is more than 1.5 dB. The reason for this is not discussed in the report.

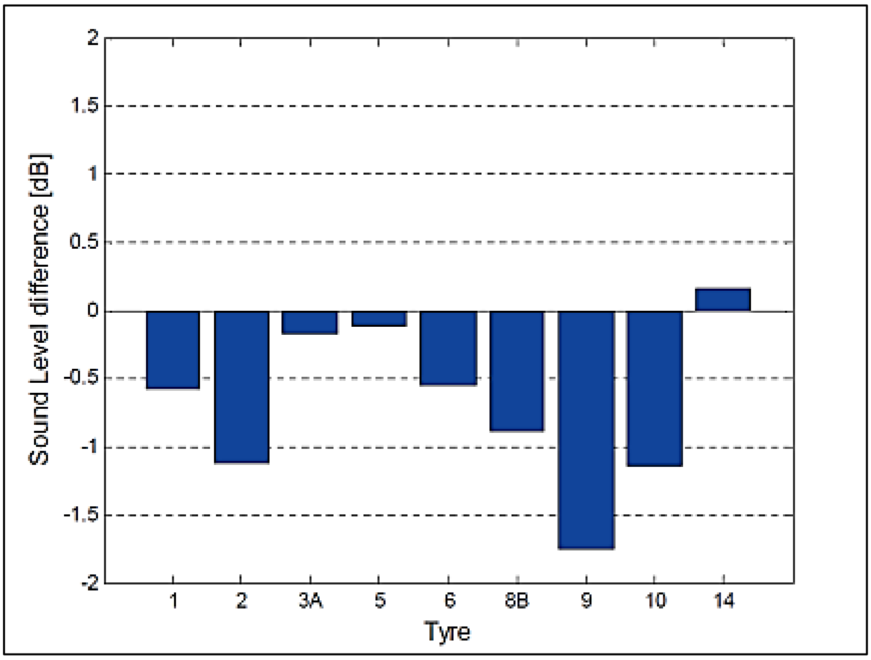

Figure 13.3 The year-to-year difference in L_{Aeq} at Kloosterzande

In the CPX-standard itself, there is an Annex K on the measurement uncertainty and typical values for the expanded uncertainty is given in table 13.2.

Table 13.2 Typical values for the expanded uncertainty in ISO/WD 11819-2

Coverage factor	Expanded uncertainty
80 %	± 0,7 dB
95 %	± 1,0 dB

14 Conclusions and recommendations

The introduction of a new labelling system in Europe from 2012, is a positive step to promote tyres that have a potential to reduce CO_2 emissions, reduce traffic noise (tyre/road noise) and at the same time provide the necessary safety properties (wet grip, etc.). The labelling of tyres may improve the awareness of the vehicle owners on these environmental issues.

Concerning noise labelling of tyres, there are several challenges, as this report has presented: From a Nordic perspective, the most important are:

- Due to significant differences between the ISO surface, used for type testing of noise from tyres and the types of surfaces used in some of the Nordic countries (like Norway and Sweden), the ranking of the tyres can be different on real roads than the labelled values indicate.
- The smooth ISO surface emphasize the importance of the tread pattern of tyres, which is not so relevant on rough-textured surfaces, as found in the 3 Nordic countries that uses studded winter tyres.
- The use of the smooth ISO surface can lead to sub-optimisation of tyre noise performance, which is not reflected on other types of road surfaces.
- The labelled noise value is based on measurement on a single ISO track. Due to track-to-track variations of more than 5 dB, the uncertainty of the labelled value is rather high for consumer information. The improvement of the ISO 10844 standard can reduce this spread in the future.

The best way to improve this situation would be either to motivate the use of more "ISO-like" type of road surfaces on the roads where there is significant traffic noise problems, and/or to include a rougher textured surface in the tyre noise regulation scheme. ISO WG42 (TT), who has been working with the revision of ISO 10844, shall consider the use of a second surface for tyre noise testing.
Based on the literature review, the following conclusions can be made:

- On ISO surfaces, based on type testing data, there is a spread in noise levels from passenger tyres (C1) of 10 dB (from 66 to 76 dB(A)). This spread includes the fact that it covers tyres of widths below 185 mm to above 275 mm, and also measurement data from different ISO tracks. The influence of the ISO track variation may be a more significant than the variation in tyre width.
- For normal C2 tyres, the spread is from 68 to 75 dB(A), for snow tyres from 71 to 77 dB(A).
- For normal C3 tyres, the spread is from 67 to 78 dB(A), for snow/traction tyres from 71 to 80 dB(A).
- Based on CPX measurements on a single ISO track, the spread in levels are somewhat lower, in the range of 6-7 dB for summer tyres for cars.
- Already approximately 55 % of the present fleet of car tyres in the most common dimensions (C1B: 195, 205, 215 mm) meet the new noise limit from 2012. This should indicate a need for further reduction of the noise limits.
- Among summer tyres for cars, on typical Norwegian dense pavements, a spread in noise levels of only 2-3 dB has been found. It is likely that the situation is the same in Sweden and Finland. Since vehicles in Denmark are not using studded tyres, it is likely that the spread in noise levels from tyres is larger here. The spread among roads of the same types (not including new surface)in Norway is about the same; 2-3 dB.
- The road influence on the variation in tyre/road noise levels in the Nordic countries is much larger than the tyre influence. A combination of a new good open graded dense asphalt in

Denmark (AC6o) with 6 mm maximum chipping size and a low-noise tyre (Michelin Primacy LC) gave a reduction of approximately 13 dB, compared to the noise level on a old SMA16 surface in Norway, with a "noisy" tyre.

- On Norwegian road surfaces, a combination of tyre/road can give around 5 dB variation in levels, while a variation of 7-8 dB was found on Danish road surfaces.
- Tyre/road noise seems to be approximately 2-3 dB ***higher*** on the most common Norwegian road surfaces like SMA11, than on similar Danish road surfaces. Similar Swedish road surfaces seem to give 1-1.5 dB ***higher*** noise levels than in Norway. This is probably caused by a significant higher percentage of studded tyres during the winter season than in parts of Norway. Since Finland has about the same percentage of studded tyres (~ 85 %), it is assumed that the tyre/road noise levels here are comparable to Sweden.
- Studded tyres are considered to be 2-4 dB more noisy than non-studded in the speed range 50-80 km/h, but this is based on data nearly 10 years old.
- A non-studded winter tyre was found to be 4-5 dB quieter than normal summer tyres on a Danish road surfaces, and at a temperature of + 13 °C.
- SMA/DAC11 types of surfaces are considered reference surfaces in Norway, Sweden and Denmark. It is the most common used road surface in Norway and Sweden. In Finland, SMA16 is the reference.
- There seems to be no significant differences in the noise ranking of tyres between 50 and 80 km/h.
- Based on vehicle statistics, the most common tyre dimensions of new passenger car tyres in Norway, Sweden and Finland seem to be tyres of 205-215 mm widths. In Denmark, smaller widths, like 185-195 mm may be more common, due to larger sale of smaller cars (Note: Danish tyre fleet not yet confirmed).
- Rolling resistance with different types of tyres on different types of road surfaces has been measured in Sweden and Denmark
- No correlation has been found between type testing noise levels and speed index of tyres.
- No correlation has been found between type testing noise levels and rolling resistance or wet grip.

Recommendations for further work:

There seems to be no good relationship between the labelled levels of C1 tyres and results of measurements on typical rough-textured pavements found in Norway and Sweden (presumably also in Finland). But this is on the basis of a relatively small number of tyres measured.

There is a need to measure the performance of a larger number of tyres on selected road surfaces in all the Nordic countries (except Iceland and in this project, surfaces in Finland will be represented by surfaces in Sweden). The motivation is:

- To evaluate the efficiency of the new labelling system
- To clarify which combinations of tyres and road surfaces that yields the lowest emission levels
- To promote the use of more "ISO-like" type of road surfaces as a mitigation tool to reduce traffic noise
- To motivate for the use of a more representative road surface during type approval of noise levels of tyres

Outline for a measurement program:

- It is recommended to use a CPX trailer for noise measurements, and preferably a two-wheeled trailer, as the use of such a device would ensure that tyres are running in the wheel tracks:

  - Two individuals of each tyre line are recommended.

- With two identical tyres, the noise levels in the left and right wheel track can be averaged.
- Good correlation with coast-by levels.
- Several different pavement types can be measured during the same run, if they are close together.

- The number of tyres should be minimum 20 tyres, preferably around 30. The tyres should be selected on the basis of available labelling levels on sound levels. The tyre manufacturers dominating the Nordic market, such as Continental, Michelin, Goodyear and Nokian must be part of the selection. It is recommended to include the SRTT tyre for comparison with other, standardised measurements of tyre/road noise,
- The tyre section width should vary from 185 to 225 mm.
  Based on a number of tyres of 30, the following distribution can be chosen:
  Summer tyres: N=15 (all C1 classes, highest number with 205/215 mm.
  All-year tyres: N=10
  Winter (non-studded) tyres: N=5
  The number of tyres in each class of C1 is not yet defined, and should be discussed within the project group.
- All tyres shall be brand new, except for the prescribed run-in distance of 100 km.
- The main group of tyre selected should be tyres with a labelled noise level at or below the new noise limit for the specific type of tyre class.
- All tyres shall be measured on selected surfaces in Denmark, Sweden and Norway
- If possible, both 50 and 80 km/h should be measured, as there may be posted speed limits of less than 80 km/h on a site.
- The road surfaces in all countries shall include SMA11/DAC11 type of pavements. The aim is to include representative "average age" pavements in the different countries. Areas with different traffic load and use of studded winter tyres (Norway/Sweden) should be included.
- The fleet of tyres should include some tyres developed for the Asian market, such as the Michelin Primacy LC and a new Yokohama dB tyre.
- Rolling resistance measurements on a laboratory drum should be made of all tyres
- If possible, measurements at different temperatures (at the same location/pavements) should be included.

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Front page picture is taken from an information movie on the EU-labelling of tyres by Continental (http://www.conti-online.com/generator/www/no/no/continental/automobile/themes/tirelabel/eu_label_movie_no.html), by permission of Frank Larsen, Continental Norge.

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