SINTEF REPORT

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TITLE

Tyre/road noise modelling:
Measurements of passenger car tyres on an ISO track and frequency analysis of results.

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ABSTRACT

22 passenger car tyres have been measured on the ISO surface at the Kloosterzande test track in the Netherlands. All measurements have been done with the Norwegian CPX-trailer.
The results are compared to similar measurements on different road surfaces in Norway, including normally used SMA surfaces.
The analysis show that the ranking on the ISO surface differs significantly from the ranking on SMA surfaces exposed to winter conditions and studded tyres. The correlation is improved if the ISO-levels are compared to surfaces not exposed to winter conditions.

A 1/3rd octave band frequency analysis have been performed on all CPX-measurements, and compared with *SPERoN* modelling results. The analysis shows that there is some correlation at the low frequency (315 Hz), but zero or negative correlation at higher frequencies. The lack of correlation can be related to comparing levels within the uncertainty range of the *SPERoN* model and uncertainty in the relationship between near field measurements (CPX) and far field (CPB) modelling.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Acoustics	Akustikk
GROUP 2	Noise	Støy
SELECTED BY AUTHOR	Tyres	Bildekk
	ISO surface	ISO-dekke
	Frequency analysis	Frekvensanalyse

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Foreword

This report presents the results from projects jointly financed by the Norwegian Public Roads Administration and the Norwegian Research Council, and a project financed by the Norwegian Pollution Control Authorities (SFT).

Contact persons at the Roads Administration have been Jannicke Sjøvold and Ingunn Milford. Contact person at SFT has been Jan Boe Kielland.

Research Scientist Truls Berge has been the project leader and engineer Frode Haukland partly responsible for the noise measurements.

1 Introduction

In previous studies[1, 2, 3] 10 to15 passenger car tyres have been investigated through CPX-measurements on existing road surfaces in Norway and also measured on different replica of road surfaces on a laboratory drum facility in Gdansk/Poland. In addition, 11 of the tyres have been modelled using the *SPERoN* model on an ISO track and on a selection of typical Norwegian road surfaces, where texture data have been available. Using all these approaches, it has been shown that it is difficult to use these results to rank the noise level based on overall A-weighted maximum sound levels only, by comparing modelling and measurement (CPX/drum) conditions.

The overall aim of the project has been to study the ranking of noise levels of frequently used passenger car tyres on normal road surfaces in Norway, compared to the ranking on a standard ISO surface, used for type approval of noise levels for tyres[4].

The use of the *SPERoN* model did not give the sufficient information. It is probably due to the following reasons:

- Based on overall A-weighed levels only, there was no correlation between measured and modelled results on the ISO track (Sperenberg) or on the SMA surfaces in Norway. This could be somewhat expected: The noise generation mechanism of a tyre running over a road texture is a complex system and has a non-linear behaviour in the frequency domain.
- The spread in level for one tyre using the model on a range of the Norwegian road surfaces is small – about 1.5 dB(A), which is in the range of the uncertainty of the model itself.

To improve the foundation for the evaluation of noise behaviour of the tyres, it was decided to include CPX-measurement of the tyres on an existing ISO track.

This report presents the results of measurements on the ISO track at the test area in Kloosterzande, the Netherlands. In addition, a frequency analysis has been performed on a selection of measurement and modelling results, to study correlations based on linear regression.

2 Tyres

In table 1, all the tyres that were measured in Kloosterzande are listed.
The numbering of tyres 1-15 is in accordance with previous reported results[2].

Table 1 *Tyres and technical data*

Tyre no	Name	Dimensions	Load/ Speed index	Prod. week/ year	Shore hardness – Tread 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 dB AVS500**	**185/65 R15**	92 H	1604	73
14	**Hankook Ventus Prime K105**	**205/65 R15**	95 W	5207	67
15	**Pirelli P7**	**205/65 R15**	94 V	0707	64
42	**Uniroyal Tigerpaw SRTT**	**225/60 R16**	97 S	4206	65
43	**Uniroyal Tigerpaw SRTT**	**225/60 R16**	97 S	4206	66
44	**Avon AV4**	**195/80 R14**	106/104N	0607	62
45	**Avon AV4**	**195/80 R14**	106/104N	0607	62
13	**Michelin Energy Saver**	**205/65 R15**	94 T	1508	70
46	**Michelin Energy Saver**	**205/65 R15**	94 T	1508	70
47	**Michelin Energy Saver**	**205/65 R15**	94 T	1709	68
48	**Michelin Energy Saver**	**205/65 R15**	94 T	1709	69

Tyres 42-45 are the new standard reference tyres for the CPX-method (to be published as ISO/TS 11819-3).

Tyre 13 was also measured in the previous investigation[2], and since the noise levels were in the high range on several road surfaces, it was decided to include 3 more samples in this test. The intention was to compare these 4 tyres not only during CPX-measurements, but also to include controlled pass-by (CPB) measurements (a “type approval test”) with the tyres mounted on a test vehicle. However, these measurements had to be skipped, due to rim problems.

3 Measurement set-up

The measurements were performed at the test area (a former road, now closed for traffic) in Kloosterzande, the Netherlands.
Measurements were performed on the 29th of September 2009. The weather was overcast, no rain and with and air temperature of + 19 °C and a road surface temperature of + 24 °C. The wind was moderate to calm and always below 5 m/s.

All measurements were done using the CPX-trailer of the Norwegian Public Roads Administration, as shown in figure 1.

Figure 1 *CPX-trailer*

The tyres were mounted on the trailer according to table 2.

Table 2 *Tyre mounting*

Set no	Tyre no	Mounting side **R**ight/**L**eft
1	1 Dayton T110	R
	2 Sportiva G70	L
2	3 Barum Brilliantis	R
	4 Toyo 330	L
3	5 Goodyear Excellence	R
	6 Conti PremiumContact2	L
4	7 Toyo Proxes T1R	R
	8 Nokian Hakka H	L
5	9 Michelin Pilot Primacy	R
	10 Firestone Firehawk	L
6	11 Conti EcoContact 3	R
	12 Yokohama dB AVS	L
7	15 Pirelli P7	R
	14 Hankook Ventus Prime	L
8	13 Michelin Energy Saver	R
	46 Michelin Energy Saver	L
9	47 Michelin Energy Saver	R
	48 Michelin Energy Saver	L
10	44 Avon AV4	R
	45 Avon AV4	L
11	42 Uniroyal SRTT	R
	43 Uniroyal SRTT	L

For tyres 1-15 and 46-48 the tyre pressure was 180 kPa, and 200 kPa for tyres 42-45 (CPX-reference tyres).

4 Measurement results

4.1 Result from the ISO surface

The measurement results are given separately for each run/wheel track and as well as the average of two runs/wheel tracks. One run was in the north driving direction and one run in the south direction, except for tyres 1 to 4, and the CPX-reference tyres, which were measured in one direction (north) only and with one run only.
The length of the ISO track is approx. 80 m long and the whole section is included in the analysis.

Table 3 and 4 shows results at 50 km/h and 80 km/h, with no temperature correction applied (air temperature was + 19 °C).

Table 3 *CPX-measurement on the ISO track, 50 km/h*

Tyre no	Tyre	Run 1 Wheel track	Run 1 La, dB(A)	Run 2 Wheel track	Run 2 La, dB(A)	Average dB(A)
1	**Dayton D110**	East	85.2	East	85.6	**85.4**
2	**Sportiva G70**	West	87.6	West	88.1	**87.9**
3	**Barum Brilliantis**	East	88.4	East	88.6	**88.5**
4	**Toyo 330**	West	87.8	West	88.0	**87.9**
5	**Goodyear Excellence**	West	87.1	East	86.6	**86.8**
6	**Conti Prem.Contact 2**	East	86.4	West	86.4	**86.4**
7	**Toyo Proxes T1R**	West	86.1	East	86.0	**86.1**
8	**Nokian Hakka H**	East	85.2	West	85.5	**85.4**
9	**Michelin Pilot Primacy**	West	85.1	East	84.9	**85.0**
10	**Firestone Firehawk**	East	85.9	West	85.8	**85.9**
11	**Conti EcoContact 3**	West	86.0	East	85.6	**85.8**
12	**Yokohama dB AVS500**	East	84.9	West	84.7	**84.8**
14	**Hankook Ventus Prime**	East	86.1	West	85.8	**86.0**
15	**Pirelli P7**	West	88.6	East	66.5	**88.6**
42	**Uniroyal SRTT**	East	87.0	East	-	**87.0**
43	**Uniroyal SRTT**	West	87.1	West	-	**87.1**
44	**Avon AV4**	East	89.0	East	-	**89.0**
45	**Avon AV4**	West	88.8	West	-	**88.8**
13	**Michelin Energy Saver**	West	88.1	East	87.9	**88.0**
46	**Michelin Energy Saver**	East	87.9	West	87.9	**87.9**
47	**Michelin Energy Saver**	West	87.4	East	86.8	**87.1**
48	**Michelin Energy Saver**	East	86.7	West	86.4	**86.6**

Table 4 *CPX-measurement on the ISO track, 80 km/h*

Tyre no	Tyre	Run 1		Run 2		Average dB(A)
		Wheel track	La, dB(A)	Wheel track	La, dB(A)	
1	**Dayton D110**	East	93.4	East	93.5	**93.5**
2	**Sportiva G70**	West	95.7	West	95.8	**95.8**
3	**Barum Brilliantis**	East	95.0	East	94.9	**95.0**
4	**Toyo 330**	West	95.1	West	94.6	**94.9**
5	**Goodyear Excellence**	West	93.4	East	92.9	**93.2**
6	**Conti Prem.Contact 2**	East	93.3	West	93.9	**93.6**
7	**Toyo Proxes T1R**	West	93.0	East	93.0	**93.0**
8	**Nokian Hakka H**	East	92.3	West	92.6	**92.5**
9	**Michelin Pilot Primacy**	West	92.4	East	93.0	**92.7**
10	**Firestone Firehawk**	East	93.1	West	93.3	**93.2**
11	**Conti EcoContact 3**	West	93.3	East	93.2	**93.3**
12	**Yokohama dB AVS500**	East	91.4	West	91.2	**91.3**
14	**Hankook Ventus Prime**	East	93.1	West	92.9	**93.0**
15	**Pirelli P7**	West	96.1	East	95.8	**96.0**
42	**Uniroyal SRTT**	East	93.9	East	-	**93.9**
43	**Uniroyal SRTT**	West	96.4	West	-	**96.4**
44	**Avon AV4**	East	97.8	East	-	**97.8**
45	**Avon AV4**	West	95.5	West	-	**95.5**
13	**Michelin Energy Saver**	West	96.1	East	96.1	**96.1**
46	**Michelin Energy Saver**	East	96.7	West	96.8	**96.8**
47	**Michelin Energy Saver**	West	94.3	East	94.3	**94.3**
48	**Michelin Energy Saver**	East	94.8	West	94.7	**94.8**

In figure 2, the average levels in tables 3 and 4 are presented.
The data is sorted so the tyres with the smallest widths (175 mm, se table 1) are to the left and the widest tyres (225 mm) are to the right.

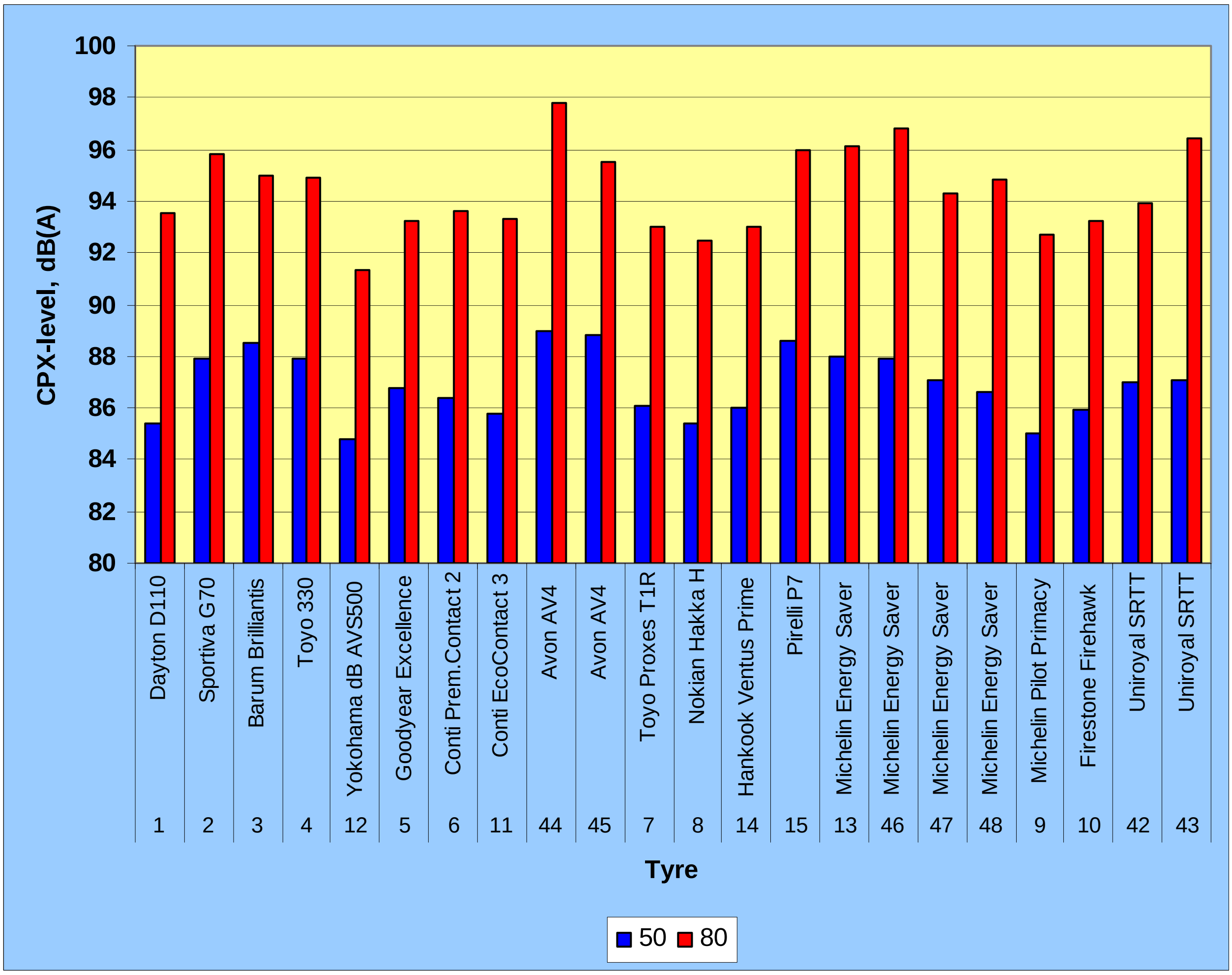


Figure 2 *CPX-measurements at the ISO track at Kloosterzande, 50 and 80 km/h.*

Some conclusions can be made from these results:

- The spread in levels are approximately **4 dB(A)** at 50 km/h and **6 dB(A)** at 80 km/h.
- The highest levels are measured with the CPX-reference tyres Avon AV4, which have a rather aggressive block tread pattern (to simulate noise from truck tyres). But, even if these tyres are not included in the comparison, the range in noise levels is in the same area.
- There seems to be no relationship between measured CPX-levels and the width of the tyres included in this test.
- The two SRTT-reference tyres have similar noise levels at 50 km/h. However, at 80 km/h, there is a clear difference of about 2.5 dB(A). The same was found for the two Avon AV4-tyres; a difference of 2.3 dB(A) at 80 km/h. This indicates a different speed dependency of two more or less identical tyres, which is of concern, since these tyres (SRTT and Avon) recently have been selected as new reference tyres in the CPX-standard.
- The noise levels of the 4 Michelin tyres can be separated according to production date. The two tyres from week/year 1508 are approximately 1-2 dB(A) noisier than the two tyres from 1709. The newest tyres have slightly lower shore hardness, but the difference is so small that it would not explain such a difference. Other production variances must be the main reason.

In addition to the ISO surface, all tyres have been measured on surfaces 2-23 on the test area, including a new poroelastic surface (Surface 12: Rollpave PERS). The results from these measurements are not included in this report.

4.2 Influence of wheel track

Previous measurements at the test track[5] have shown that there is a slight difference in the texture spectra in the east and west wheel track. The west wheel track has about 2-4 dB lower texture levels over the measured range of 1 to 200 mm. Thus, one could expect somewhat lower noise levels when the tyres run in the **west** wheel track. This is the main reason to do a separate analysis of the results for each wheel track.

According to the results in table 4, the levels of the two sets of reference tyres (SRTT/Avon) vary with more than 2 dB(A) at 80 km/h. These tyres was measured in one direction only and therefore it was of interest to study the difference in noise levels for the other tyres driven in both wheel tracks, too see if the difference in the texture could explain this.

In the figures 5-24 a blue column is given for a tyre running on the **east** wheel track and red column for a tyre running on the **west** wheel track.

For the reference tyres, SRTT/Avon (figures 5 and 6), one tyre is running on the east and one on the west track, as the driving direction was the same for all runs. This is also the case for tyres 1-4 (two runs on the same wheel track), as shown in figures 7-10.

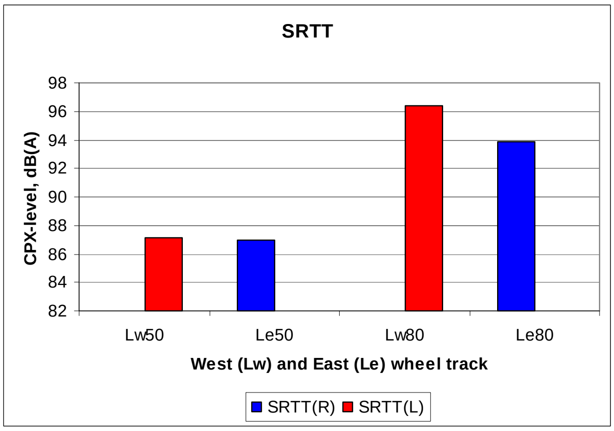


***Figure 5** Tyres 42 and 43 - SRTT*

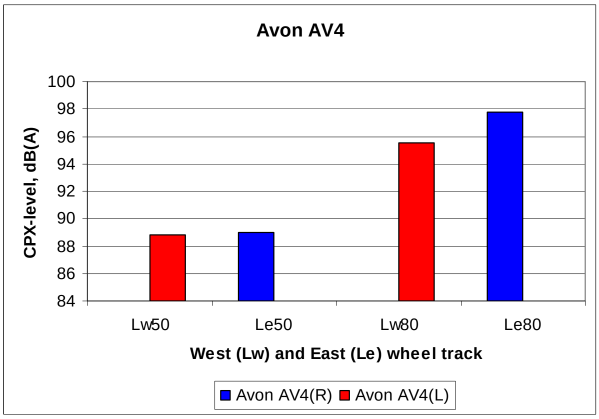


***Figure 6** Tyres 44 and 45 – Avon AV4*

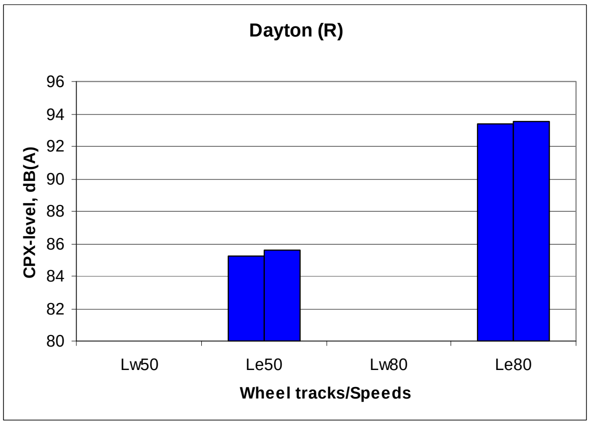


***Figure 7** Tyre 1 Dayton T110*

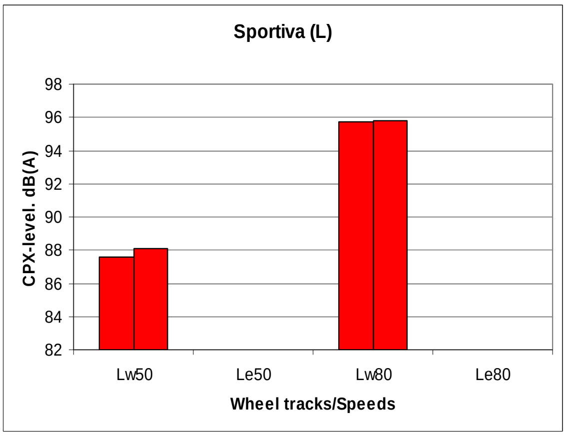


***Figure 8** Tyre 2 Sportiva G70*

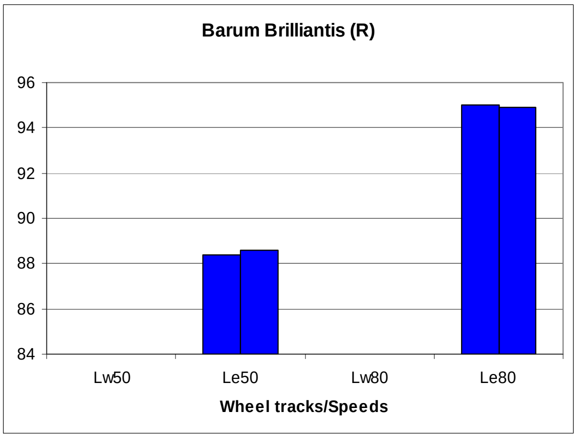


Figure 9 *Tyre 3 Barum Brilliantis*

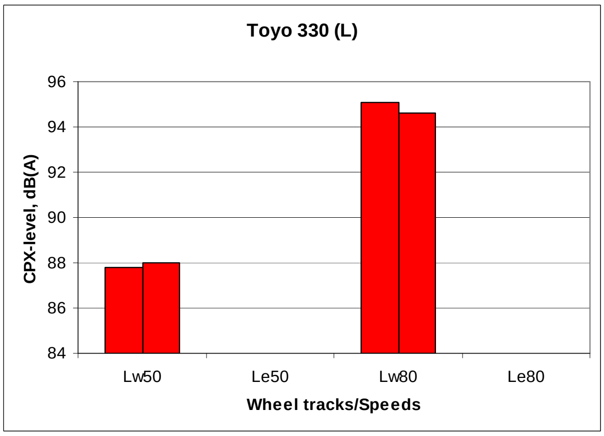


Figure 10 *Tyre 4 Toyo 330*

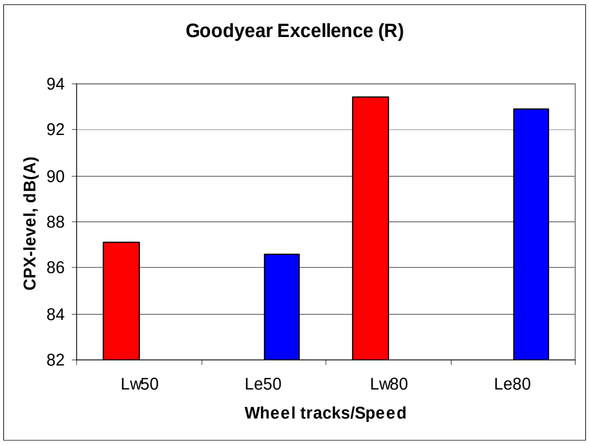


Figure 11 *Tyre 5 Goodyear Excellence*

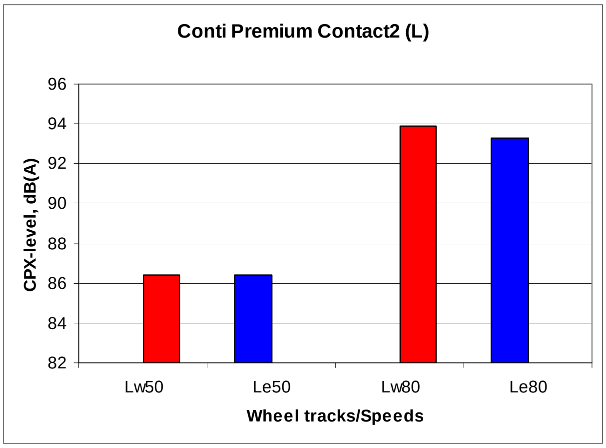


Figure 12 *Tyre 6 Conti Premium Contact2*

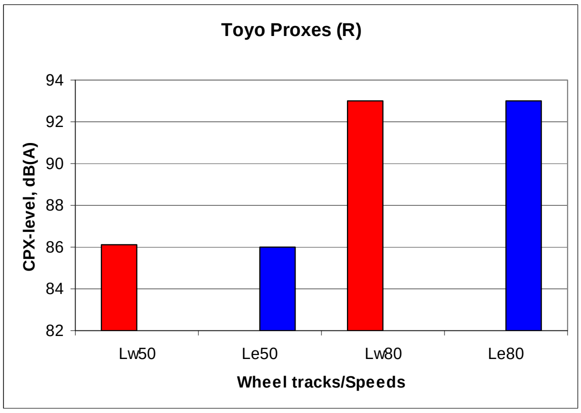


Figure 13 *Tyre 7 Toyo Proxes T1R*

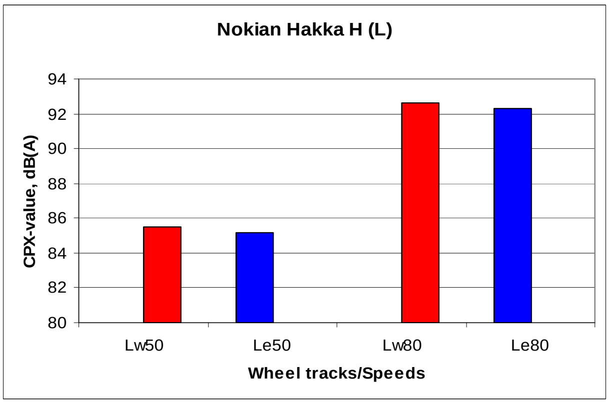


Figure 14 *Tyre 8 Nokian Hakka H*

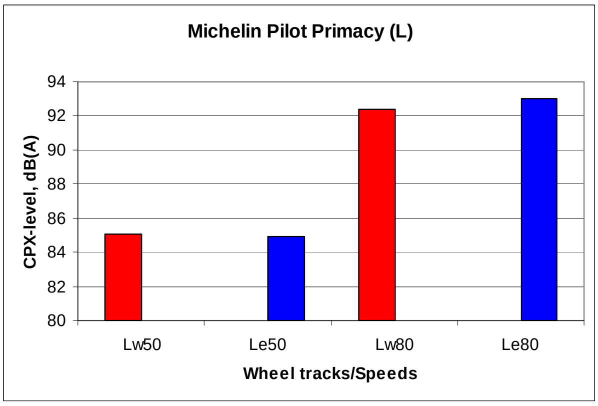


Figure 15 *Tyre 9 Michelin Pilot Primacy HP*

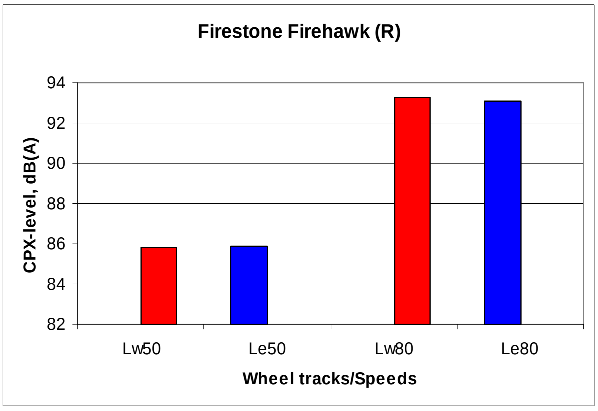


Figure 16 *Tyre 10 Firestone Firehawk TZ200*

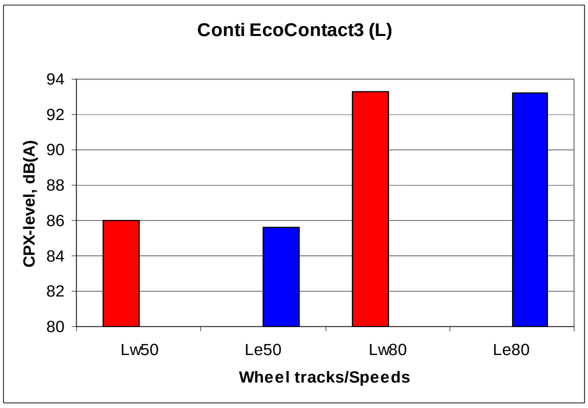


Figure 17 *Tyre 11 Conti EcoContact3*

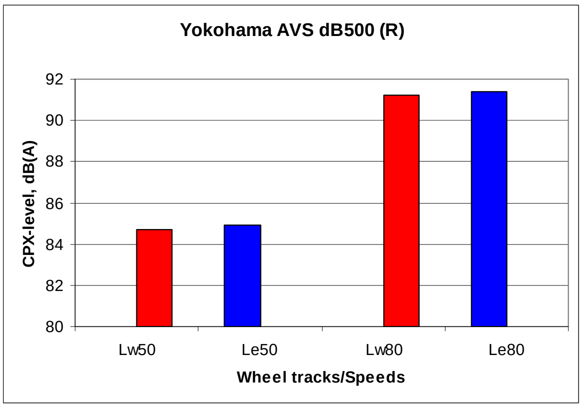


Figure 18 *Tyre 12 Yokohama AVS dB500*

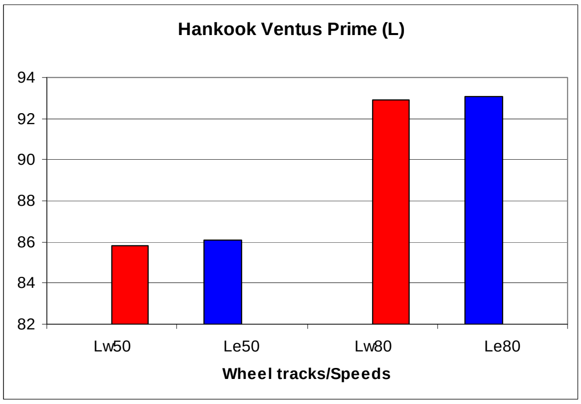


Figure 19 *Tyre 14 Hankook Ventus Prime*

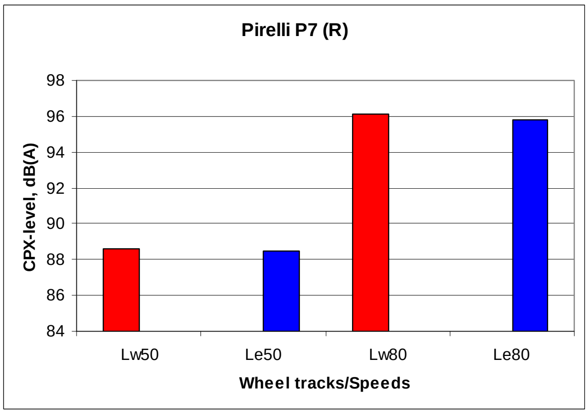


Figure 20 *Tyre 15 Pirelli P7*

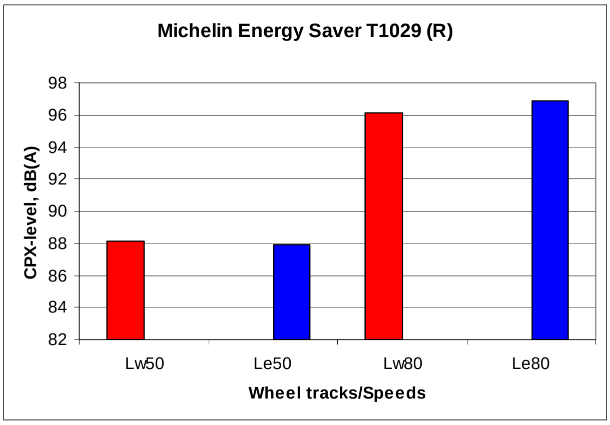


Figure 21 Tyre 13 Michelin Energy Saver

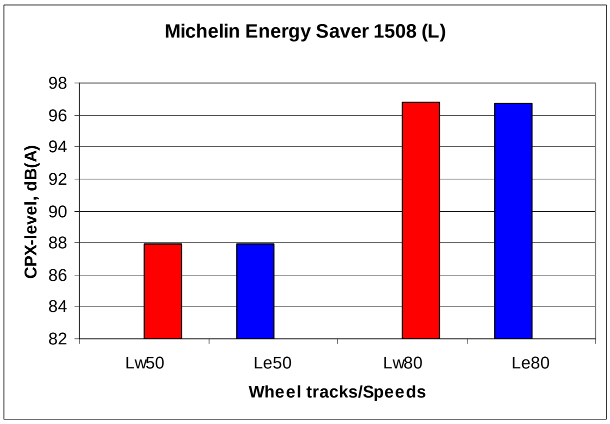


Figure 22 Tyre 46 Michelin Energy Saver

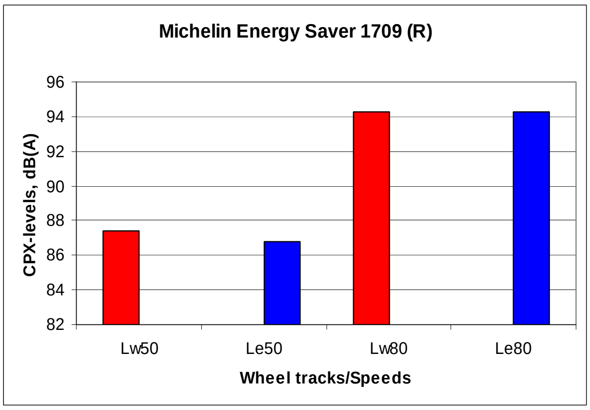


Figure 23 Tyre 47 Michelin Energy Saver

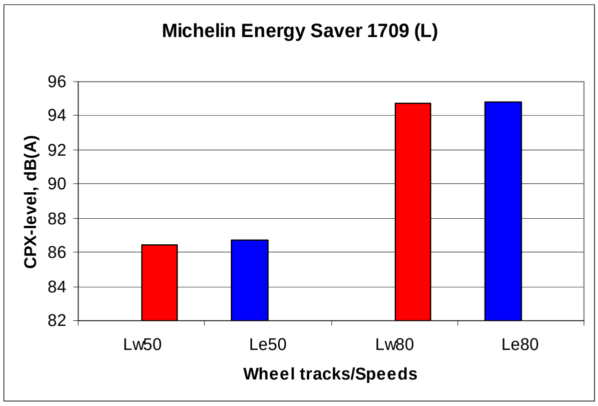


Figure 24 Tyre 48 Michelin Energy Saver

The results show no real influence on the measured CPX-levels by the small differences in the texture spectra in the two wheel tracks. The variation is within the repeatability of the measuring method. Thus, the differences at 80 km/h of the reference test tyres (figures 5 and 6) could not be related to the road surface, but must be caused by some tyre related parameters. However, the road surface could ***excite*** such noise differences. A further analysis of the measurement results on other road surfaces at the Kloosterzande test area is necessary to investigate possible speed related behaviour.

4.3 Comparison with the *SPERoN* modelling results

Tyres 1-11 have previously been modelled with the *SPERoN* tyre/road interaction model[3], using the texture spectra of the ISO surface at the Sperenberg test area.

In table 5 and figures 25 and 26, the *SPERoN* modelling results are compared with the results from Kloosterzande. The *SPERoN* model gives results at a distance of 7.5 m. For comparison reasons, all the CPX-results at Kloostezande have been recalculated to 7.5 m using an average difference of 22.5 dB(A) of the propagation filter between CPX and CPB, as found by Anfosso-Lédée[6] for dense surfaces. In the figures, the tyres are sorted according to tyre width.

Table 5 Comparison of SPERoN modelling and measurements, Kloosterzande. Speeds: 50 and 80 km/h. All values in dB(A) at 7.5 m.

Tyre no	Tyre	SPERoN 50	SPERoN 80	ISO Kloosterzande 50	ISO Kloosterzande 80
1	Dayton D110	65.7	73.6	62.9	71.0
2	Sportiva G70	65.7	71.8	65.4	73.3
3	Barum Brilliantis	65.5	70.7	66.0	72.5
4	Toyo 330	65.8	71.9	65.4	72.4
5	Goodyear Excellence	65.5	75.9	64.3	70.7
6	Conti Prem.Contact 2	66.2	71.6	63.9	71.1
7	Toyo Proxes T1R	66.1	71.7	63.6	70.5
8	Nokian Hakka H	66.4	72.3	62.9	70.0
9	Michelin Pilot Primacy	66.5	74.6	62.5	70.2
10	Firestone Firehawk	67.0	75.0	63.4	70.7
11	Conti EcoContact 3	65.9	72.1	63.3	70.8
	Average	66.0	72.8	64.0	71.2
	Max difference	1.5	5.2	3.5	3.3

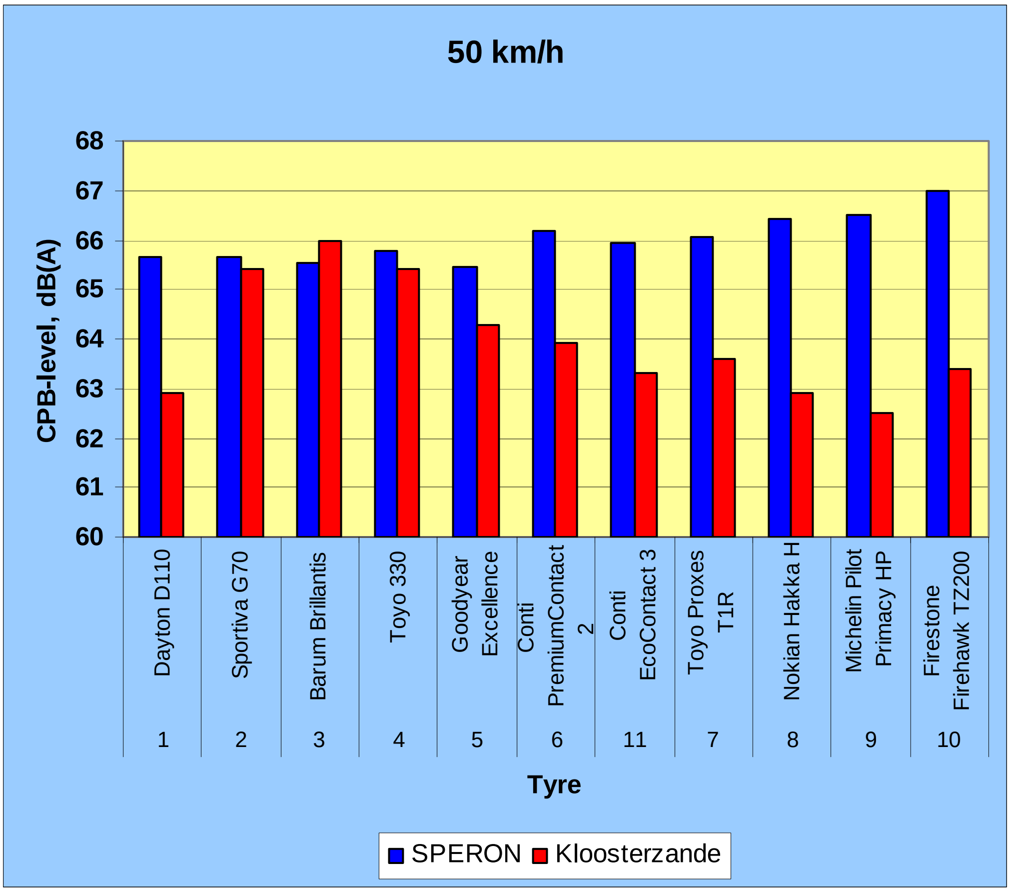


Figure 25 *SPERoN model (ISO) and Kloosterzande (ISO), 50 km/h*

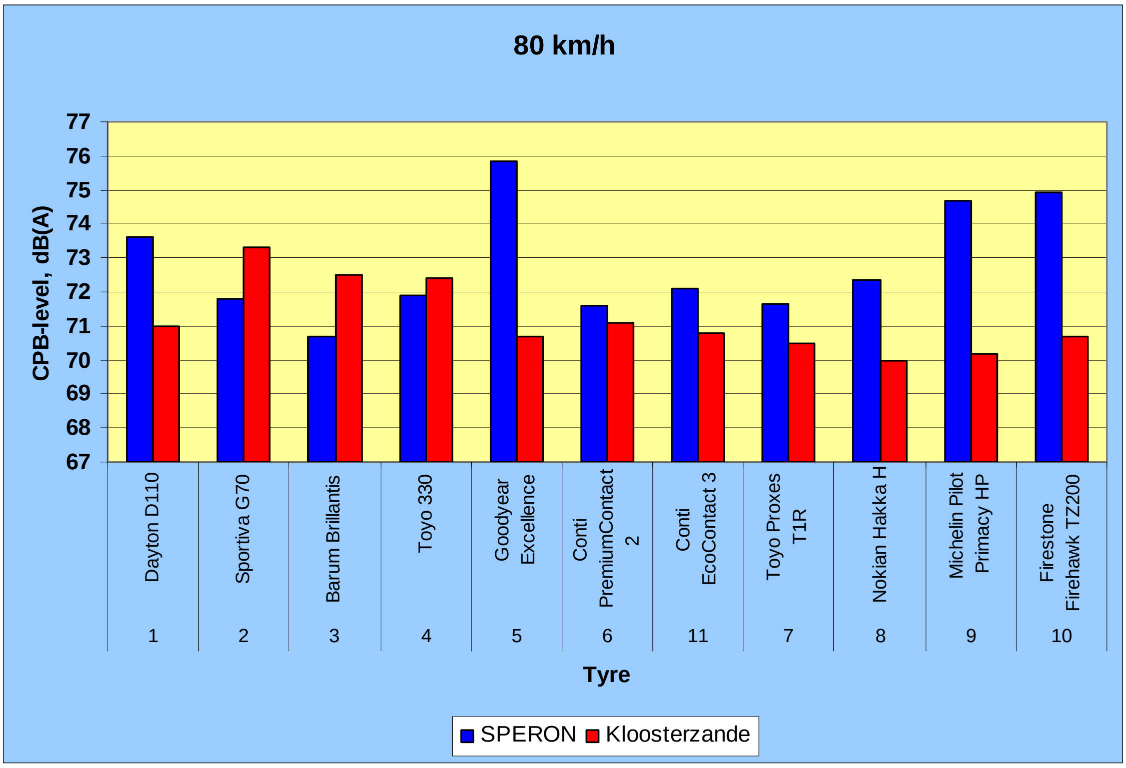


***Figure 26** SPERoN model (ISO) and Kloosterzande (ISO), 80 km/h*

From these figures, it is clear that there is no positive correlation between the ranking of the tyres using the Sperenberg ISO surface with the *SPERoN* model and the actual measurements on the ISO surface at Kloosterzande, based on overall A-weighted sound levels. Technically, there could be differences between these two ISO surfaces, but it is unlikely that this could explain this lack of correlation. A more detailed frequency analysis has been made on the datasets and is presented in Chapter 5.1.
From table 5, it seems that the *SPERoN* model overestimates the results at 50 km/h, while underestimate the levels somewhat at 80 km/h, compared to measurements. However, this comparison is influenced both by the uncertainty of the model, and by the accuracy of the propagation filter applied for CPX-results.

4.4 Comparison with measurements on Norwegian road surfaces

One major reason to do actual measurements on the ISO surface at Kloosterzande test track was to be able to compare results where the measuring principle and equipment are identical.
It is then possible to do direct comparison of the Kloosterzande results, and measurements on typically used surfaces in Norway. In this analysis, it is distinguished between surfaces that have been in-use for at least one winter season, and newly laid (low noise) surfaces, not exposed to winter conditions. All tyres have been measured at 50 km/h and at 80 km/h. In the analysis, the comparison has been done at both speeds, to investigate if the ranking is speed dependent.

4.4.1 Older surfaces

In 2007, tyres 1-11 have been measured on a SMA11 surface (Omkjøringsveien, Surface 1[1]), when this surface was 2 years old. In figure 27 and 28 the results at 50 and 80 km/h are compared with the Kloosterzande results. The tyres are sorted according to noise levels at the ISO surface at Kloosterzande test track.

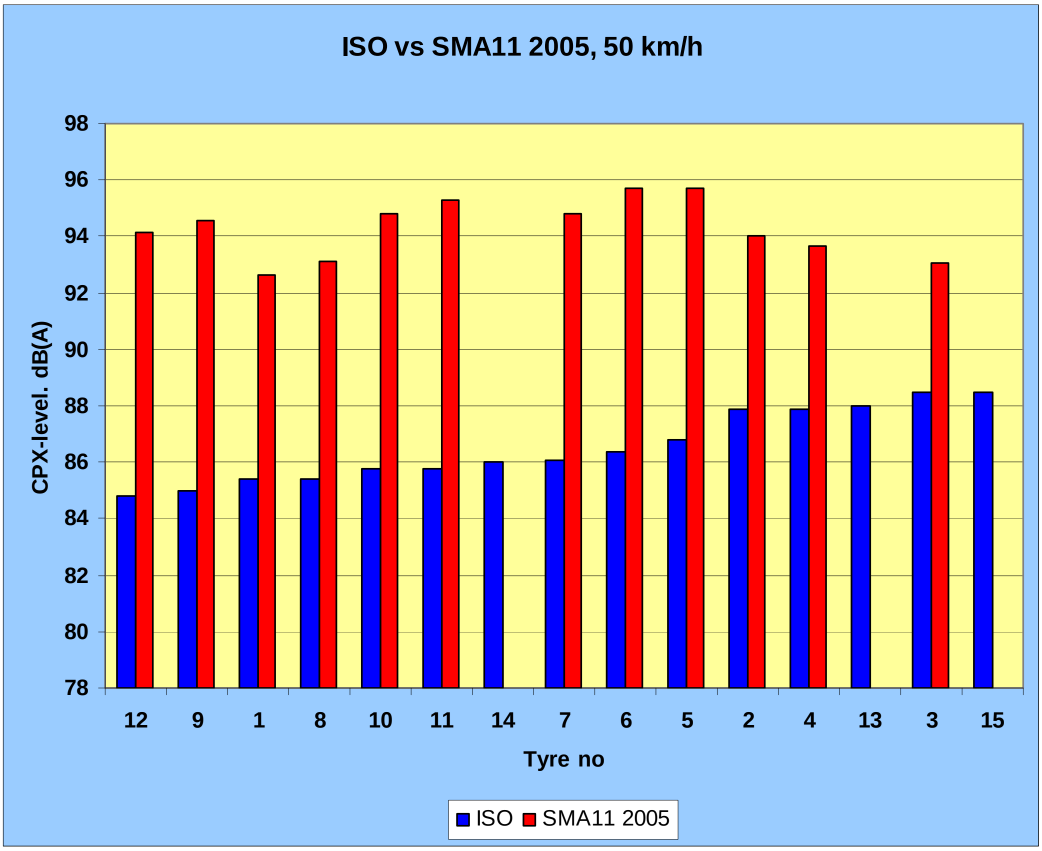


Figure 27 *SMA11 2005 and ISO surface at Kloosterzande, CPX-levels at 50 km/h.*

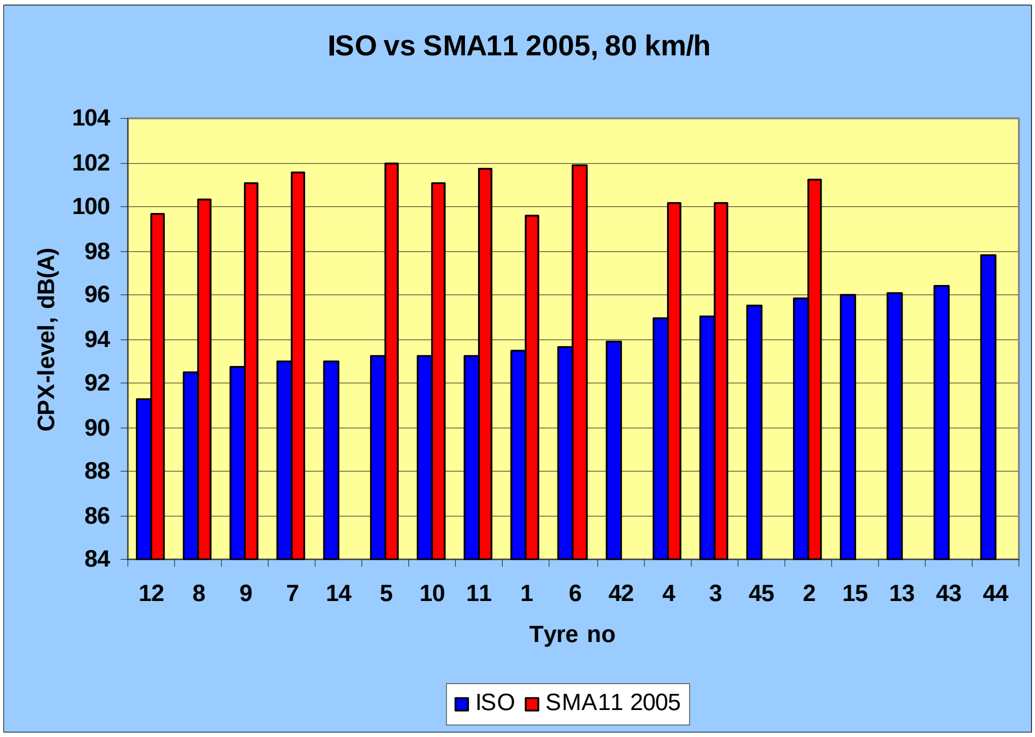


Figure 28 *SMA11 2005 and ISO surface at Kloosterzande, CPX-levels at 80 km/h.*

In figures 29 and 30, the correlation between the two tests is shown for each speed.

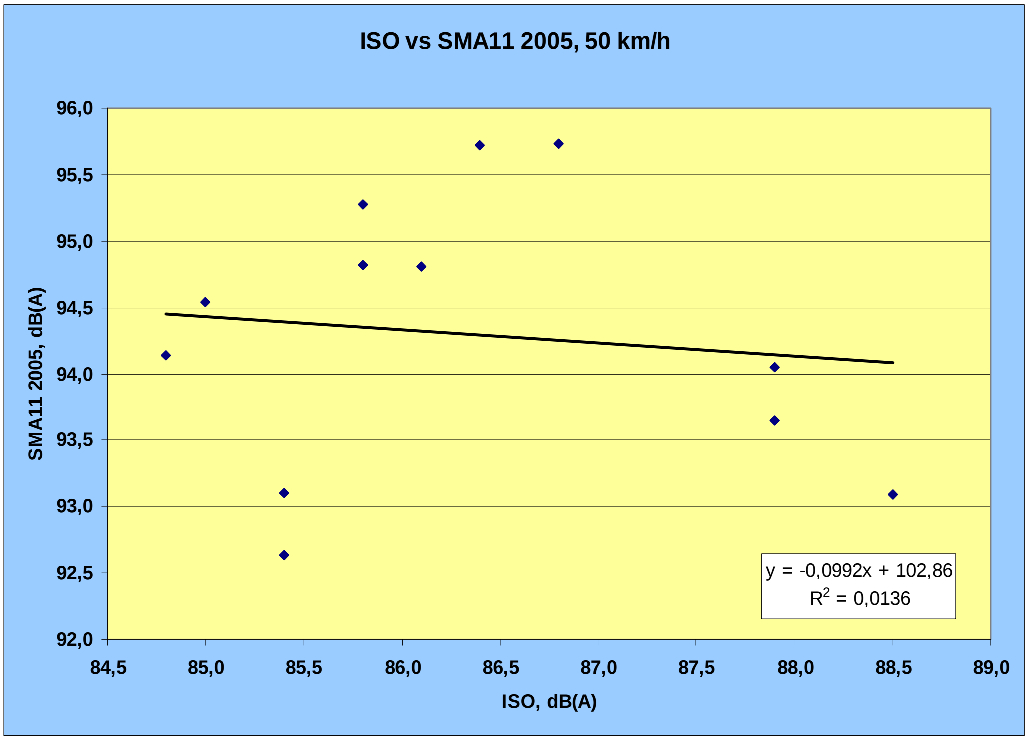


Figure 29 *Correlation between SMA11 2005 and ISO surface at Kloosterzande, CPX-levels at 50 km/h.*

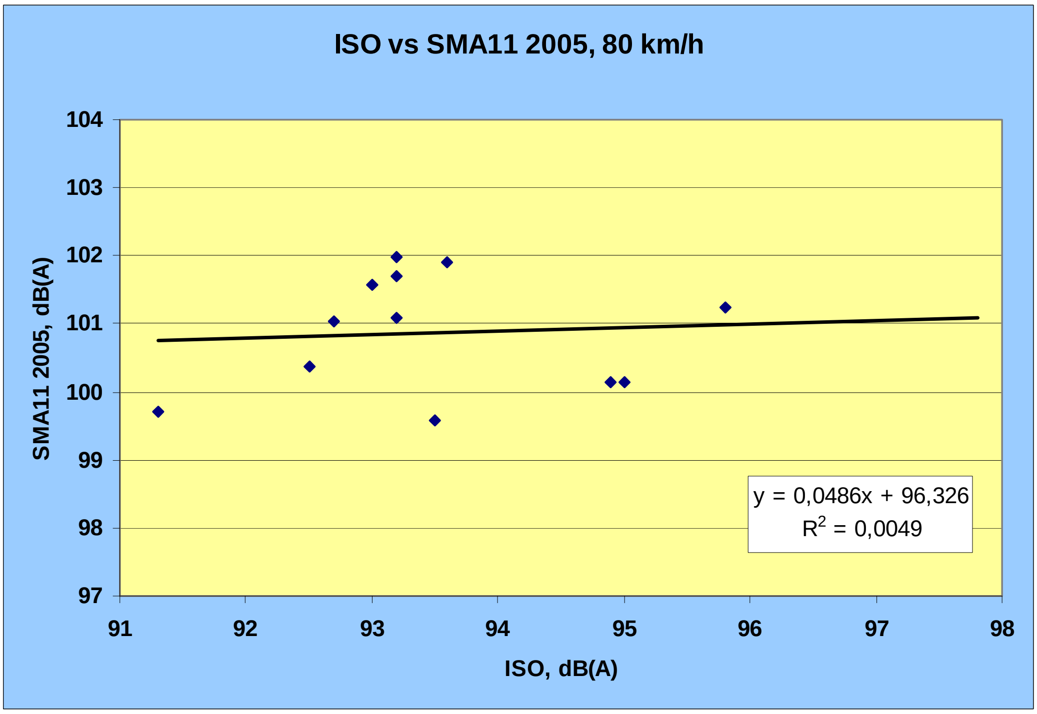


Figure 30 *Correlation between SMA11 2005 and ISO surface at Kloosterzande, CPX-levels at 80 km/h.*

To include a similar surface, but located at a different geographical region (and to include some more tyres) tyres 1, 5-6,8-11,13-15 and 42-45 were all measured on a SMA11-surface

(Bjørkelangen, Surface 7[2])., also 2 years old. In figures 31 and 32, these results are compared with the Kloosterzande data.

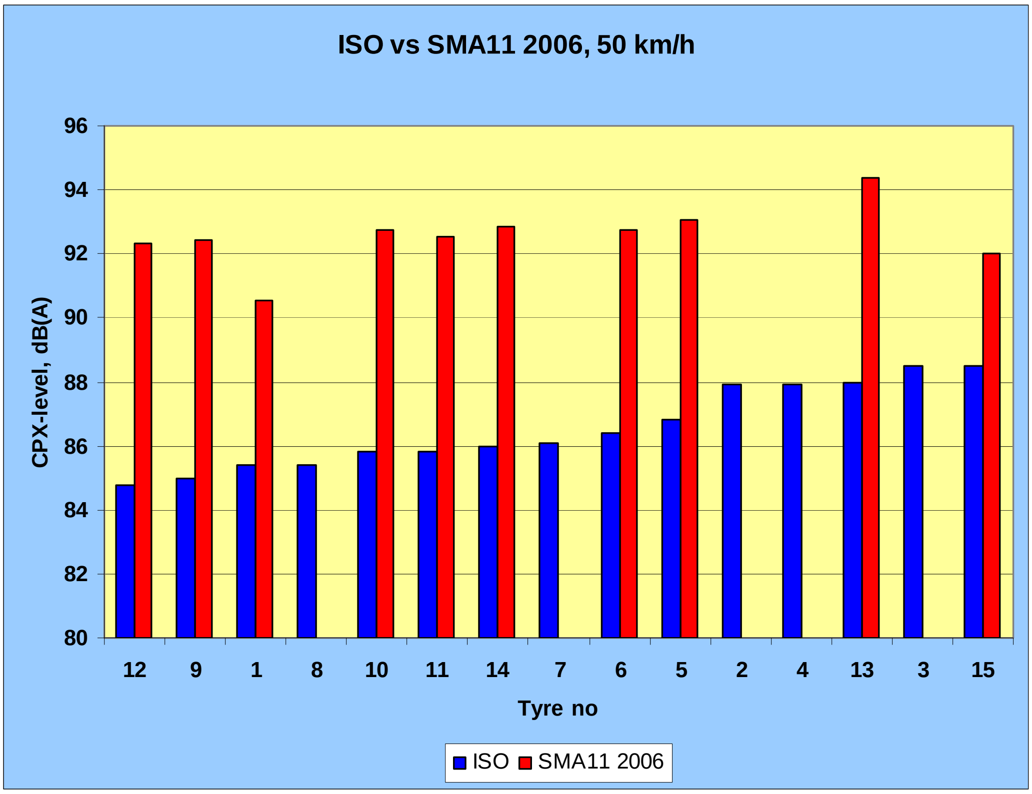


Figure 31 *SMA11 2006 and ISO surface at Kloosterzande, CPX-levels at 50 km/h.*

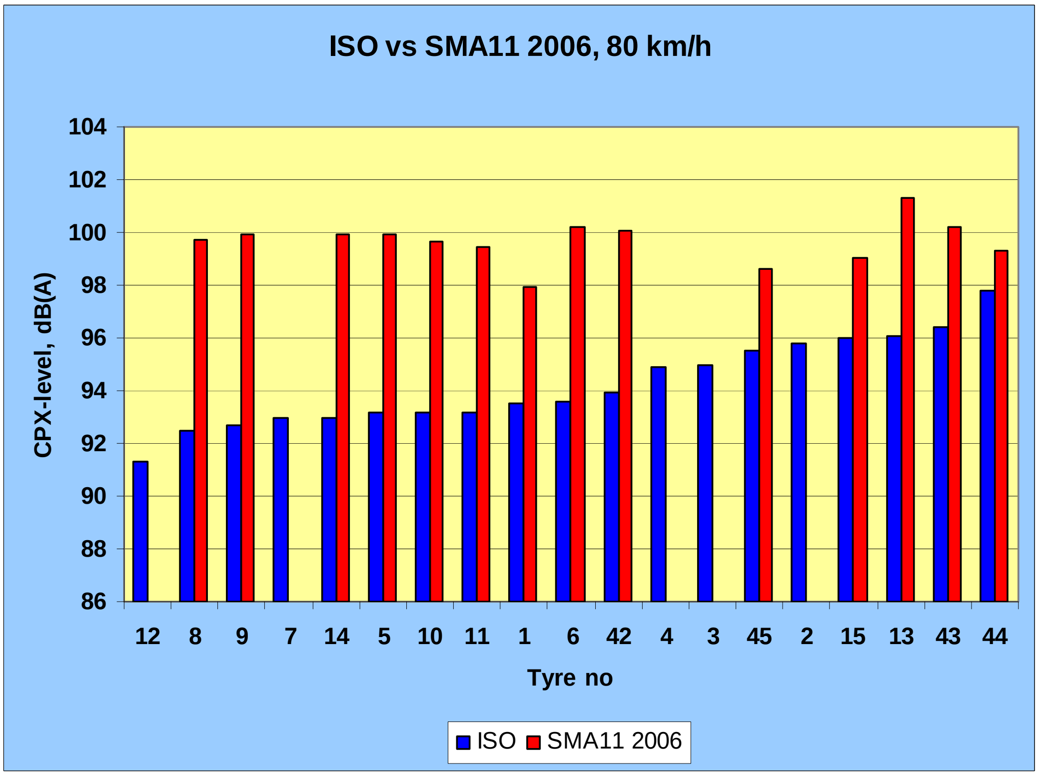


Figure 32 *SMA11 2006 and ISO surface at Kloosterzande, CPX-levels at 80 km/h.*

In figures 33 and 34, the correlation is shown.

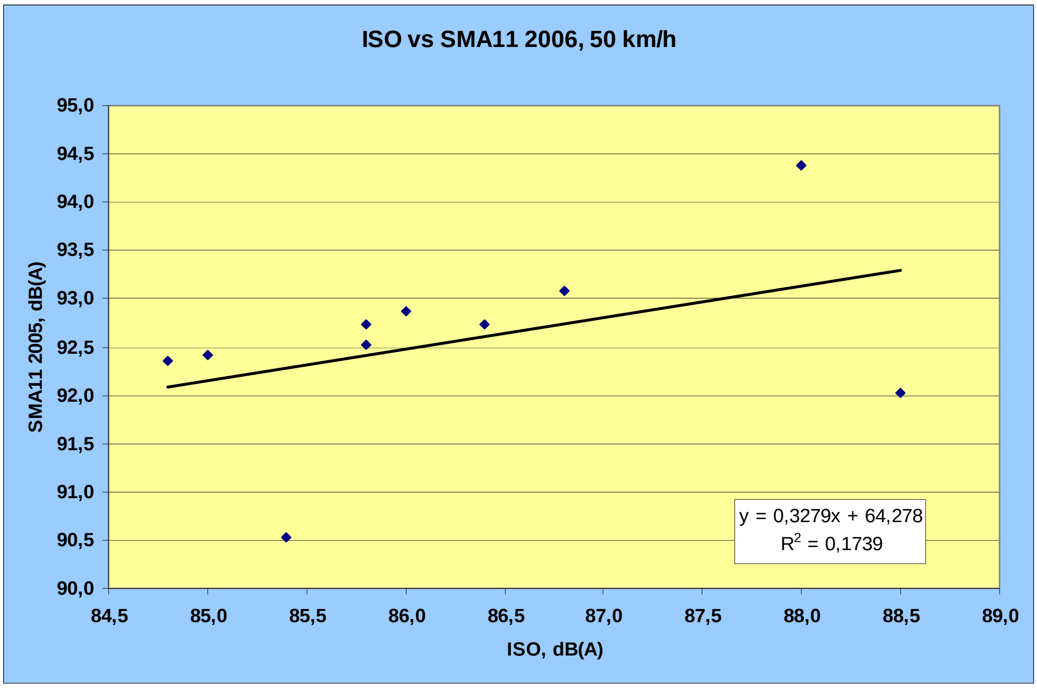


Figure 33 *Correlation between SMA11 2006 and ISO surface at Kloosterzande, CPX-levels at 50 km/h.*

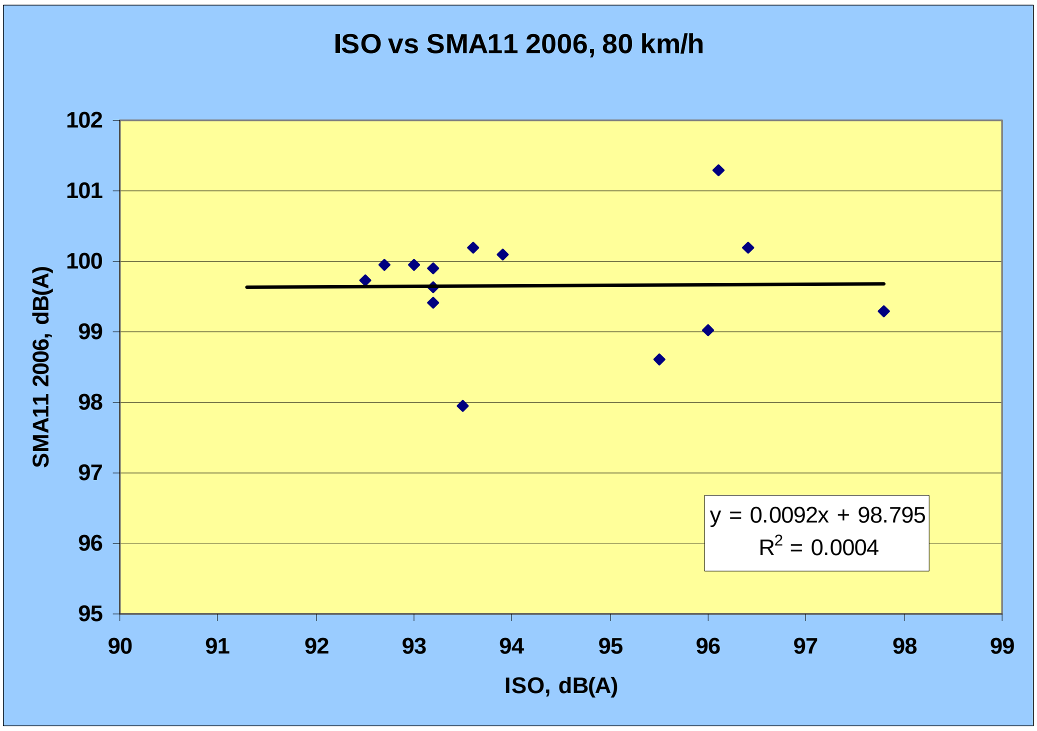


Figure 34 *Correlation between SMA11 2006 and ISO surface at Kloosterzande, CPX-levels at 80 km/h.*

Comments to the results.

Evaluating the results, one should take into account that there is a limit amount of tyres included in this investigation, only 10-15 tyres. However, these tyres were chosen to be representative for typical tyres on cars in Norway and thus the results shown here should at least show a trend for the behaviour of such tyres.

All measurements on typically existing road surfaces (SMA11) in Norway, exposed to winter conditions, show no correlation between the ranking of the tyres on the ISO surface and on the SMA surfaces.

This is a major concern, as it shows that the introduction of the new tyre noise limits in ECE Reg.117 (and corresponding EU-directive) may have a very little or literally no improvement of the traffic noise situation in Norway.

It is possible to use a model like the *TRANeCaM* to do actual calculations of the possible influence of lowering the tyre/road noise on the traffic noise situation in Norway, based on our tyre fleet and the replacement rates. However, based on these results, it is obvious that such calculations would only demonstrate the inefficiency of the new tyre regulations, as our surfaces currently are performing with regards to tyre/road noise.

Besides the lack of correlation, the spread in levels is higher on the ISO track, especially at 80 km/h. On the ISO track, there is a difference of more than 6 dB(A), while the spread is only 2.5-3.5 dB(A) on the SMA surfaces. This indicates that the tread pattern of the different tyres do not influence the noise levels as much on the rough surfaces than on a smooth ISO surface.

To be able to explain the reasons for such lack of correlation, one can look at a typical footprint (surface pressure distribution) of a smooth profiled (50 Sh) tyre on an SMA11 surface as measured by BASt[7], with the same footprint on an ISO surface, see figures 35 and 36.

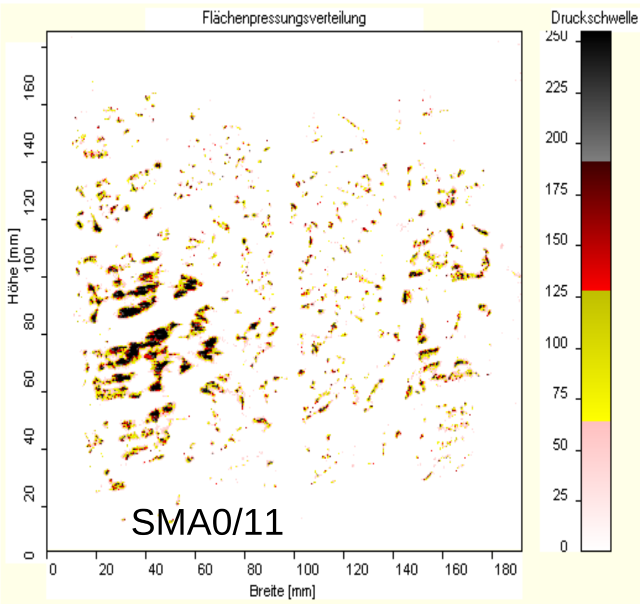


***Figure 35** Surface pressure distribution of a tyre on an SMA11 surface.*

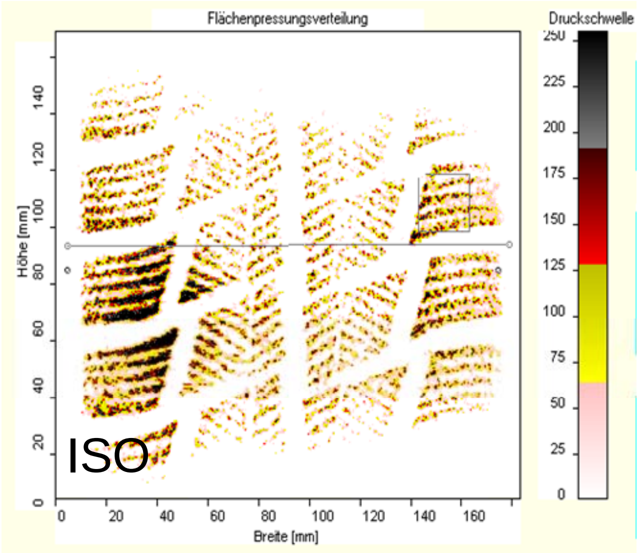


Figure 36 *Surface pressure distribution of a tyre on an ISO surface.*

These figures show a dramatically less influence of the pattern on the SMA11 surface (which may even be smoother than the measured SMA11 surface in Norway), compared to the ISO surface.

4.4.2 New surfaces

In order to investigate the ranking of the tyres on smoother road surfaces and to see if there is a better correlation with the ISO surface, measurements were done on both newly laid SMA surfaces (not exposed to winter conditions) and on porous road surfaces.

In figure 37 and 38, the results are shown for measurements on an SMA11 2008 surface (E6 at Horg) at 50 and 80 km/h, compared with the ISO surface.

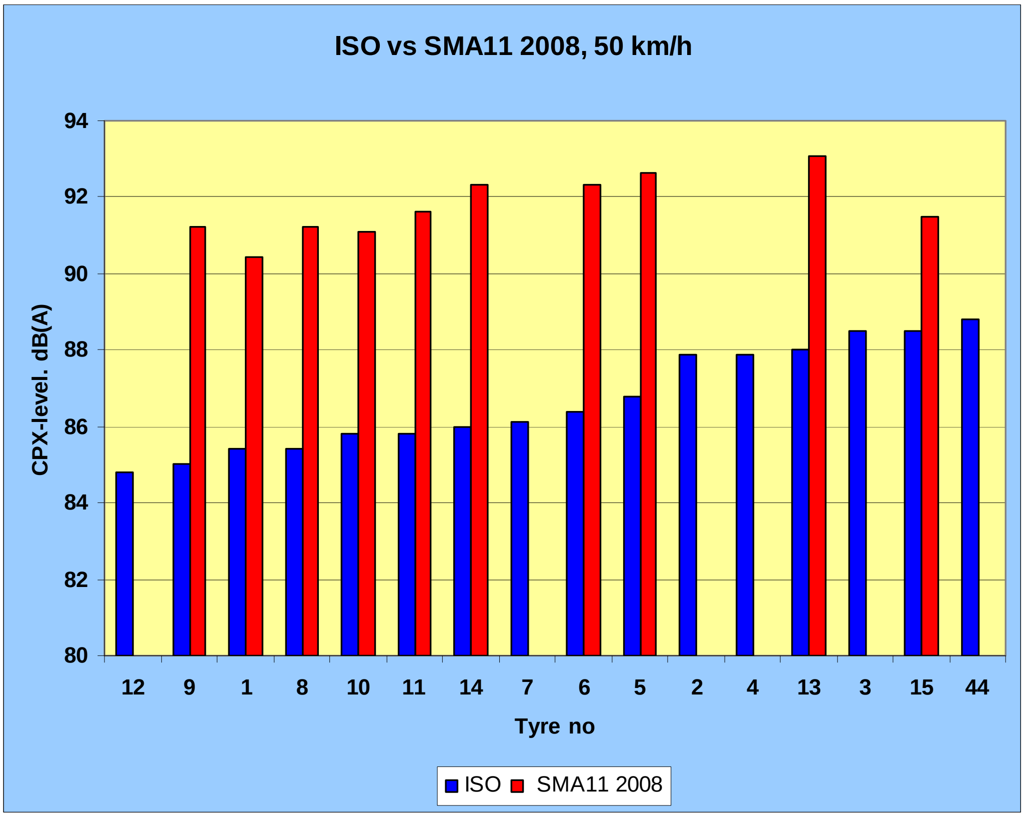


Figure 37 *SMA11 2008 and ISO surface at Kloosterzande, CPX-levels at 50 km/h.*

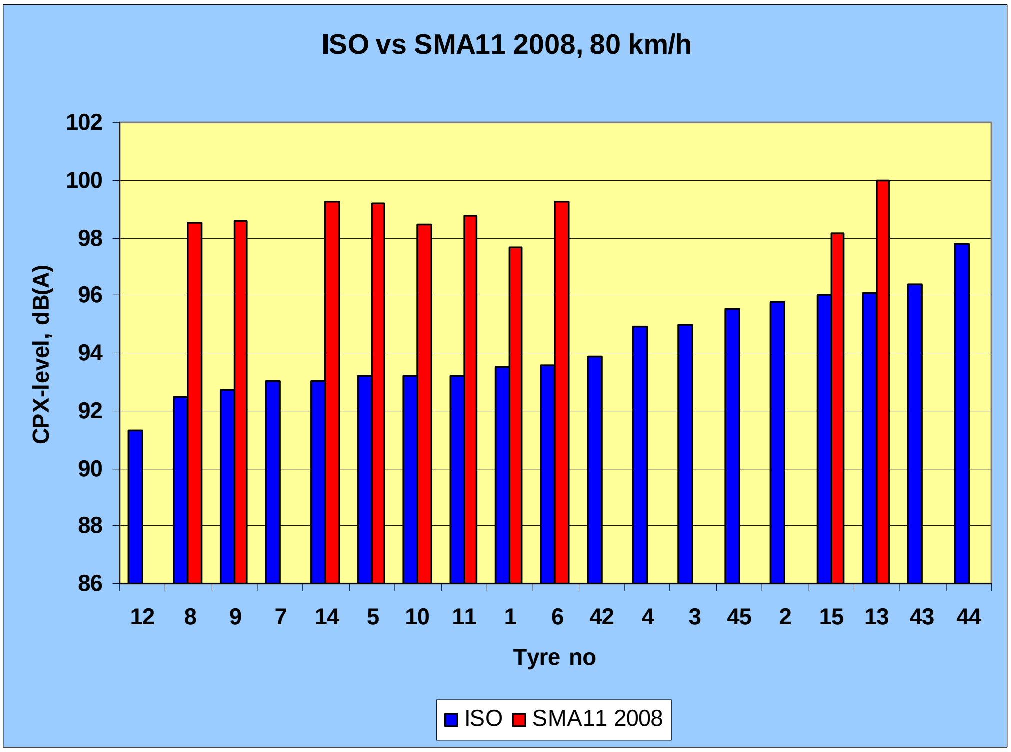


Figure 38 *SMA11 2008 and ISO surface at Kloosterzande, CPX-levels at 80 km/h.*

In figures 39 and 40, the corresponding correlation is shown.

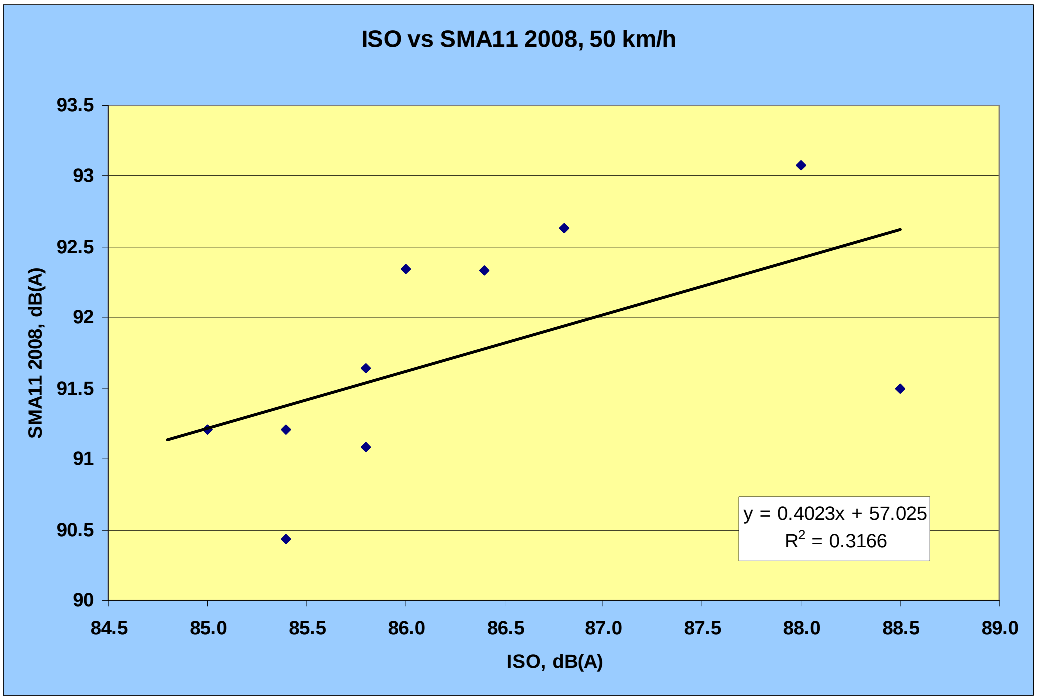


Figure 39 *Correlation between SMA11 2008 and ISO surface at Kloosterzande, CPX-levels at 50 km/h.*

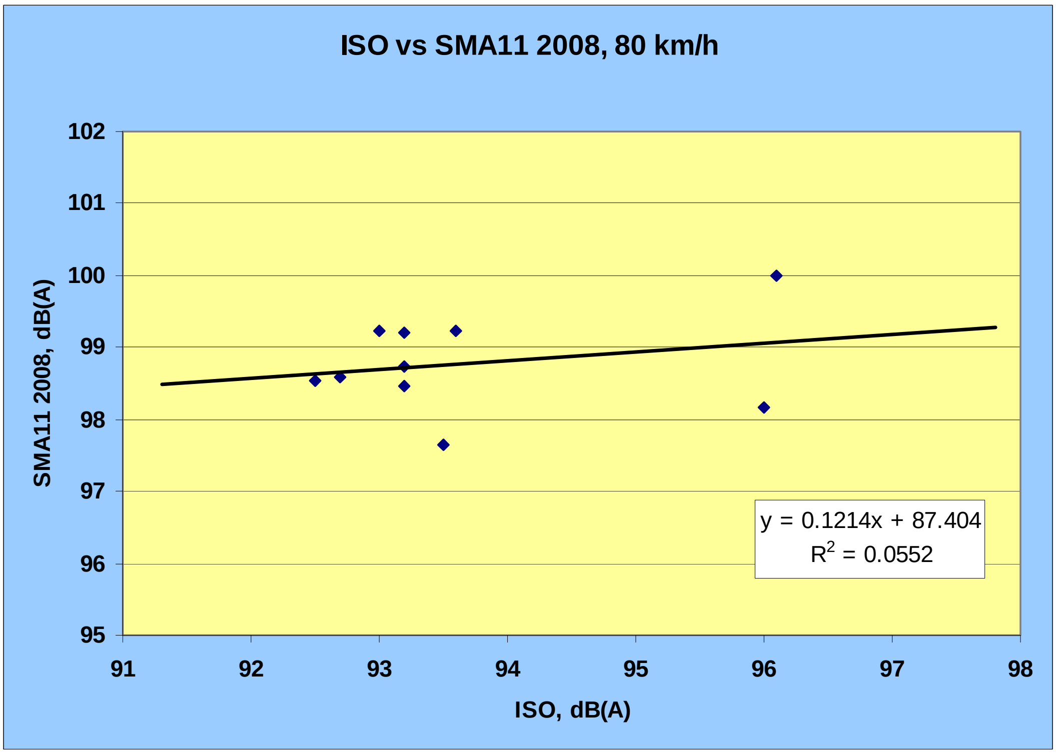


Figure 40 *Correlation between SMA11 2008 and ISO surface at Kloosterzande, CPX-levels at 80 km/h.*

The tyres were also measured on a new two-layered porous surface at E6, Horg. The results are shown in figures 41 and 42.

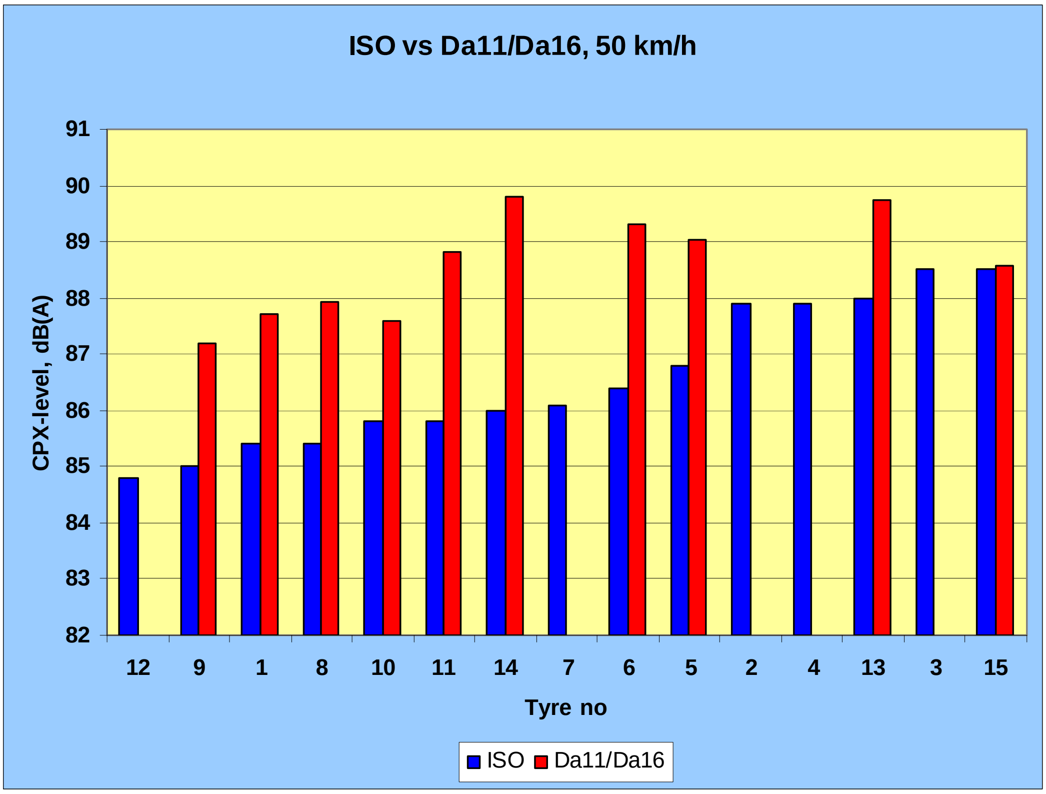


Figure 41 Da11/Da16 2008 and ISO surface at Kloosterzande, CPX-levels at 50 km/h.

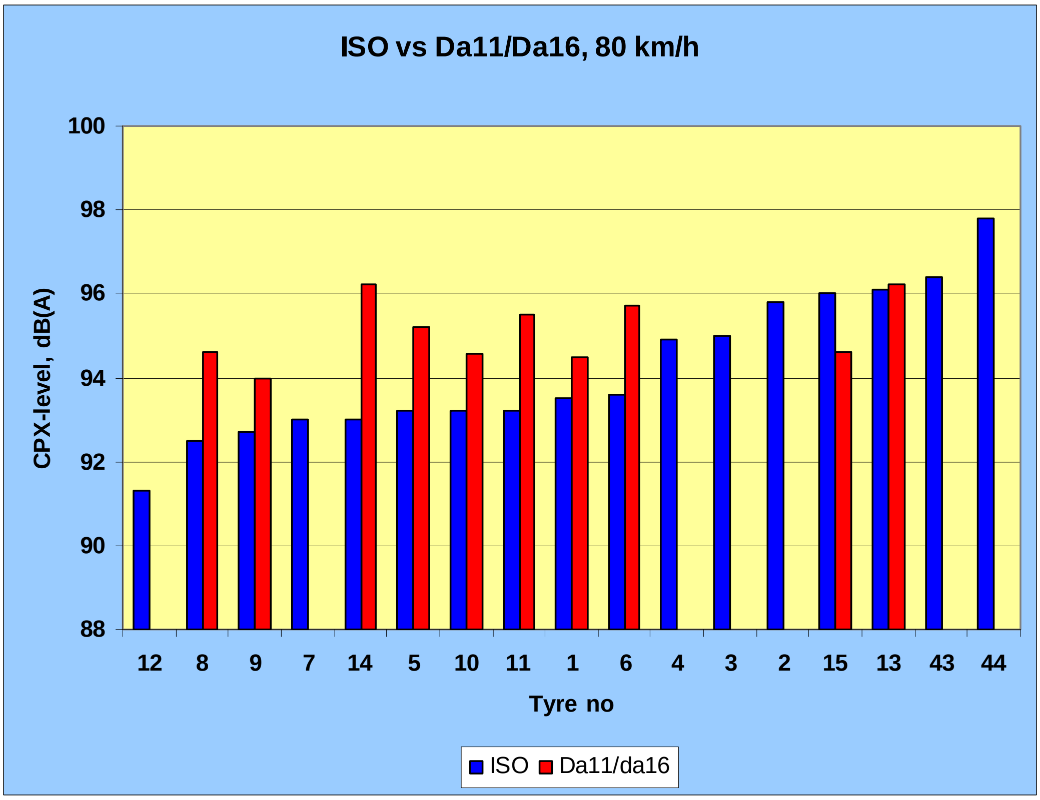


Figure 42 Da11/Da16 2008 and ISO surface at Kloosterzande, CPX-levels at 80 km/h.

As these results show, at 80 km/h there is still no good correlation between the ISO surface and the two new road surfaces. However, at 50 km/h, the correlation improves, as shown in figures 39

and 43. This is promising, as the main traffic noise problems in Norway are at lower speeds than 80 km/h.
It shows that by making the road surfaces in Norway smoother and quieter, there is an improved efficiency of the use of tyres, which are type approved and marked as low noise tyres on an ISO surface.

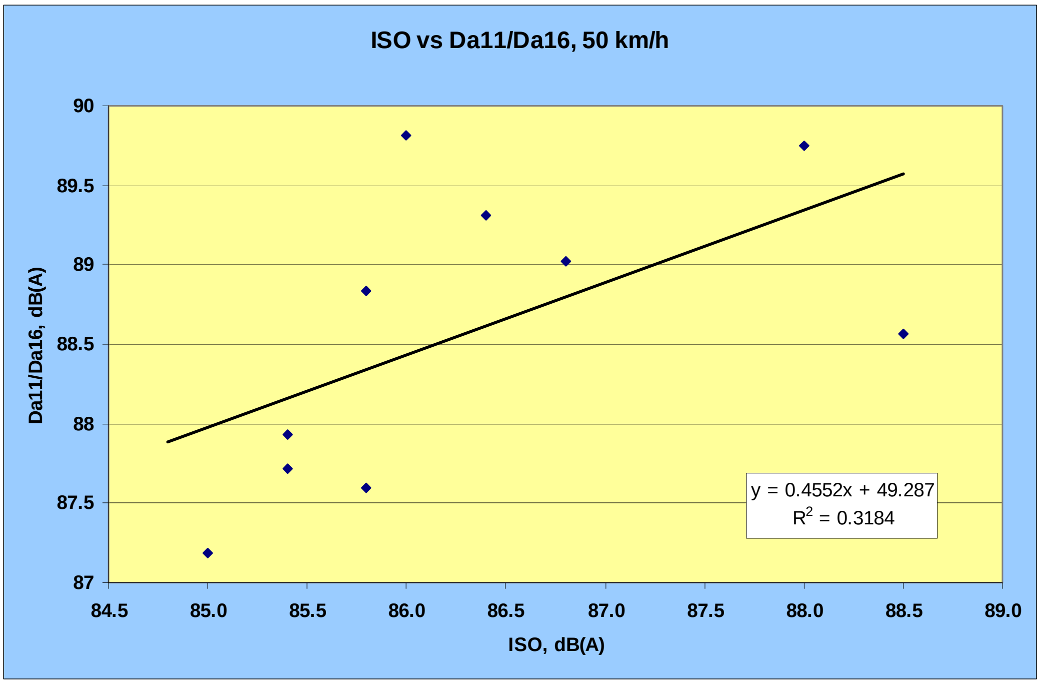


Figure 43 *Correlation between Da11/Da16 and ISO surface at Kloosterzande, CPX-levels at 50 km/h.*

4.5 Comparison with drum measurements

Selections of the tyres measured at the Kloosterzande ISO surface have previously been tested on the drum facilities of TUG in Gdansk, Poland[2]. Even if it is recognised that the generation mechanisms and propagation properties of a tyre on a drum is different from a tyre running on a road, it is interesting to see how much difference there is in the ranking of the tyres at these two test conditions. In figures 44 and 45 the results on the ISO surface at Kloosterzande are compared with the drum measurements on the ISO-replica, at 50 and 80 km/h. The corresponding correlation is shown in figures 46 and 47.

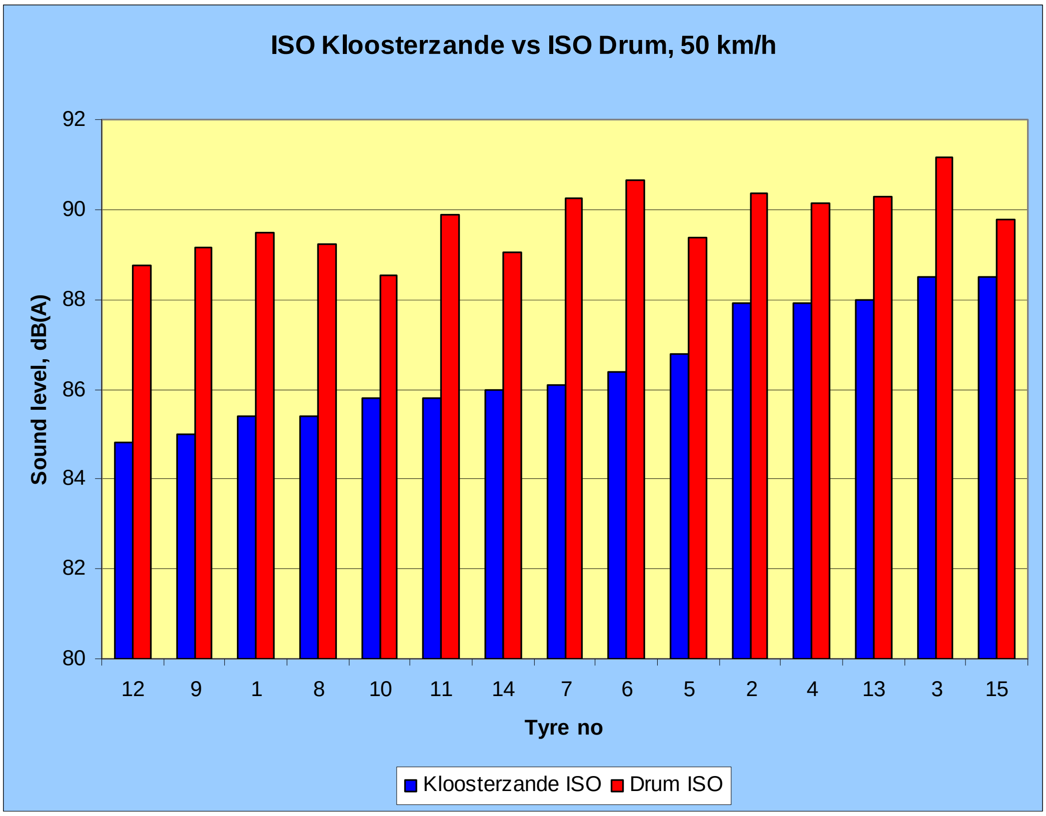


Figure 44 *ISO Kloosterzande and ISO Drum, 50 km/h*

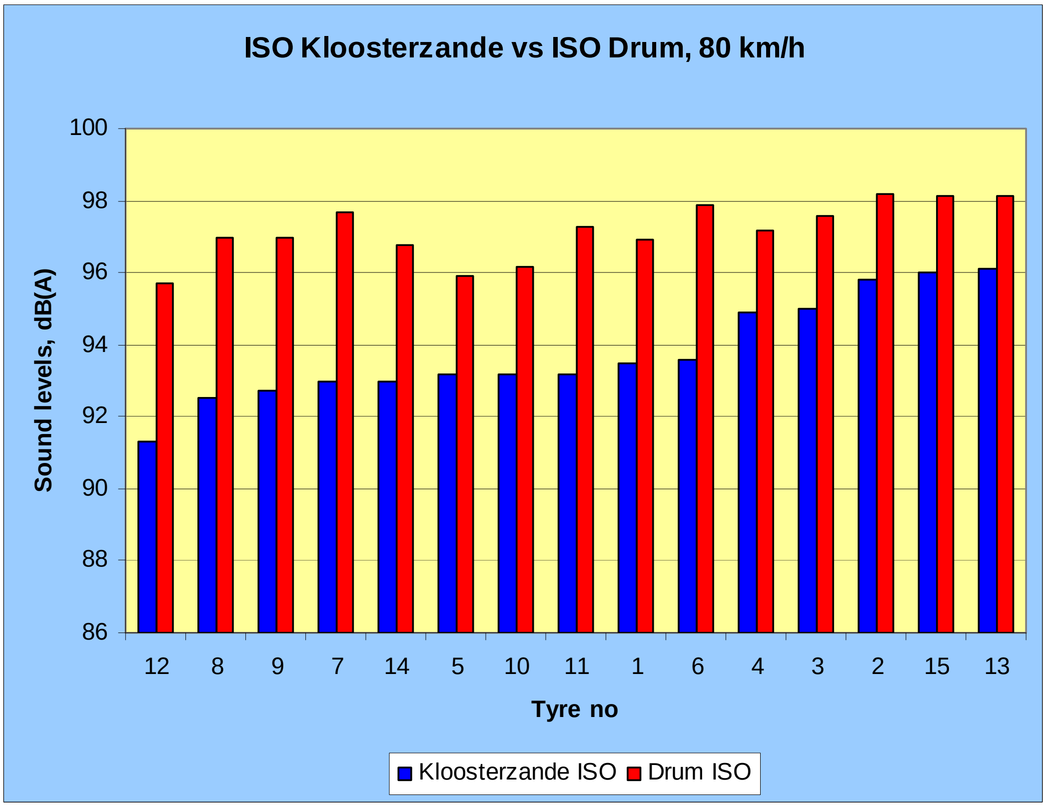


Figure 45 *ISO Kloosterzande and ISO Drum, 80 km/h*

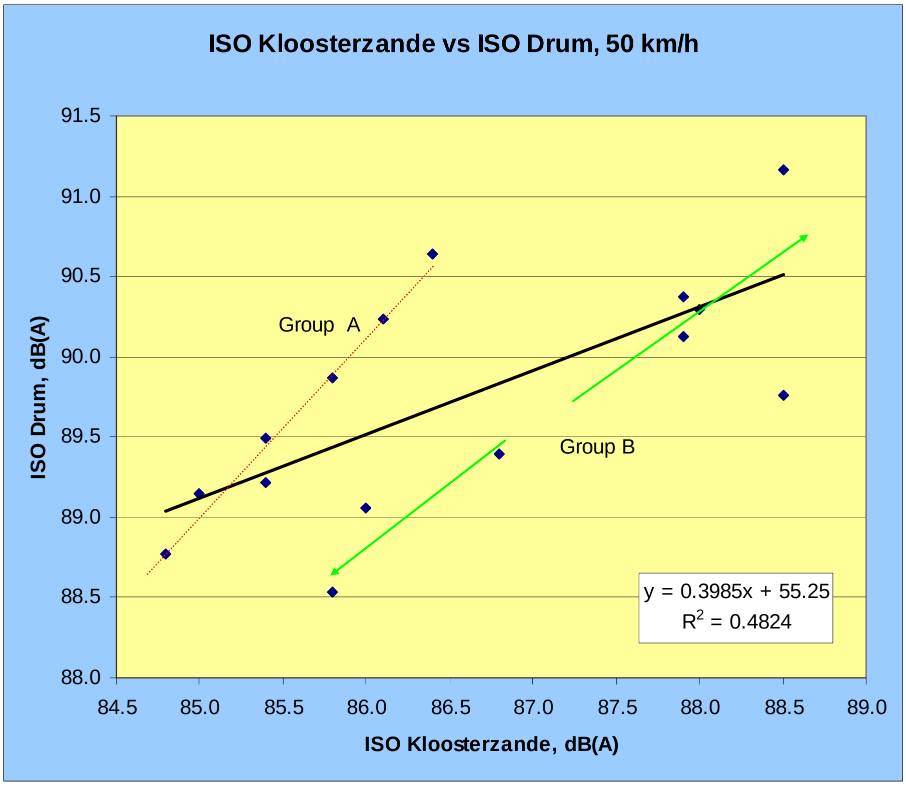


Figure 46 *Correlation between ISO Kloosterzande and ISO Drum, 50 km/h.*

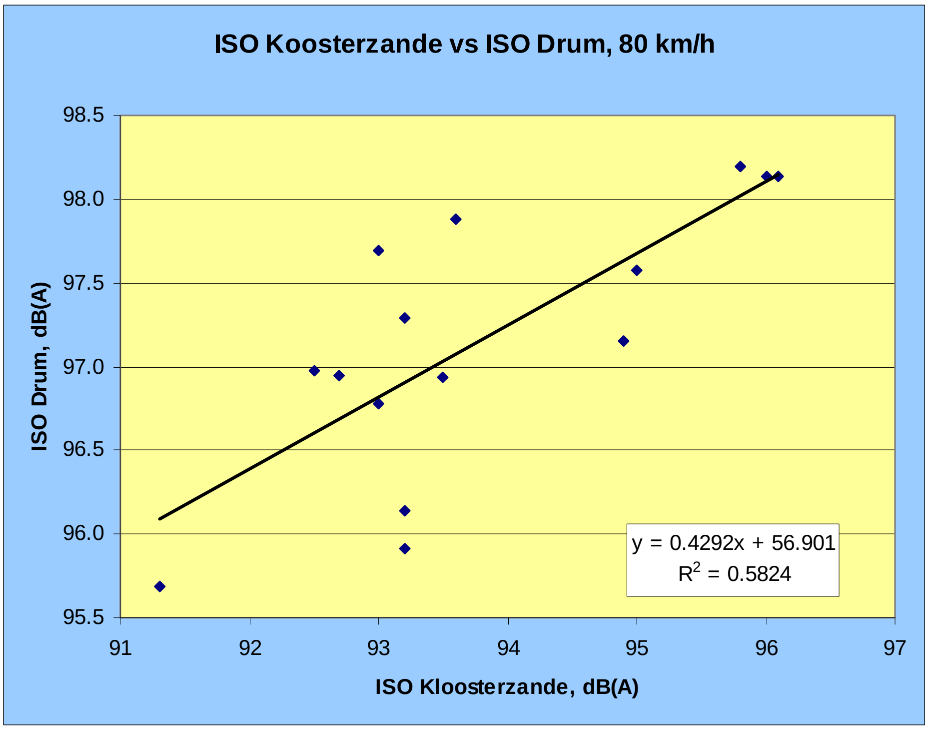


Figure 47 *Correlation between ISO Kloosterzande and ISO Drum, 80 km/h.*

Taking into account the differences in excitation and propagation processes, there is still a significant correlation between the two measurement conditions. In figure 46 (50 km/h), it seems that the tyres can be divided into two groups, with a higher correlation within the two groups. In the figure, Group A is indicated with a thin red line and Group B with green. The tyres belonging to Group A are 1,6,7,8,9,11 and 12. Group B will then be tyres 2,3,4,5,10,13,14 and 15. It is difficult to find some common factors for these two groups just by looking at technical specifications (table 1).

5 Frequency analysis

Since the correlation between modelling and measurements results is poor, based on overall A-weighted levels, a 1/3rd octave band frequency analysis have been conducted. The aim has been to investigate if the correlation is higher at specific frequency band.

5.1 Analysis of ISO-results

As informed in 4.3, the *SPERoN* results are from the Sperenberg ISO surface, while the measurements have been done on the ISO track at Kloosterzande. In addition to this, the modelling results are in a coast-by situation (CPB) at 7.5 m, while the measurements are at the CPX-positions.

The frequency spectra are compared by a recalculation of the CPX-values to a simulated CPB-position by introduction of a frequency depended correction as found by Anfosso-Lédée[6] (Note: In chapter 4.3, a fixed value was used for correction of over-all levels).

In figures 48-59, the frequency spectra for both surfaces are shown for the 11 tyres with available data for both cases. The chosen speed is 80 km/h.

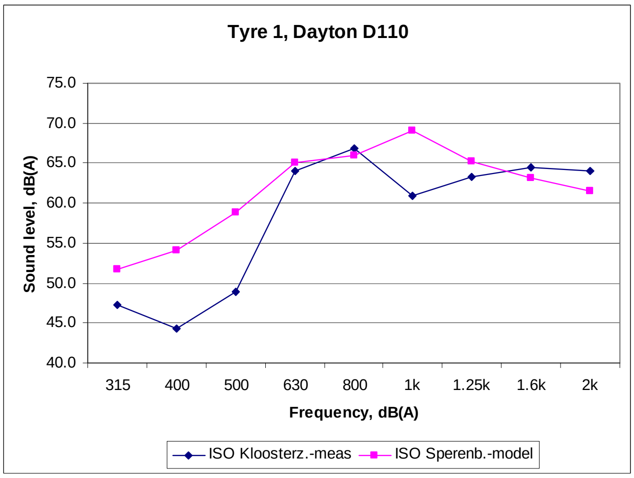


Figure 48 *ISO surfaces, Tyre 1*

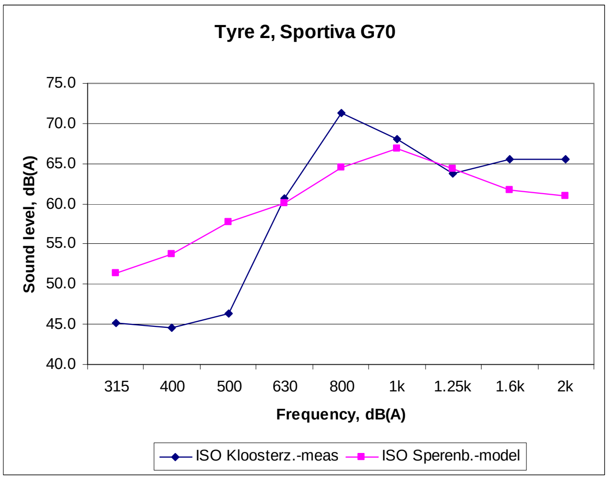


Figure 49 *ISO surfaces, Tyre 2*

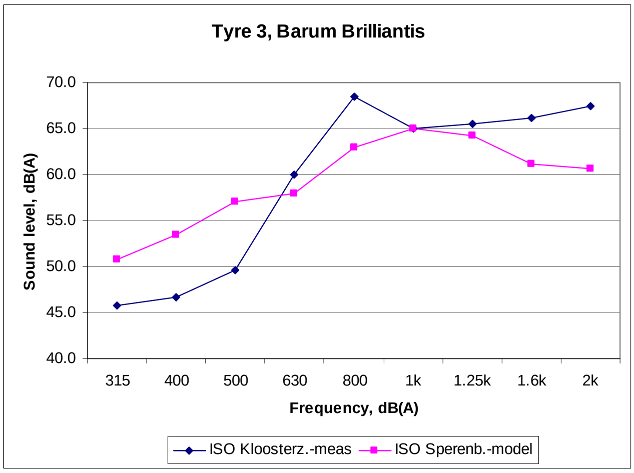


***Figure 50** ISO surfaces, Tyre 3*

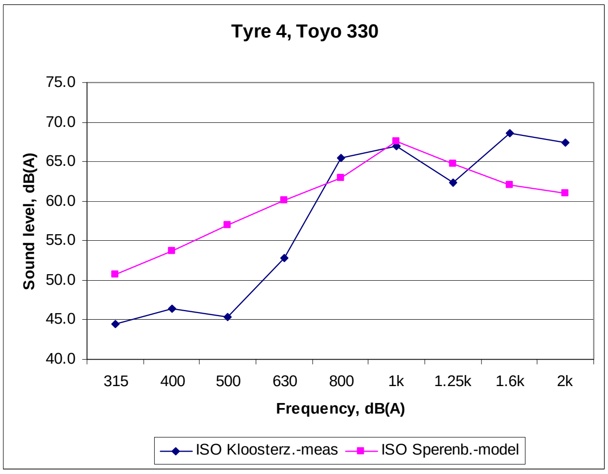


***Figure 51** ISO surfaces, Tyre 4*

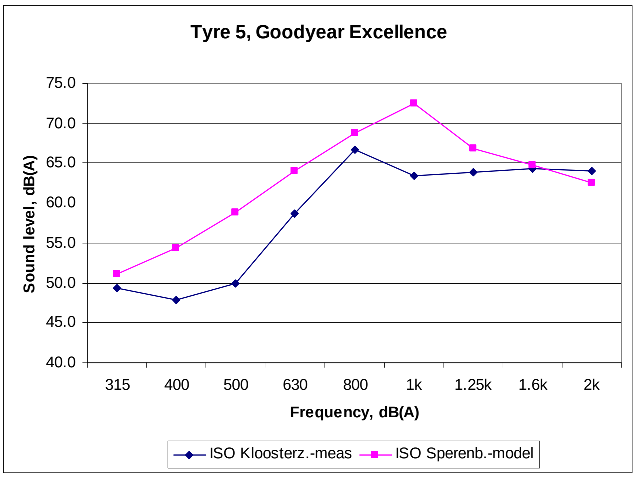


***Figure 52** ISO surfaces, Tyre 5*

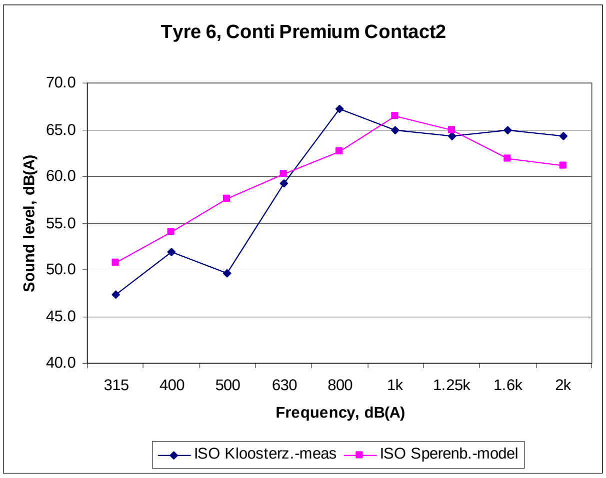


***Figure 53** ISO surfaces, Tyre 6*

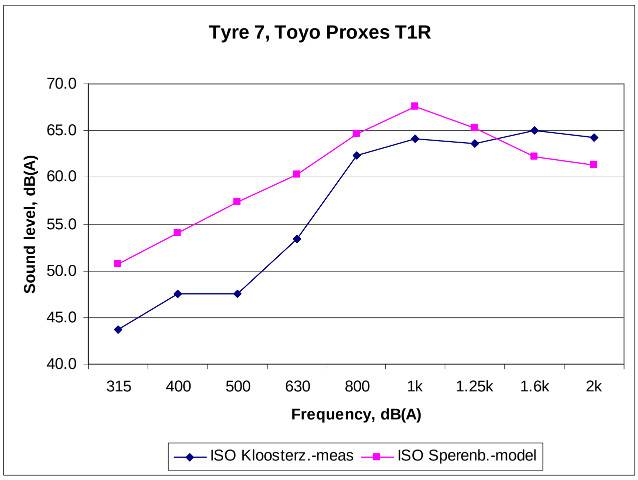


***Figure 54** ISO surfaces, Tyre 7*

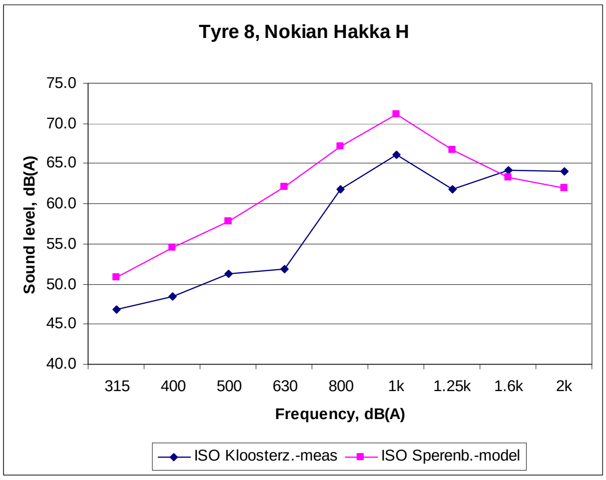


***Figure 55** ISO surfaces, Tyre 8*

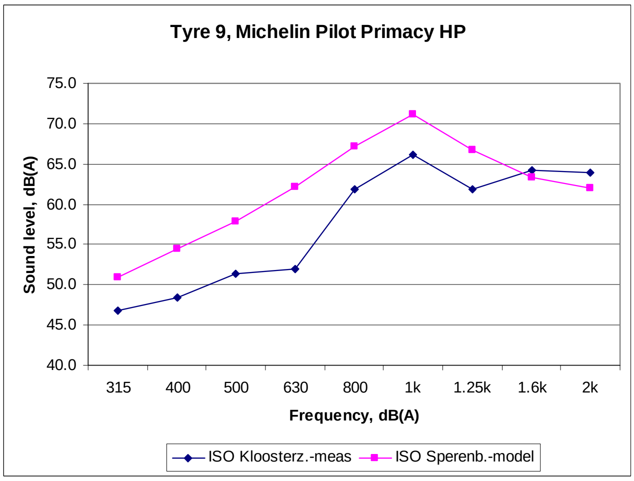


***Figure 56** ISO surfaces, Tyre 9*

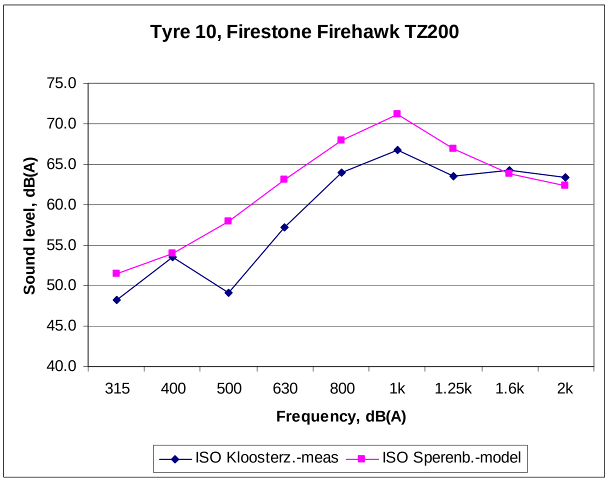


***Figure 57** ISO surfaces, Tyre 10*

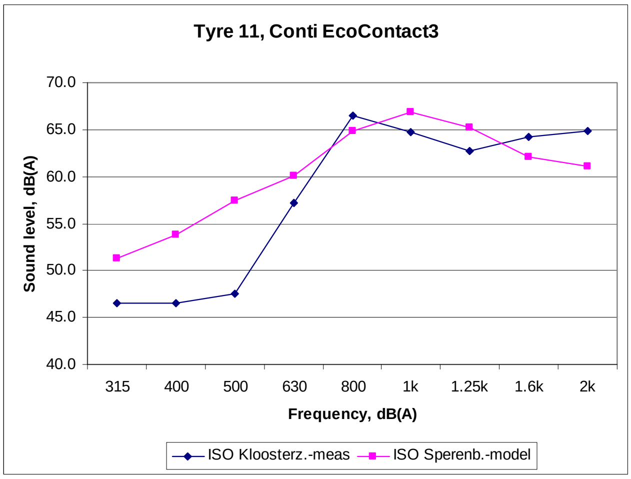


***Figure 58** ISO surfaces, Tyre 11*

In general, the model (pink colour) seems to overestimate the levels in the lower frequency range (below 800 Hz). However, one should be careful in the evaluation of these results, since the CPX-values has been recalculated to a coast-by situation (at 7.5 m) and the comparison is also done at two different ISO surfaces.

A correlation analysis, based on the individual 1/3rd frequency levels has been made. In this analysis, the original CPX-levels for the ISO surface at Kloosterzande have been used. The results of this analysis are shown in figures A1-A18 in Appendix 1. The correlation is shown for both speeds; 50 km/h and 80 km/h.

From this analysis, the following conclusions can be made:

- No improvements in the correlation between the two modes of operation were found by using the 1/3rd octave bands in the analysis. This is somewhat disappointing, but may be caused by the fact that the spread in the levels in the modelling results are in general lower than found during the CPX-measurement. Thus, the spread in the modelling results can be within the uncertainty of the model and by this, have a strong influence on the correlation results.

- A small, but positive correlation can be seen at the lower frequencies at 50 km/h (below 500 Hz), but a negative correlation at higher frequencies, but in general, there is no better correlation at 50 than 80 km/h.

5.2 Analysis of results on selected SMA surfaces

By the time (in 2007) of measurements and modelling data on surface 1 (SMA11 2005), this surface was exposed to two winter seasons of normal traffic. It is regarded as a typical dense asphalt concrete surface in Norway, also concerning tyre/road noise performance.

The 1/3rd octave band levels from the modelling part and from the CPX-measurements for tyres 1-11 are shown in figures 59-69. Again, the CPX-levels have been recalculated to 7.5 m, using the frequency dependent model of Anfosso-Lédée[6]. Only the results at 80 km/h are presented.

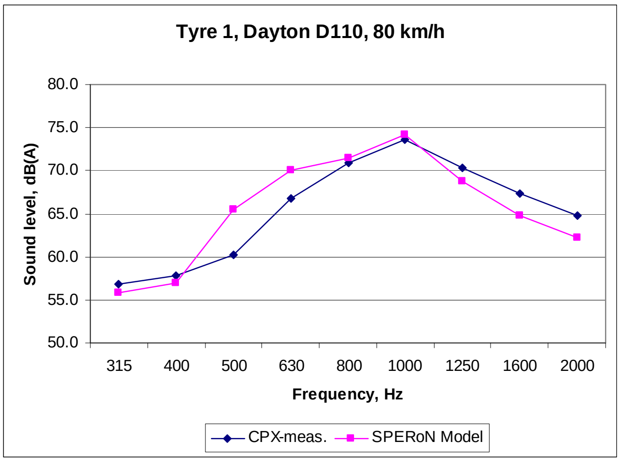


Figure 59 *SMA11 2005, Tyre 1*

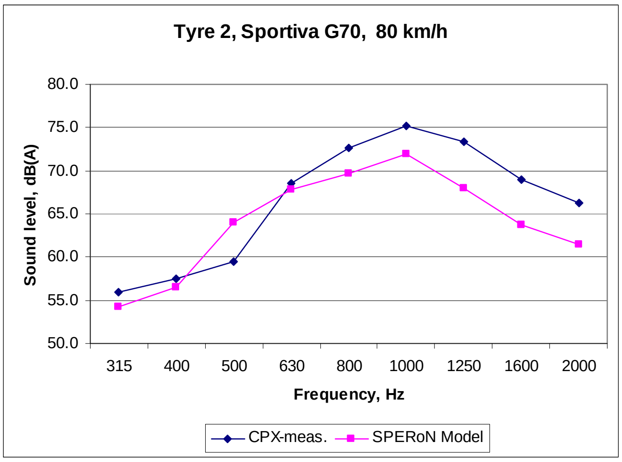


Figure 60 *SMA11 2005, Tyre 2*

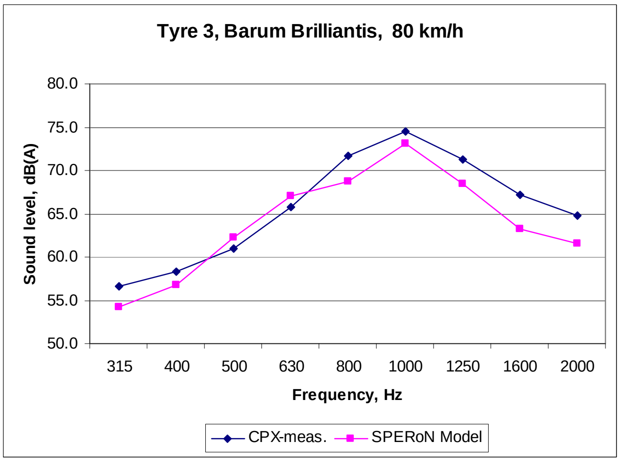


Figure 61 *SMA11 2005, Tyre 3*

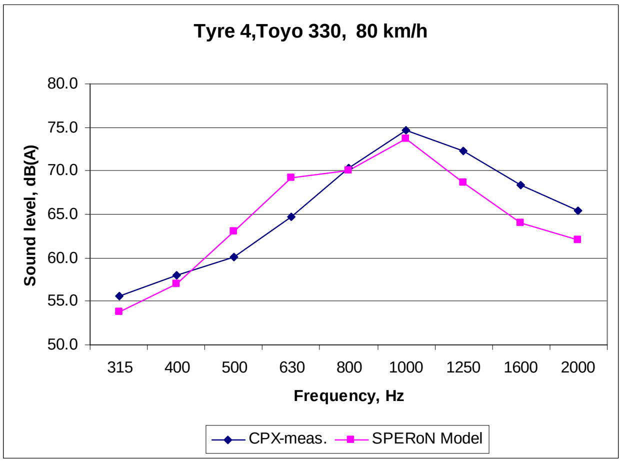


Figure 62 *SMA11 2005, Tyre 4*

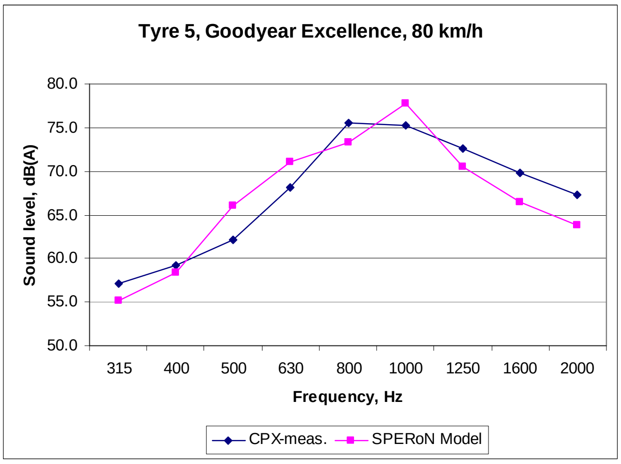


Figure 63 *SMA11 2005, Tyre 5*

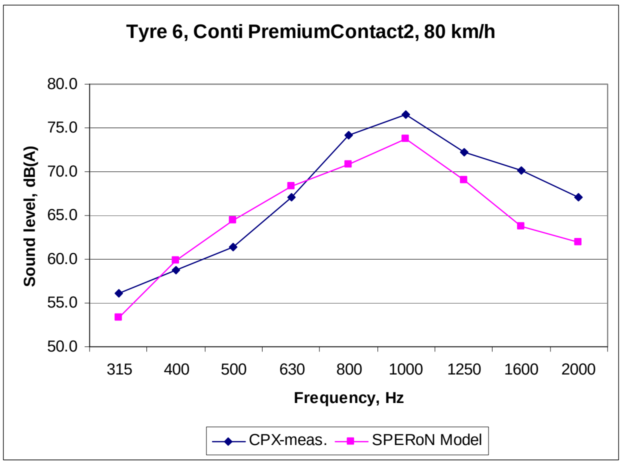


Figure 64 *SMA11 2005, Tyre 6*

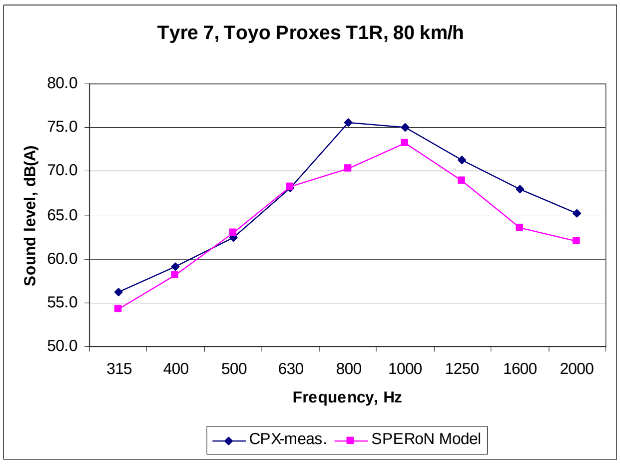


Figure 65 *SMA11 2005, Tyre 7*

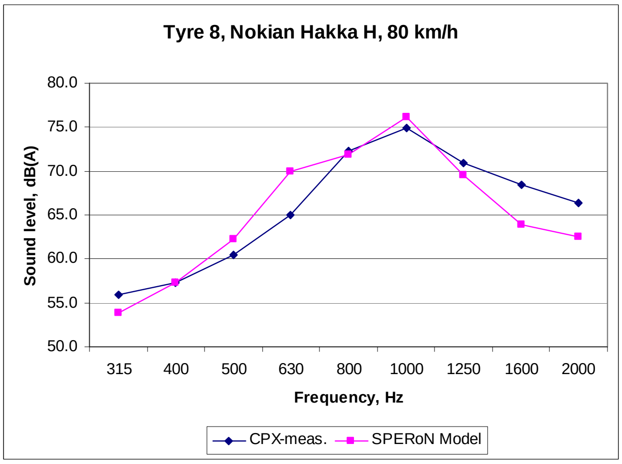


Figure 66 *SMA11 2005, Tyre 8*

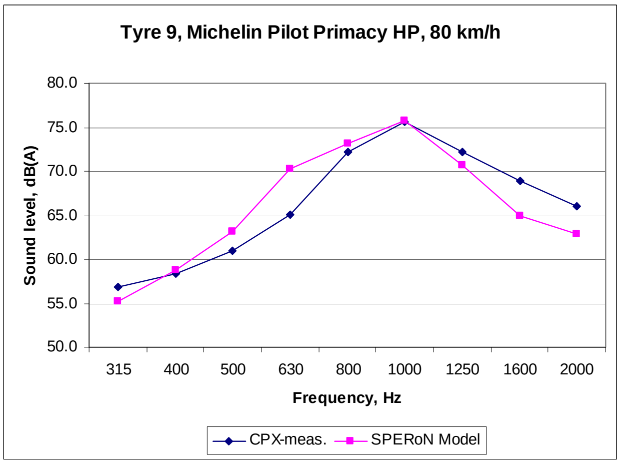


Figure 67 *SMA11 2005, Tyre 9*

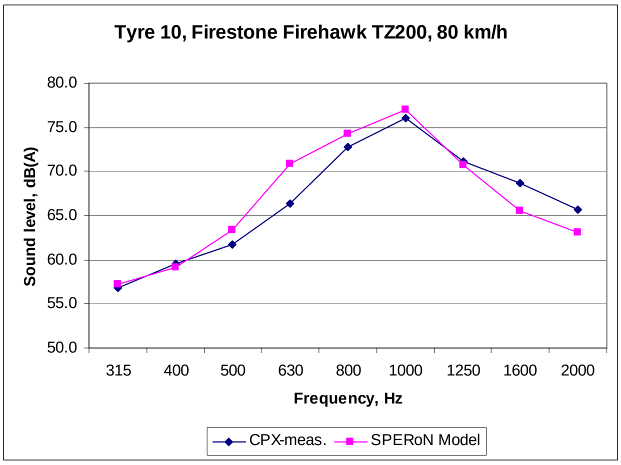


Figure 68 *SMA11 2005, Tyre 10*

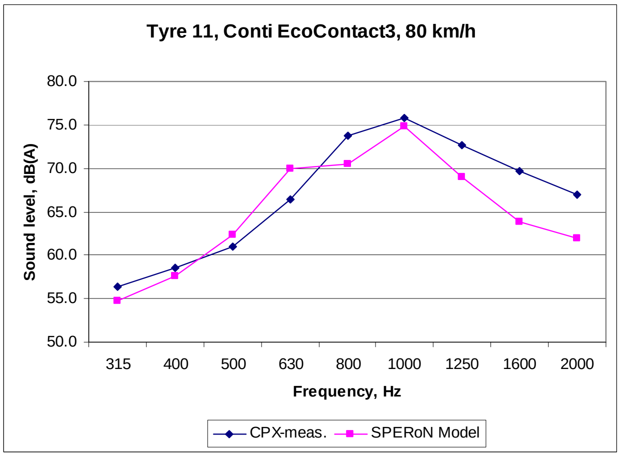


Figure 69 *SMA 11 2005, Tyre 11*

There seems to be a better agreement of the shape of the spectra for the two modes, than on the ISO surfaces. This is mostly due to the fact that one is comparing results on the same surface here.

In general, the model seems to overestimate the levels around 630 Hz, and underestimate the levels at the higher frequencies (as also found on the ISO surface).

The ranking of the tyres on this surface has also been done for this surface, by using the linear correlation technique based on the individual 1/3rd octave band frequencies. The results are shown in Appendix 2, figures A19-A26.

The general picture is that the correlation is not high. Only at the lowest frequencies (315 and 400 Hz), there is some positive correlation, with r^2 around 0.53. If this lack of correlation can be related to the status of the *SPERoN* model itself and problems of reproducing noise generation mechanisms such as the air pumping, or is influenced by the relationship between near field sound levels (CPX) and far field sound levels (CPB), should be a matter of further investigations.

From previous investigations it has been found that the noise (and texture) levels on a typical SMA surface change already after the first winter season, being exposed to studded tyres[8]. To compare the results on the ISO surface at Kloosterzande with a surface not exposed to winter conditions, the measurements done at surface 2B (SMA11 2007) for tyres 1-12 have been analysed. The correlation for each 1/3rd octave band frequencies for the speeds of 50 and 80 km/h are shown in figures A27-A44 in Appendix 2.

As these results show, the correlation is much improved in the low to medium frequency range of 315 – 1000 Hz (with an exception for 800 Hz at 80 km/h). In some cases, the r^2 is in the range of 0.6-0.8. This is a significant result, as it clearly demonstrates that if an SMA surface is not exposed to winter conditions that change the texture, there will be an improved efficiency of lowering the noise limits of tyres on an ISO surface for the current Norwegian condition.

A correlation analysis between modelling and measurements results have also been performed for Surface 3 (SMA16 1999) at both speeds, but the results are very similar to the analysis of surface 1 (figures A19-A26): The correlation is low, and even negative for some frequencies.

5.3 Additional analysis

An alternative analysis has been performed, where the levels of each tyre is shown for selected 1/3rd octave band frequencies; 315, 500, 800, 1000, 1250 and 2000 Hz. This analysis has been done for the CPX-measurements of tyres 1-12 (in 2007) on the following surfaces:
Surface 1 (SMA11 2005)
Surface 2 (SMA11 2006)
Surface 2B (SMA11 2007)
Surface 3 (SMA16 1999)
Surface 4 (SMA11 2005, 1% rubber granulate in the mix).
Surface 5 (SMA11 2005, 3% rubber)

In addition, a similar analysis has been done for the *SPERoN* modelling of tyres 1-11 on surfaces:
Surface 1 (SMA11 2005)
Surface 2 (SMA11 2006)
Surface 3 (SMA16 1999)
Surface 4 (SMA11 2005, 1% rubber granulate in the mix).
Surface 5 (SMA11 2005, 3% rubber)
Surface 6 (DAC16 1992)

For the CPX-measurements, the results are presented in figures 70 – 76 and for the *SPERoN* model figures 77 - 82. The oldest surfaces are to the left.

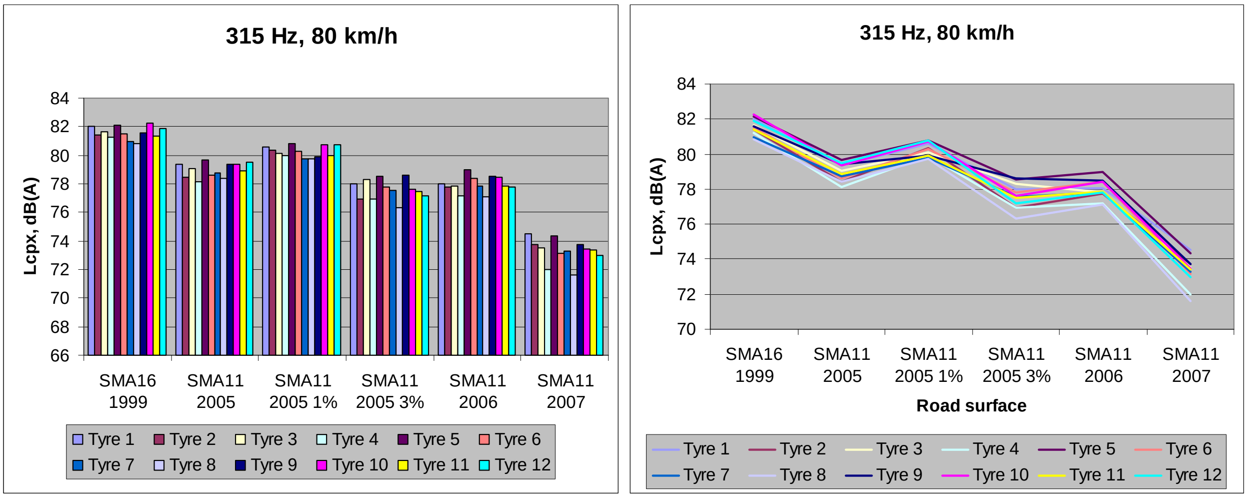


Figure 70 *CPX-measurements, 315 Hz, 80 km/h*

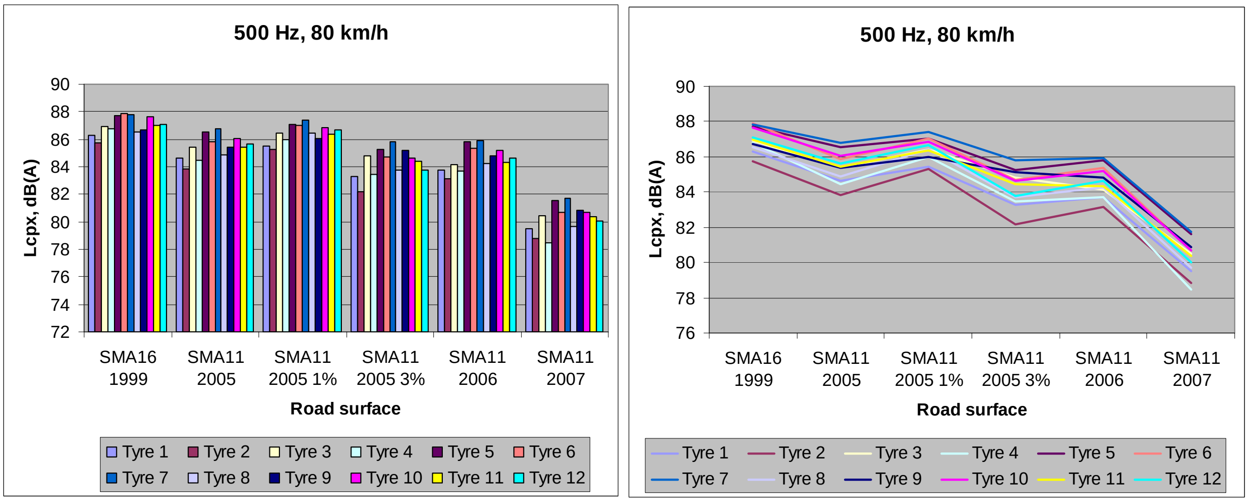


Figure 71 *CPX-measurements, 500 Hz, 80 km/h*

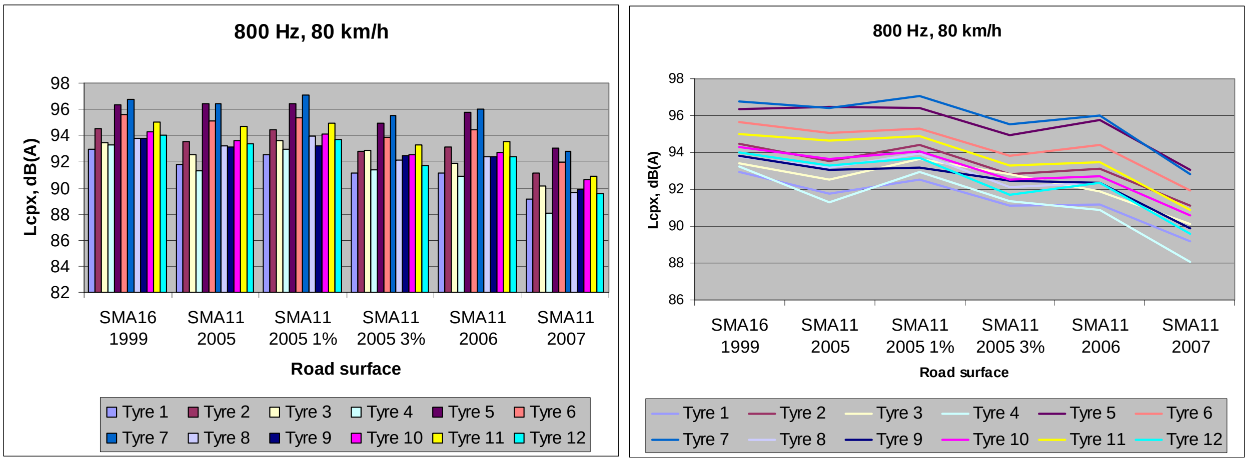


Figure 72 *CPX-measurements, 800 Hz, 80 km/h*

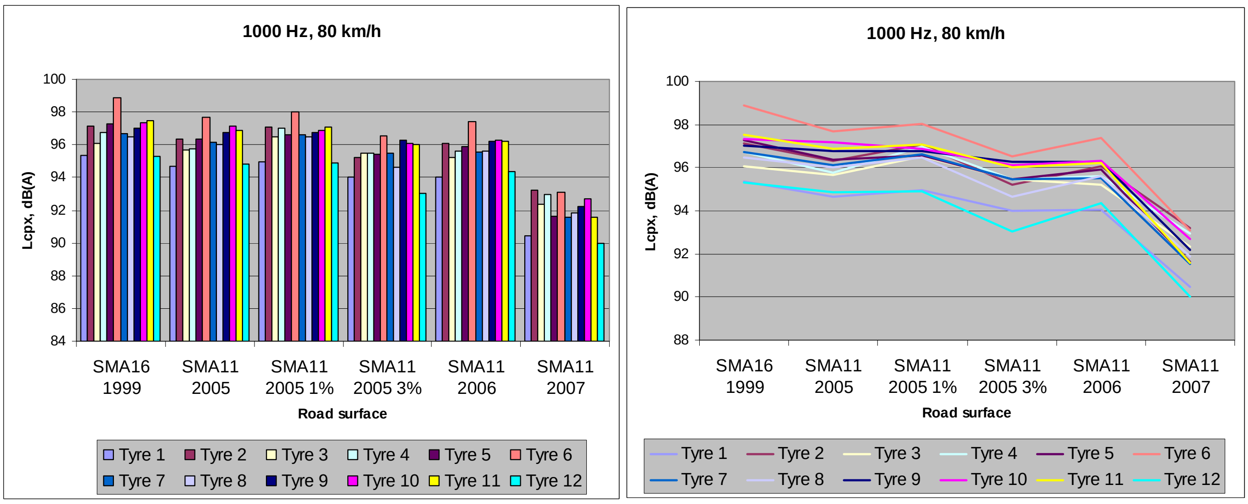


Figure 73 *CPX-measurements, 1000 Hz, 80 km/h*

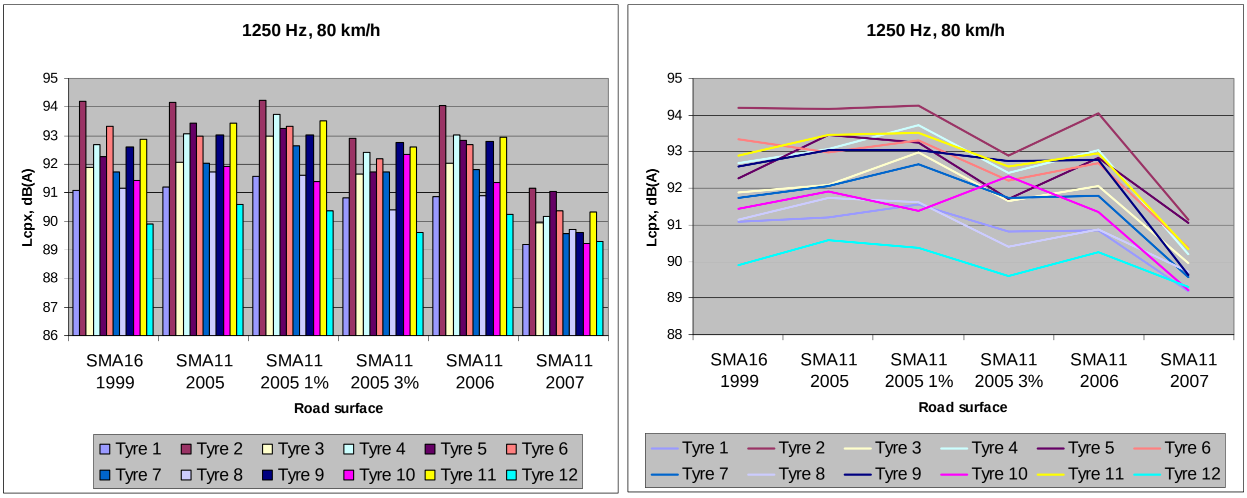


Figure 74 *CPX-measurements, 1250 Hz, 80 km/h*

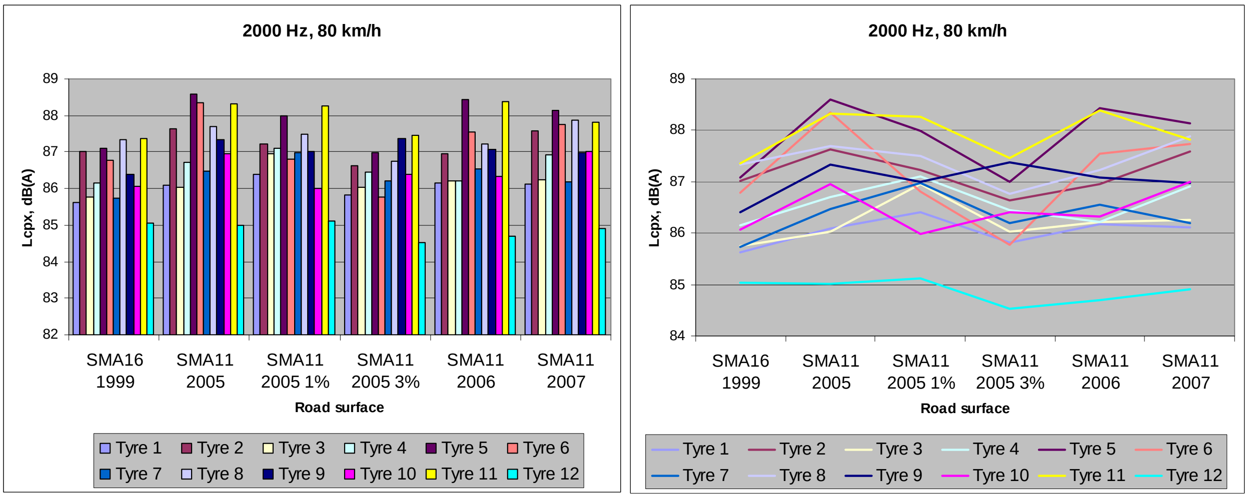


Figure 75 *CPX-measurements, 2000 Hz, 80 km/h*

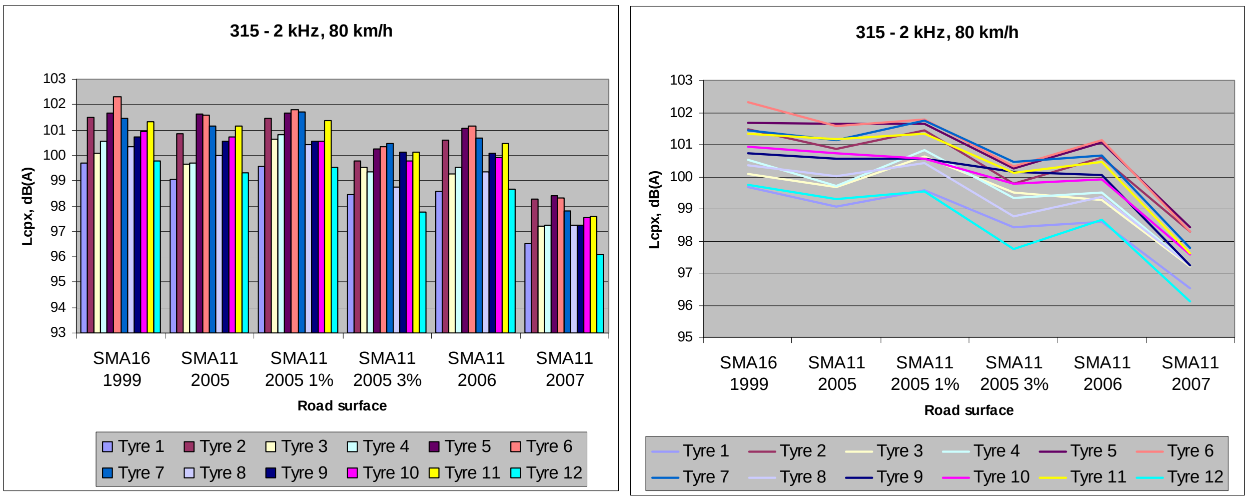


Figure 76 *CPX-measurements, 315-2000 Hz, 80 km/h*

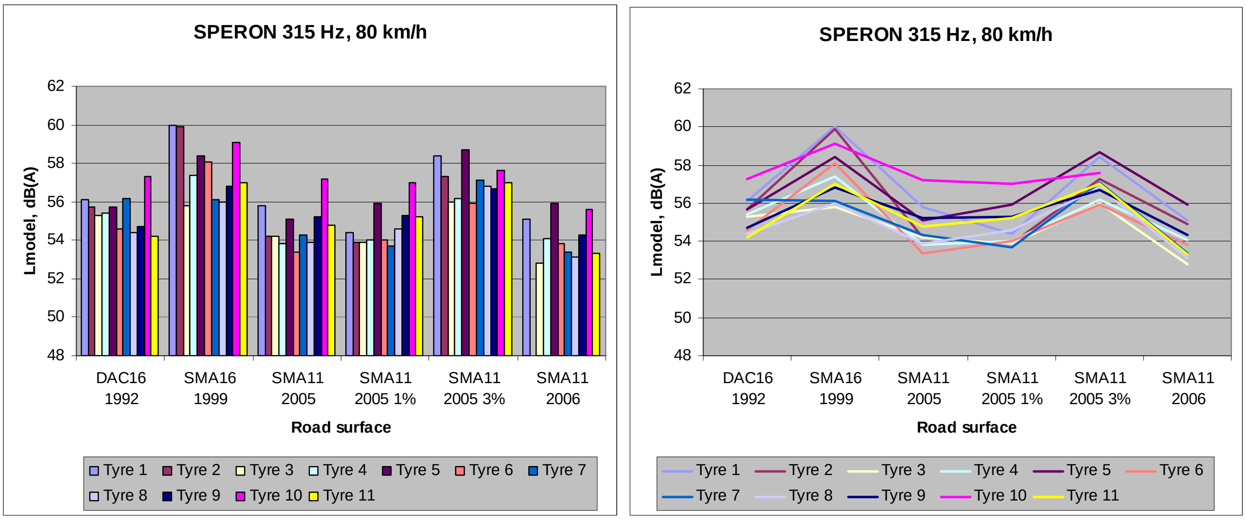


Figure 77 *SPERoN model, 315 Hz, 80 km/h*

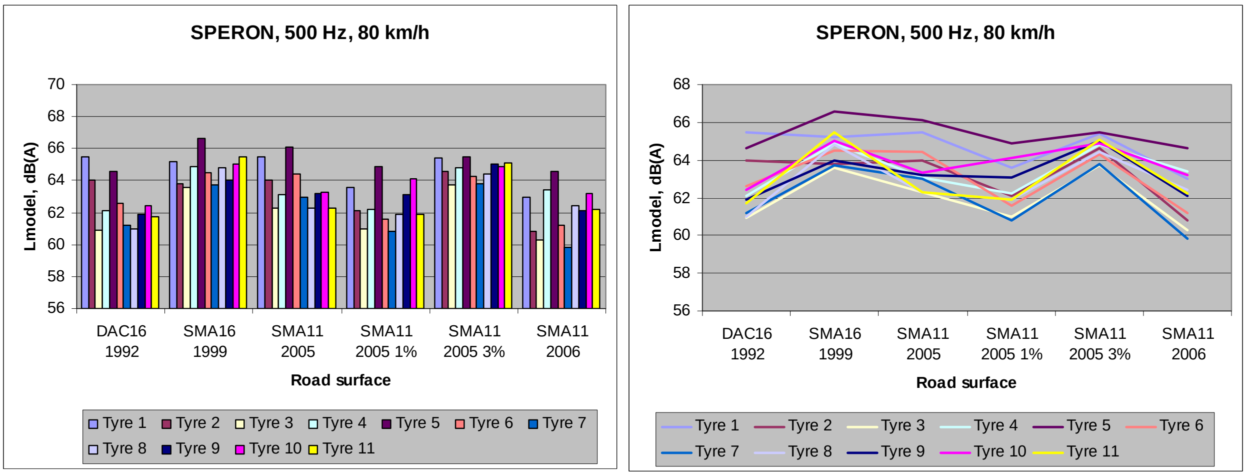


Figure 78 *SPERoN model, 500 Hz, 80 km/h*

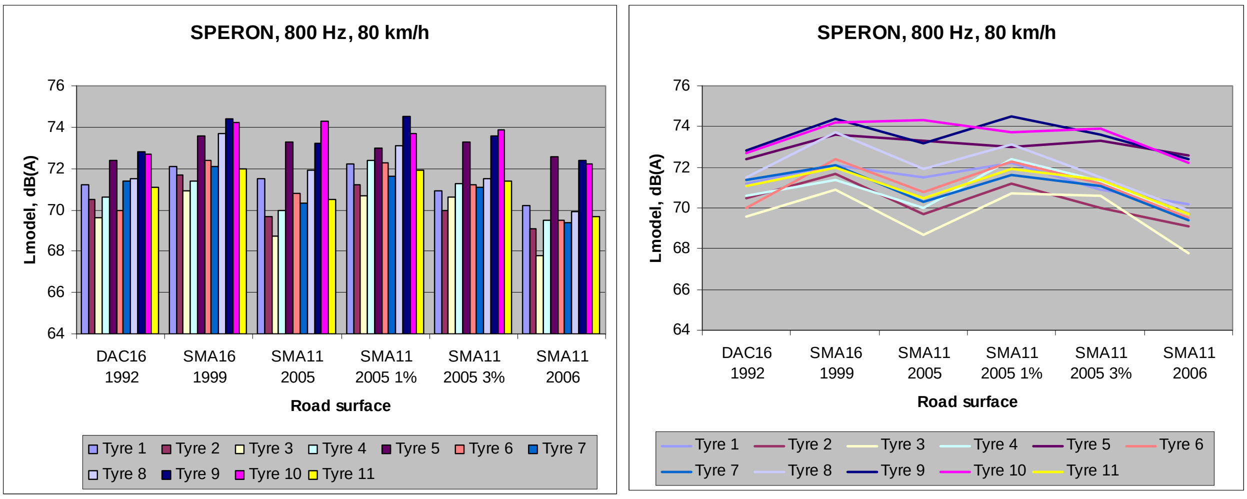


Figure 79 *SPERoN model, 800 Hz, 80 km/h*

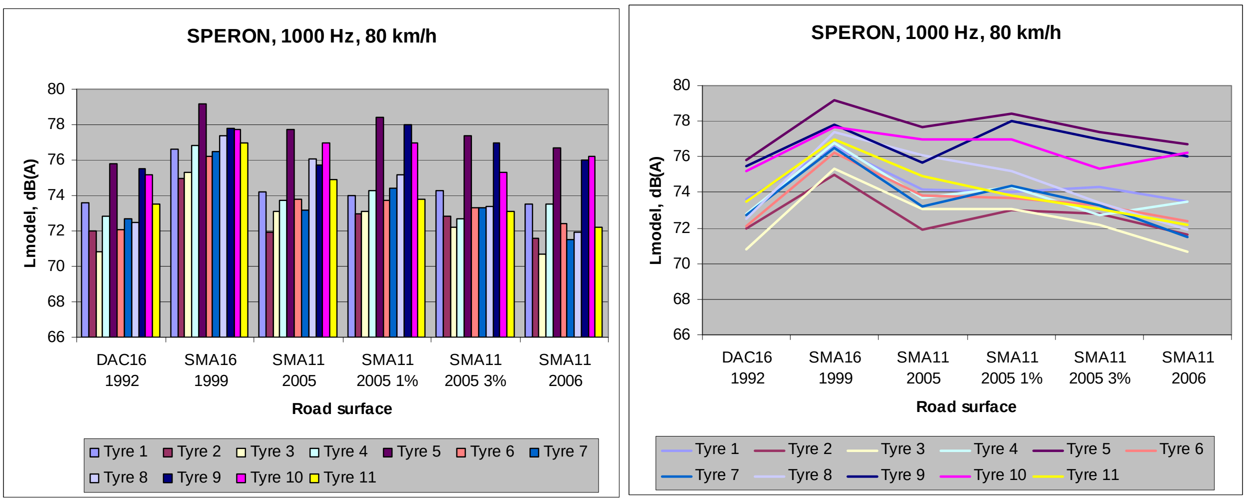


***Figure 80** SPERoN model, 1000 Hz, 80 km/h*

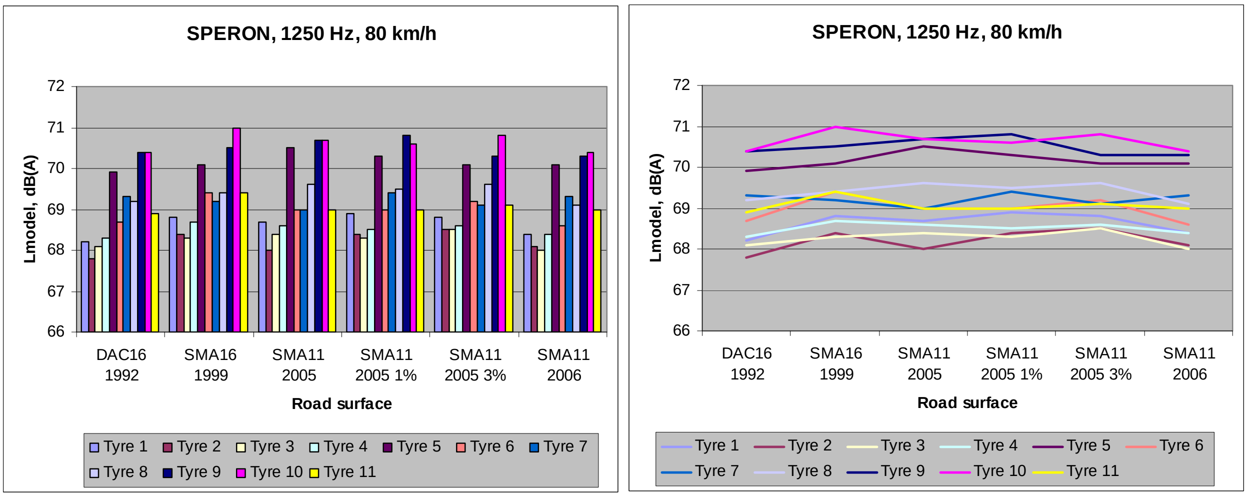


***Figure 81** SPERoN model, 1250 Hz, 80 km/h*

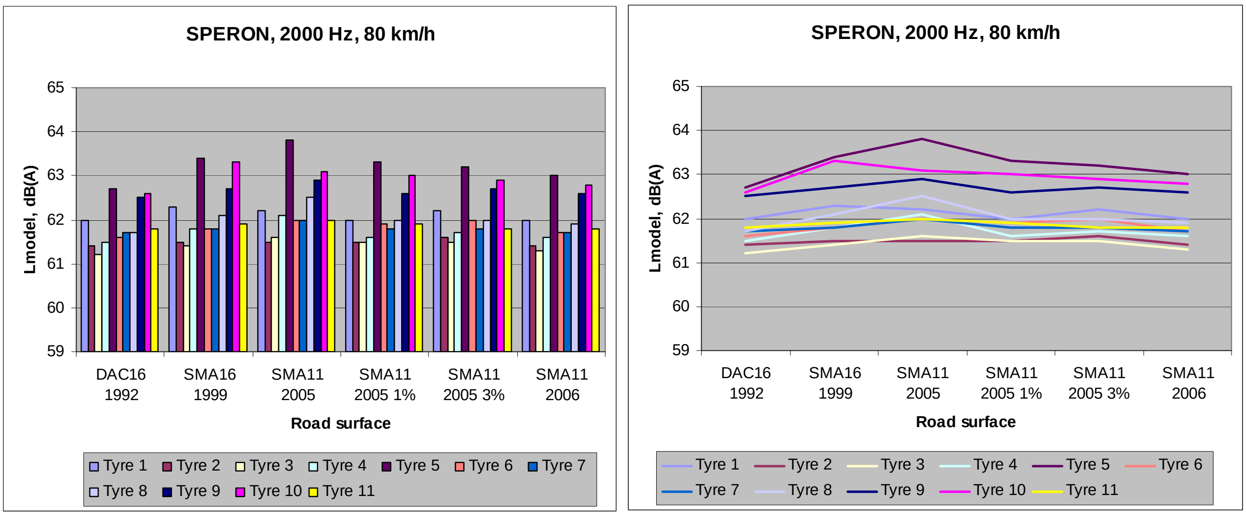
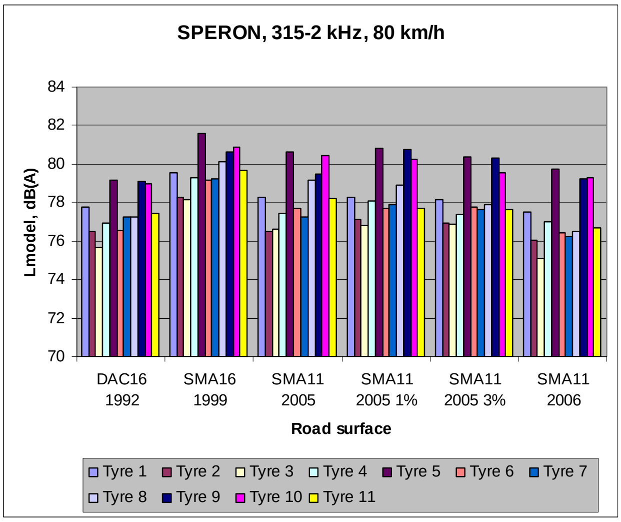


***Figure 82** SPERoN model, 2000 Hz, 80 km/h*



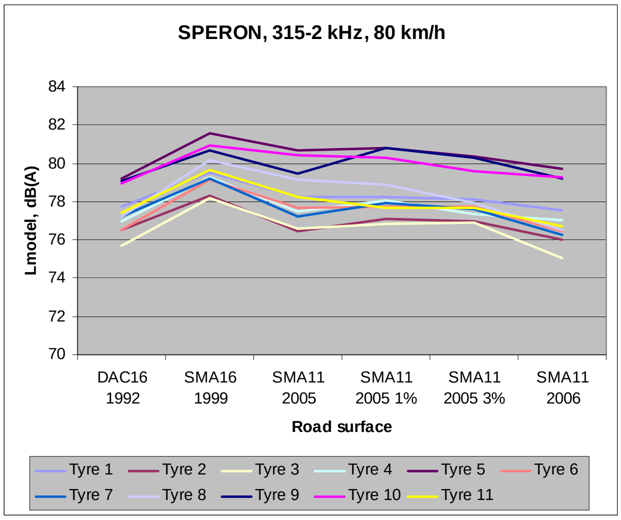


Figure 82 *SPERoN model, 315 - 2000 Hz, 80 km/h*

From these results, some general conclusions can be made:

- On actual roads (CPX-measurements), there is not much difference in noise levels in the low frequency area around 315 Hz (figure 70). At the newest surface (SMA11 2007 – not exposed to a winter), there seems to be a bigger variation in levels, as found in chapter 5.2). This means that the tread pattern (and tyre size within the measured range) is not influencing the generation mechanism. The vibration of the tyres is the main source.
- At the higher frequencies (above 800 Hz), differences in tread pattern is probably the main reason for higher noise differences.
- The *SPERoN* model seems to give ***higher*** differences in the low frequency area (315 Hz), than the actual measurements (figure 77).
- The *SPERoN* model seems to generate ***higher*** noise levels on Surface 5 (SMA11 2005 3%) than found during the CPX-measurements.
- Tyre 5 seems to generate high levels around 2 kHz, both in the model and in CPX-mode (figures 75 and 82).

For the tyres 1,5,6,7,8,9,10,13,14 and 15, the same analysis of CPX-measurements have been made for the chosen 1/3rd octave band frequencies on the surfaces 7-13 (measurements in 2008):
Surface 7: SMA11 2006
Surface 8: DaFib11/DaFib16 2006 (twin layer porous)
Surface 9: ViaQ11/ViaQ16 2006 (twin layer porous)
Surface 10: Wa8/Da16 2006 (twin layer porous)
Surface 11: Da16 2006 (single layer porous)
Surface 12: Da11/Da16 2008 (twin layer porous
Surface 13 SMA11 2008

The results are shown in figures 83-89. The oldest surface is to the left.

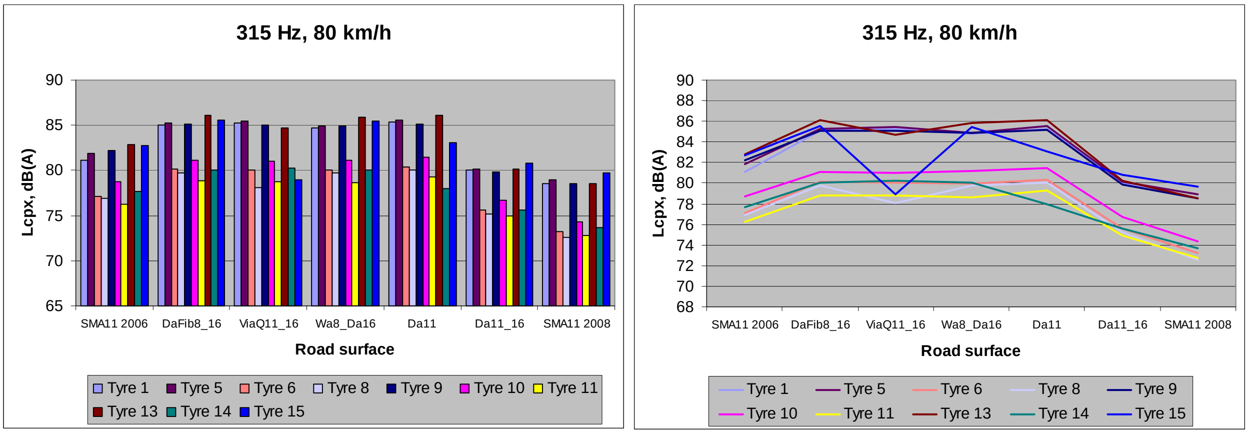


Figure 83 *CPX-measurements, 315 Hz, 80 km/h*

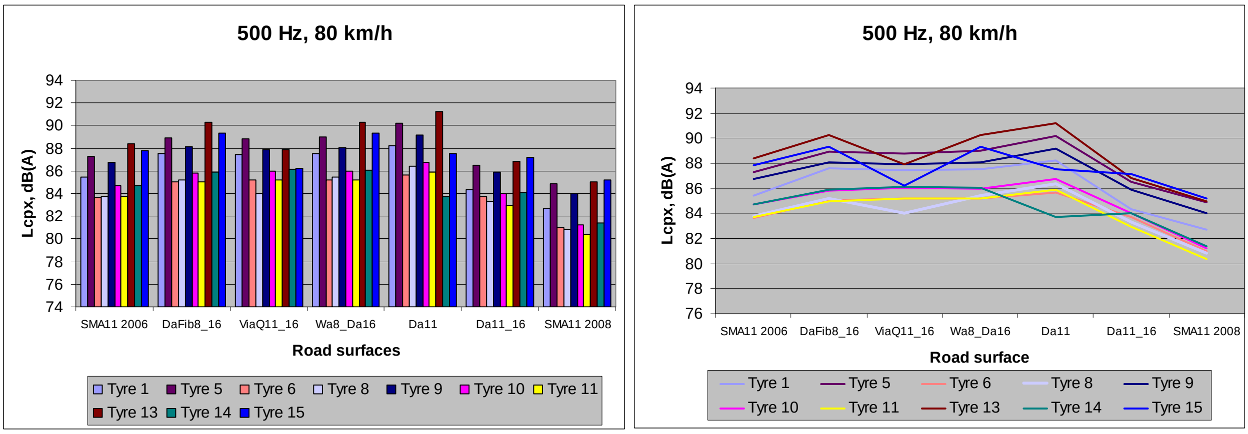


Figure 84 *CPX-measurements, 500 Hz, 80 km/h*

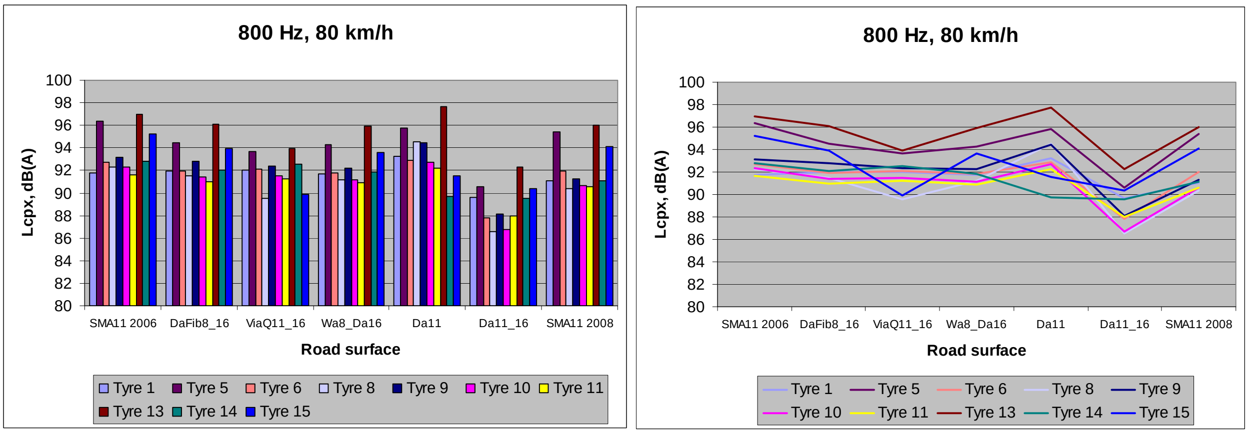
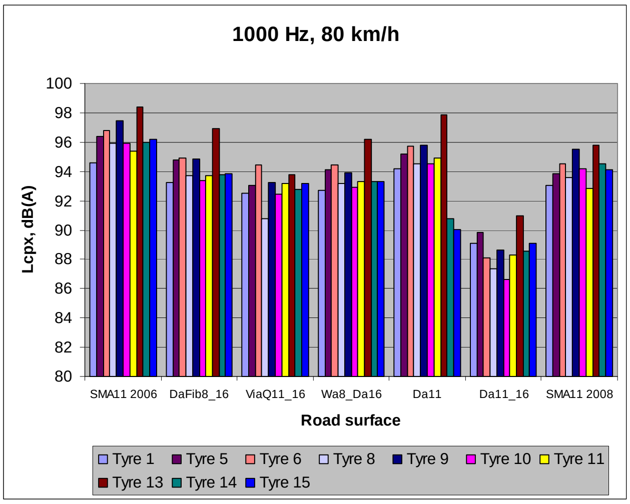


Figure 85 *CPX-measurements, 800 Hz, 80 km/h*



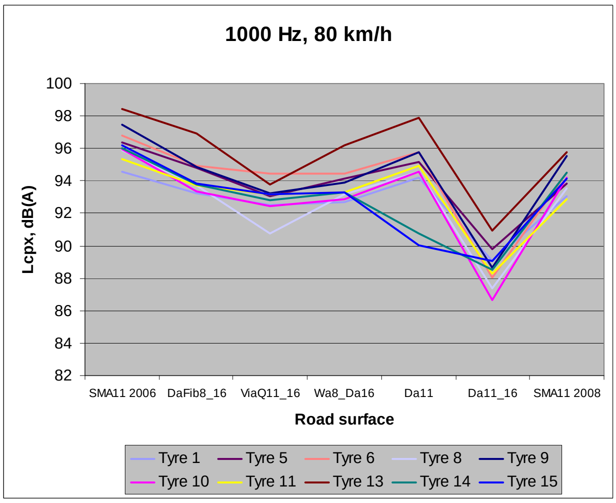
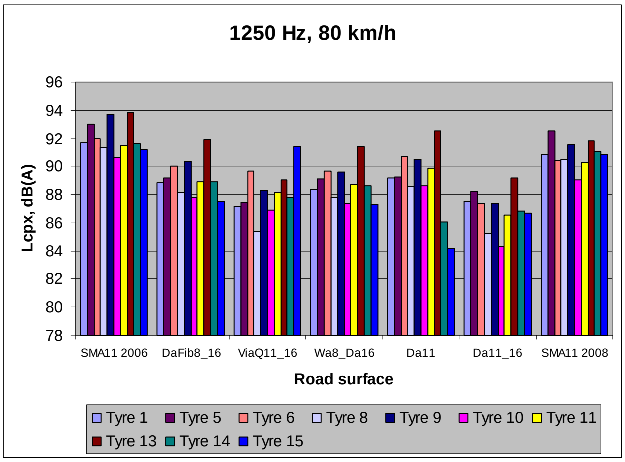


Figure 86 *CPX-measurements, 1000 Hz, 80 km/h*



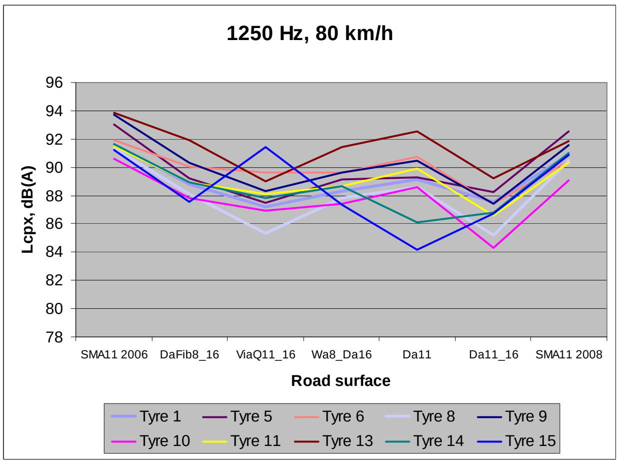
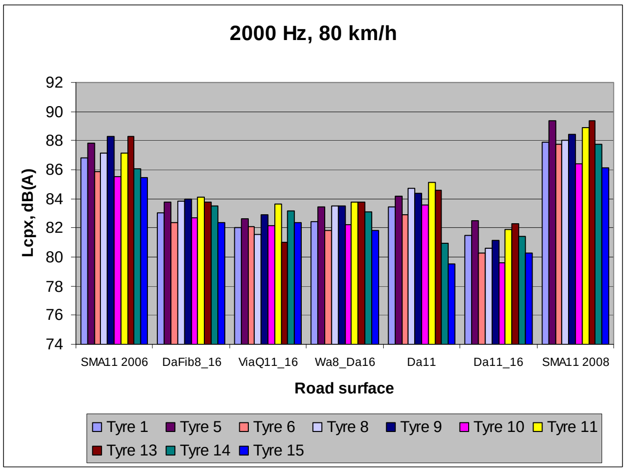


Figure 87 *CPX-measurements, 1250 Hz, 80 km/h*



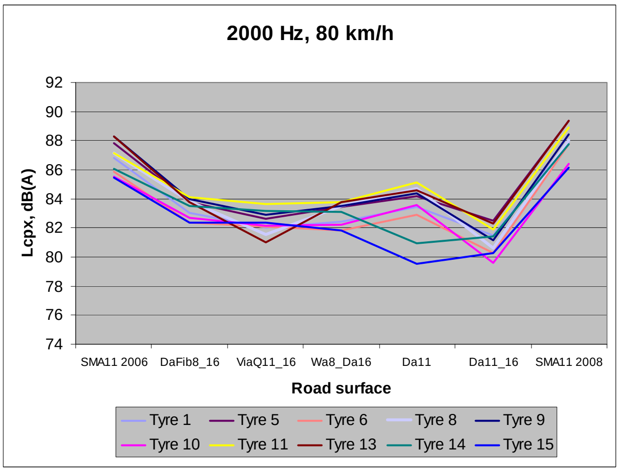


Figure 88 *CPX-measurements, 2000 Hz, 80 km/h*

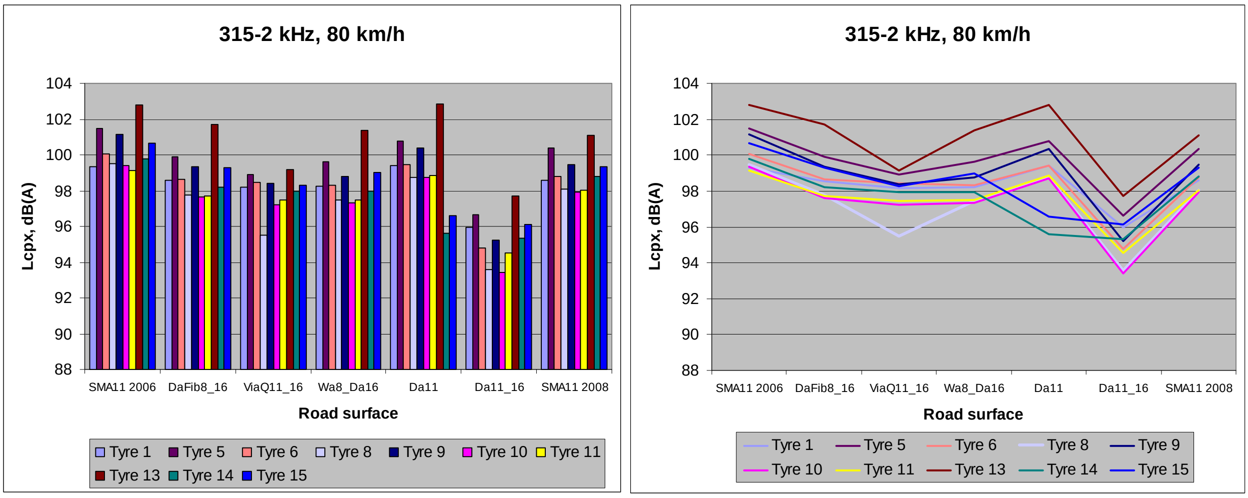


Figure 89 *CPX-measurements, 315 - 2000 Hz, 80 km/h*

From these results, the following conclusions can be made:

- Tyre 15 (Pirelli P7) has a different "noise behaviour" on Surface 9 (ViaQ11_16) at two frequencies; 315 and 1250 Hz. The reason for this has not been investigated.
- At the lowest frequency (315 Hz), the tyres can be separated into two groups (except for tyre 15 on ViaQ11_16): Group A ("noisy"): Tyres 1, 5,9,13,15 Group B; Tyres 6, 8,10,11,12,14 Within this project, it has not been possible to study if there are common tyre design parameters within these two groups.
- At the high frequency (2000 Hz), the reduced air pumping effect is clearly separating the porous road surfaces from the dense (figure 88).

5.4 Analysis of drum measurements

The tyres 1-15 have all been measured on 3 replica road surfaces at the drum facilities of TUG/Gdansk[2]. The following 3 surfaces were measured:

- ISO 10844
- GRB-S (dense asphalt concrete)
- APS-4 (rough textured surface).

In figures 90 -96, the noise ranking in the selected 1/3rd octave band frequencies are shown along with the total level, on the 3 surfaces.

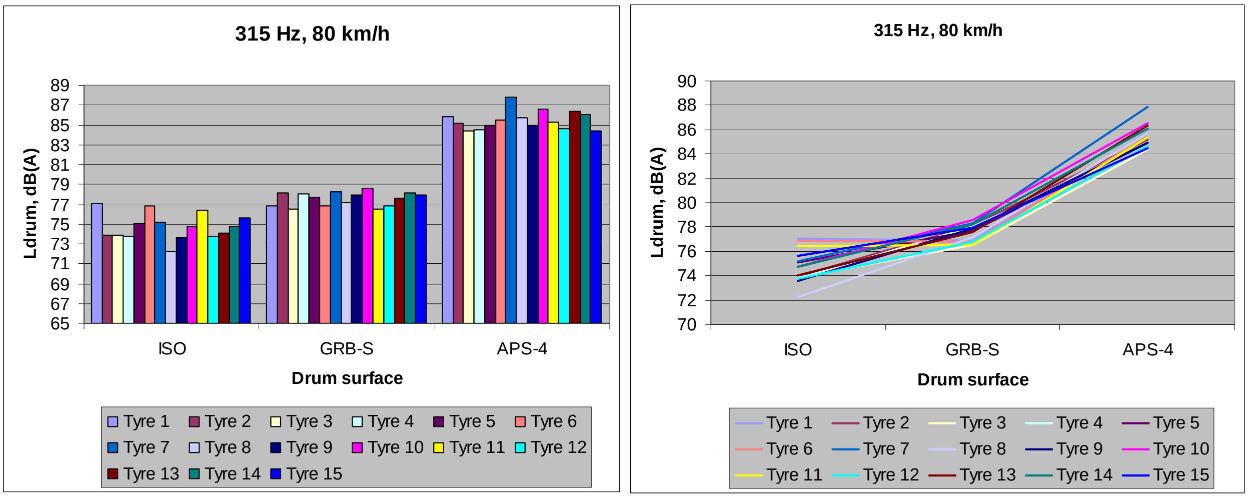


Figure 90 *Drum measurements, 315 Hz, 80 km/h.*

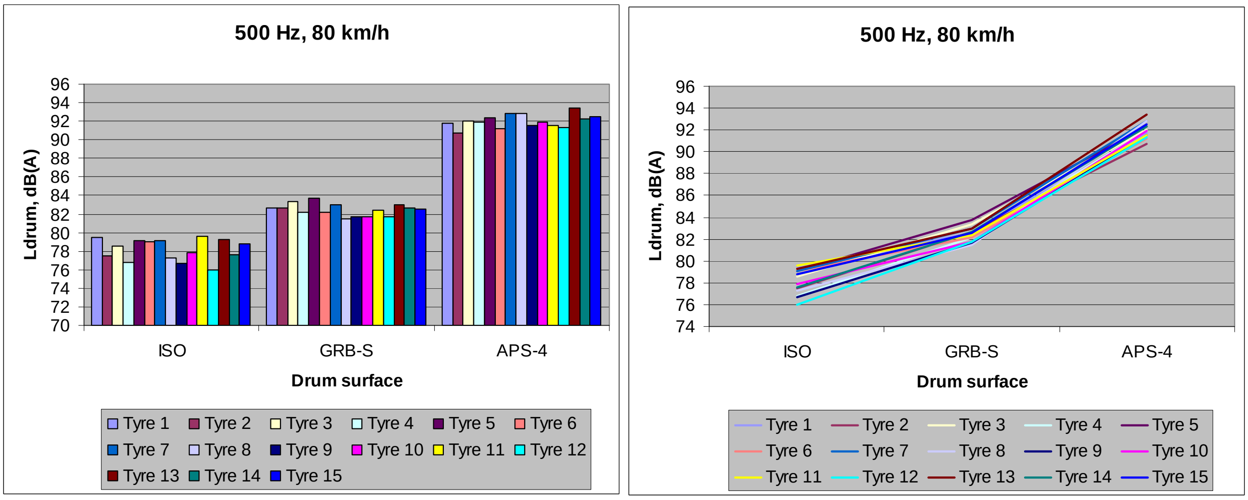


Figure 91 *Drum measurements, 500 Hz, 80 km/h.*

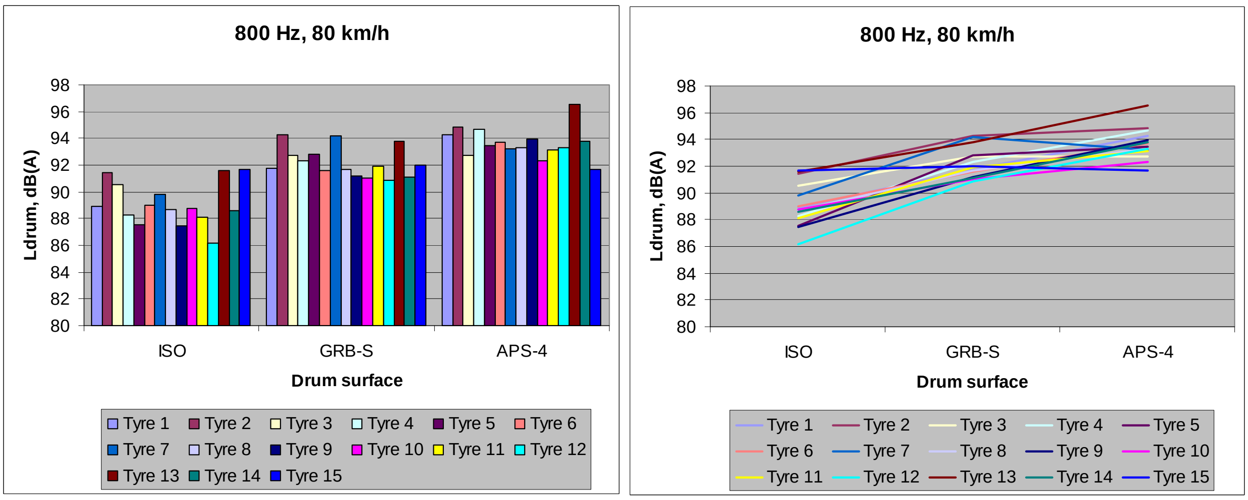


Figure 92 *Drum measurements, 800 Hz, 80 km/h.*

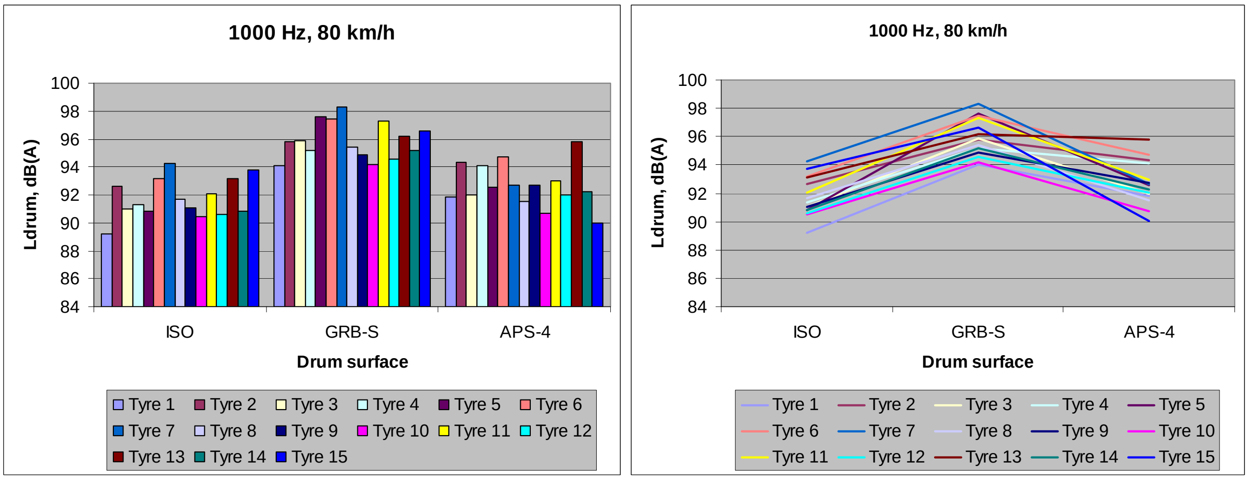


Figure 93 *Drum measurements, 1000 Hz, 80 km/h.*

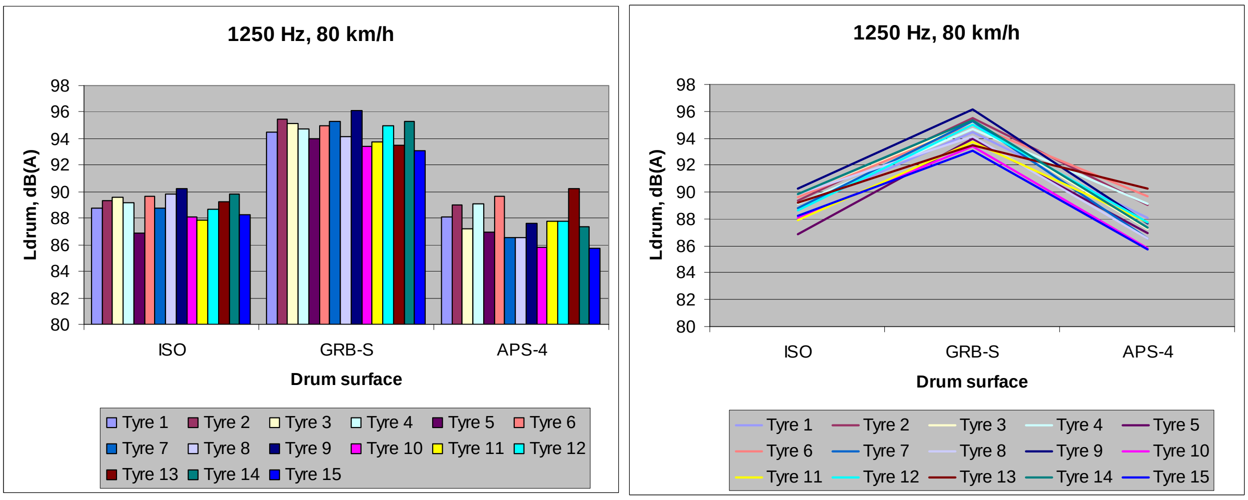


Figure 94 *Drum measurements, 1250 Hz, 80 km/h.*

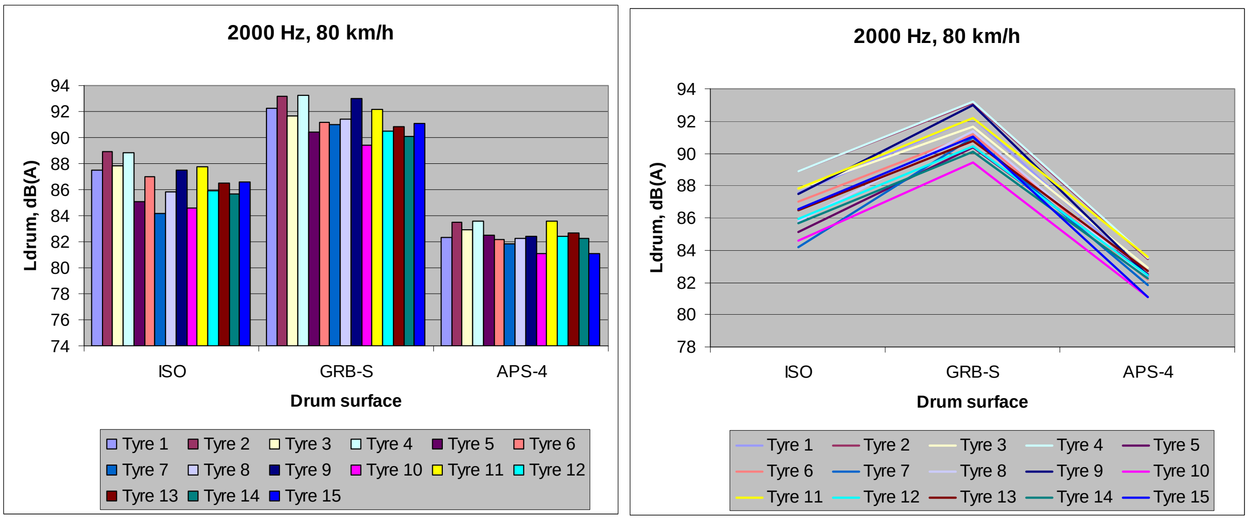


Figure 95 *Drum measurements, 2000 Hz, 80 km/h.*

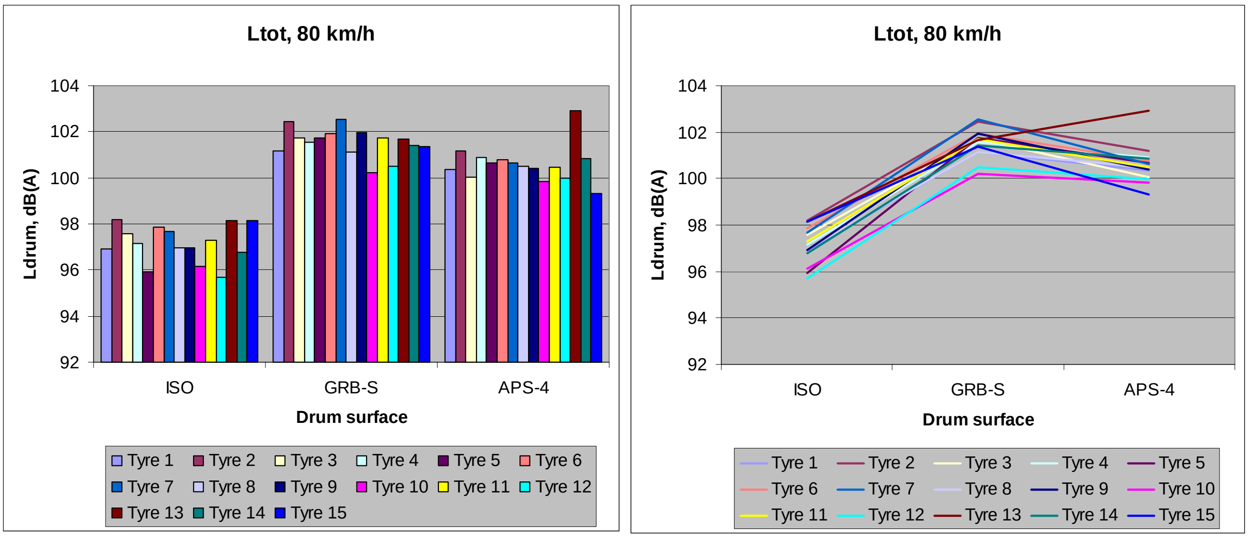


***Figure 96** Drum measurements, Total level, 80 km/h.*

Also on the drum measurements, one can see a smaller spread in levels at the lowest frequency (315 Hz, figure 90), than for at the high frequencies (2000 Hz, figure 96), where differences in the tread pattern is probably dominating.

Figure 90 show that the highest low frequency levels are generated (vibrations) on the rough APS-4 surface. Interesting is, however, that this changes as the frequency increases. Already at 1000 Hz, it is the “normal” asphalt concrete surface that is the noisiest surface. It would have been interesting to do a more deep analysis of the relationship between texture components of the surfaces and the noise levels, but this is not within the scope of this project.

6 Summary and conclusions

22 passenger car tyres of dimensions between 175/70 R14 and 225/60 R16 have been measured on the ISO surface at the test area in Kloosterzande, the Netherlands. The new reference tyres of the CPX-method (WD of 3rd CD11819-2, 2009), SRTT and Avon AV4, are included in the measurement program.

All measurements have been performed using the CPX-trailer of the Norwegian Public Roads Administration.

The spread in CPX-noise levels between the tested tyres is about **4 dB(A)** at 50 km/h and about **6 dB(A)** at 80 km/h.

4 tyres of the same brand, type and dimensions (Michelin) with a low rolling resistance were found to have noise levels in the higher range.

11 of the tyres have previously been modelled, using the *SPERoN* model. Based on overall dB(A) levels, no significant correlation was found between the measured CPX-levels on the ISO surface at Kloosterzande and the modelled levels on the ISO surface at Sperenberg at both speeds.

Comparing the CPX-results on the ISO surface at Kloosterzande with CPX-results at two different 2 years old SMA11-surfaces in Norway, showed no correlation of the noise ranking.
This indicates that reducing the noise limits of tyres according to EU/ECE-regulations will have little or no effect on typically used Norwegian road surfaces. However, it should be noted that this conclusion is based on a limited number of passenger car tyres.

If the ranking at the ISO surface is compared with the results on a SMA surface ***not*** exposed to winter conditions, or to a double layer porous surface (new), there is a better correlation at 50 km/h. This indicates that an improved effect of more stringent tyre noise limits can be achieved by improvements of the commonly used road surfaces in Norway.

A frequency analysis has been performed, comparing the 1/3rd octave band results between 315 and 2000 Hz.
At the lowest frequency of 315 Hz, there seems to be a somewhat better correlation between the modelling results and the CPX-measurements. At higher frequencies (above 1000 Hz), in general there is a negative correlation between the two modes (modelling/measurements).

It should be noted that in several cases, the correlation is based on modelling levels that are within the uncertainty range of the model.

Further work should be focussed on studying the relationship between CPX and CPB-levels.
In addition, further measurements of tyres with low rolling resistance and low noise levels (in ISO surface) on SMA surfaces in Norway is recommended.

7 References

[1] T.Berge, A.Ustad, F.Haukland, "Tyre/road noise modelling – noise measurements of 12 passenger car tyres".
SINTEF Report A5424, February 2008.

[2] T.Berge, F.Haukland, A.Ustad, "Noise ranking of car tyres, Results from road measurements, *SPERoN* modelling and drum measurements".
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[4] ISO 10844:1994 "Acoustics – Specification of test track for the purpose of measuring the ' noise emitted by road vehicles and their tyres. (Under revision).

[5] W.Schwanen, H.M. van Leeuwen, A.A.A.Peeters, "Acoustic Optimization Tool. RE3: Measurement data Kloosterzande test track".
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[6] F.Anfosso-Lédée, "Modeling the local propagation effects of tire-road noise: propagation filter between CPX and CPB measurements".
Proceedings of Inter-Noise 2004, Prague, Czech Republic, August 2004.

[7] E-U.Saemann, Personal communication with Dr.E-U. Saemann, Continental, Manager NVH, Passenger and Light Truck Tyres.Dec.2009.

[8] T.Berge, F.Haukland, A.Ustad, "Environmentally friendly pavements: Results from noise measurements 2005-2008". SINTEF Report A9721, February 2009.

APPENDIX 1 Correlation analysis - ISO surfaces

Figures A1 to A18 show the correlation analysis for each 1/3rd octave band from 315 to 2000 Hz between modelling results of 11 tyres on the ISO surface at Sperenberg and CPX-measurements at the ISO surface at Kloosterzande. Speeds are 50 and 80 km/h.

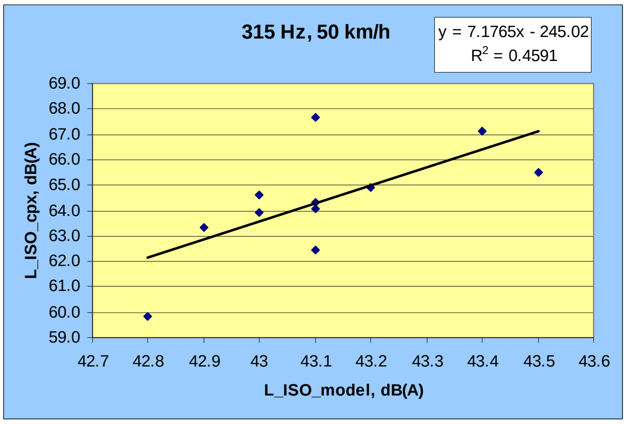

***Figure A1**: 315 Hz, 50 km/h*

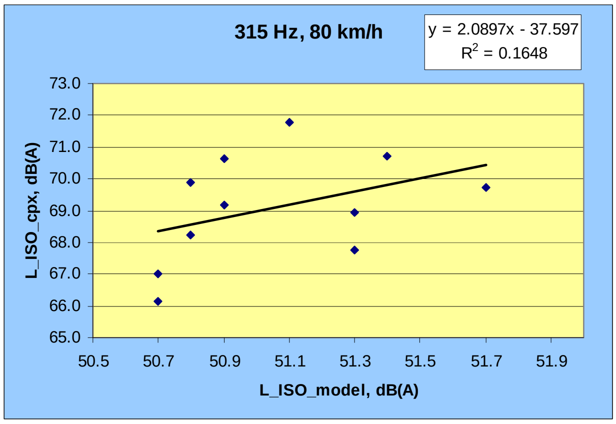

***Figure A2**: 315 Hz, 80 km/h*

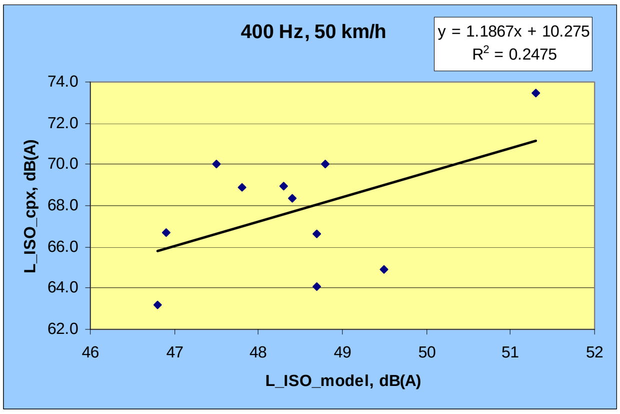

***Figure A3**: 400 Hz, 50 km/h*

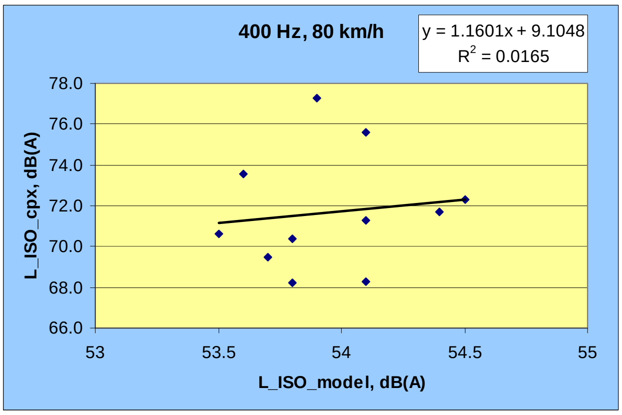

***Figure A4:** 400 Hz, 80 km/h*

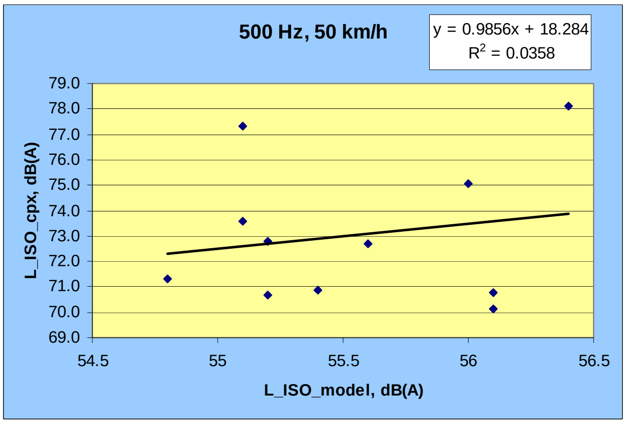

***Figure A5:** 500 Hz, 50 km/h*

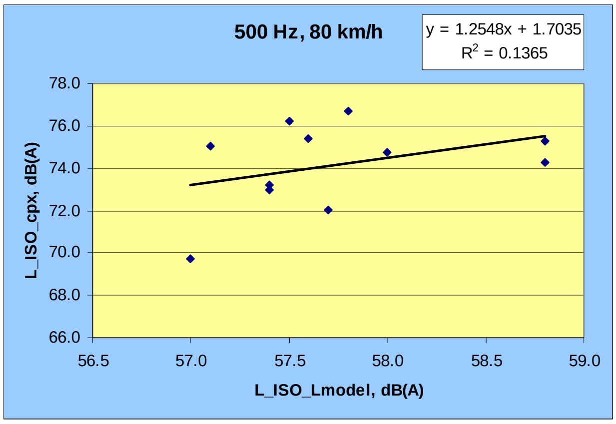

***Figure A6:** 500 Hz, 80 km/h*

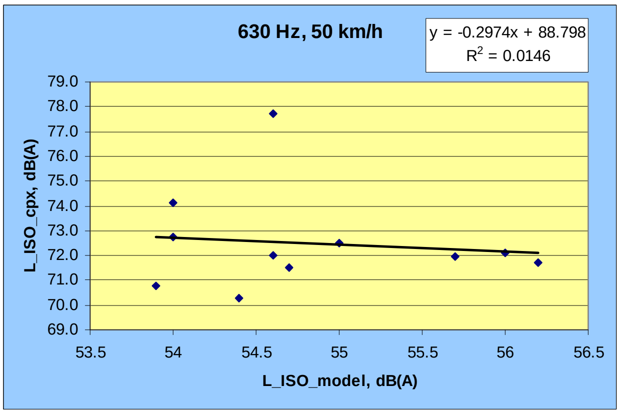

Figure A7: *630 Hz, 50 km/h*

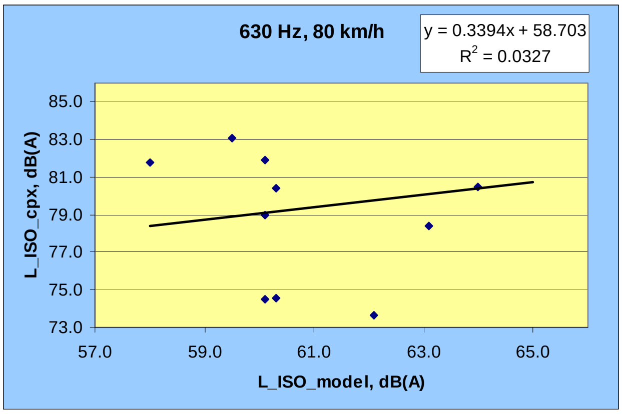

Figure A8: *630 Hz, 80 km/h*

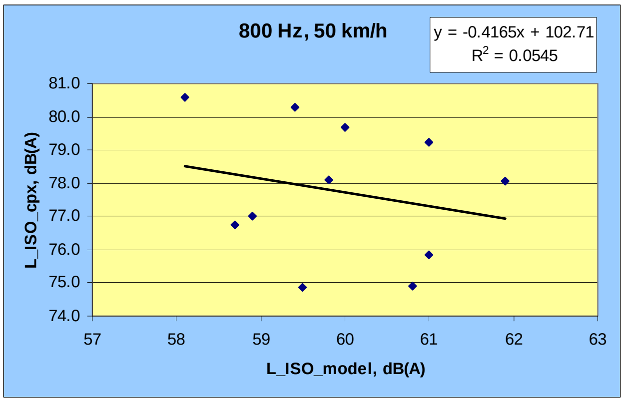

Figure A9: *800 Hz, 50 km/h*

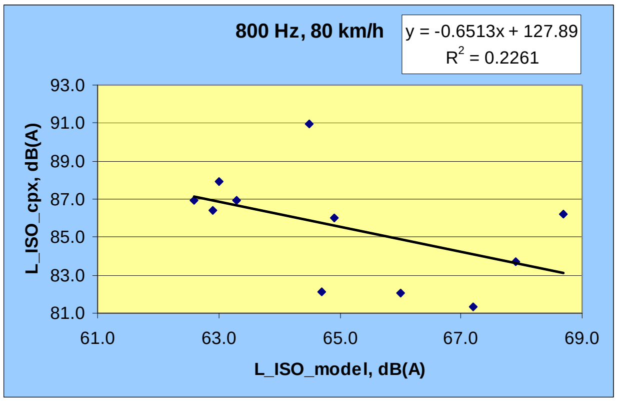

Figure A10: *800 Hz, 80 km/h*

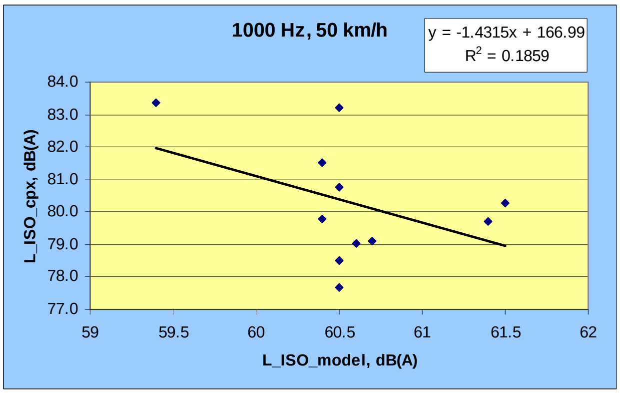

Figure A11: *1000 Hz, 50 km/h*

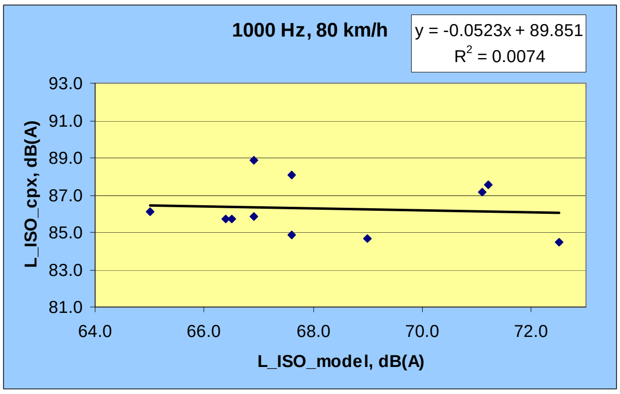

Figure A12: *1000 Hz, 80 km/h*

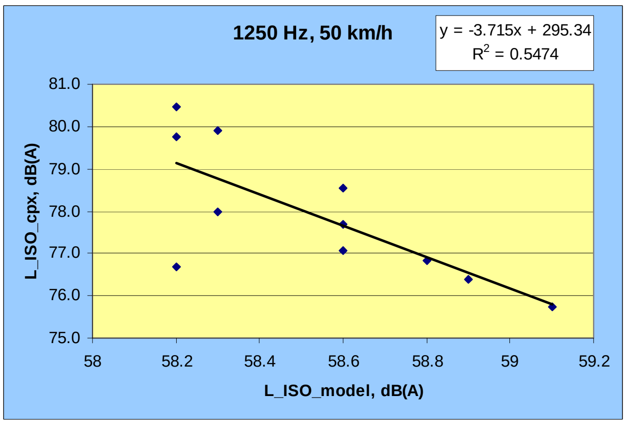

Figure A13: *1250 Hz, 50 km/h*

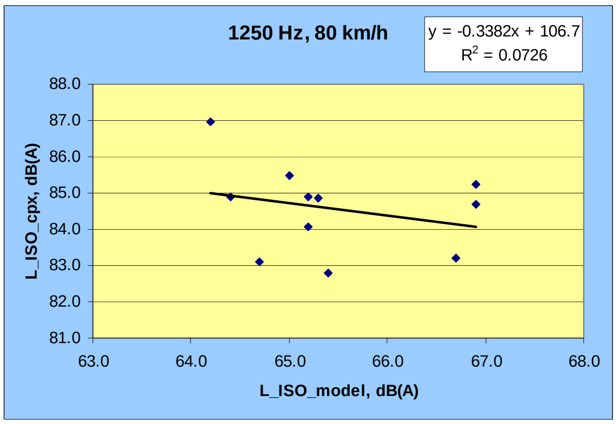

Figure A14: *1250 Hz, 80 km/h*

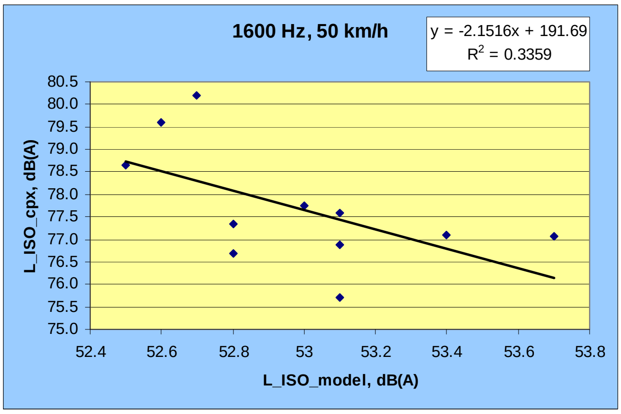

Figure A15: *1600 Hz, 50 km/h*

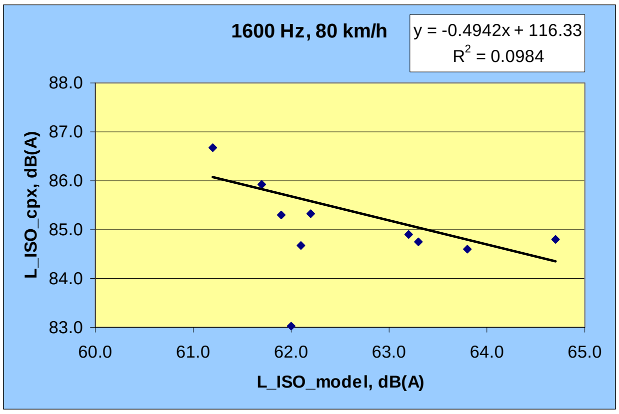

Figure A16: *1600 Hz, 80 km/h*

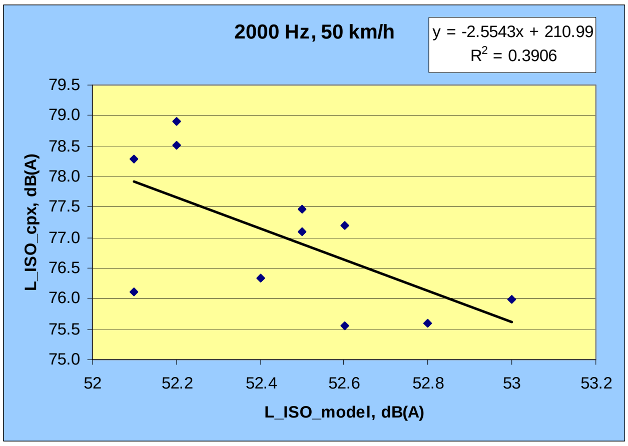

Figure A17: *2000 Hz, 50 km/h*

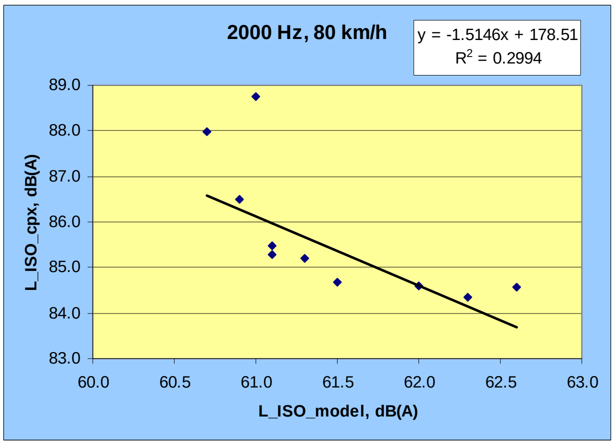

Figure A18: *2000 Hz, 80 km/h*

APPENDIX 2 Correlation analysis - SMA surfaces

Figures A19 to A26 show the correlation analysis for each 1/3rd octave band from 315 to 2000 Hz between ***modelling*** results of 11 tyres on the SMA11 2005 and the corresponding ***measured*** CPX-levels (uncorrected). The speed is 80 km/h.

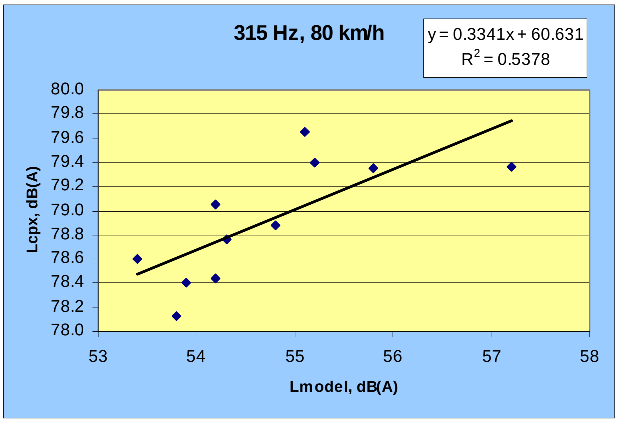

Figure A19*: SMA11 2005, 315 Hz*

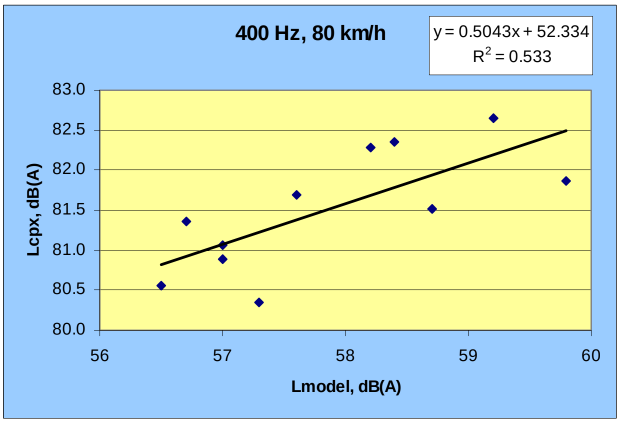

Figure A20: *SMA11 2005, 400 Hz*

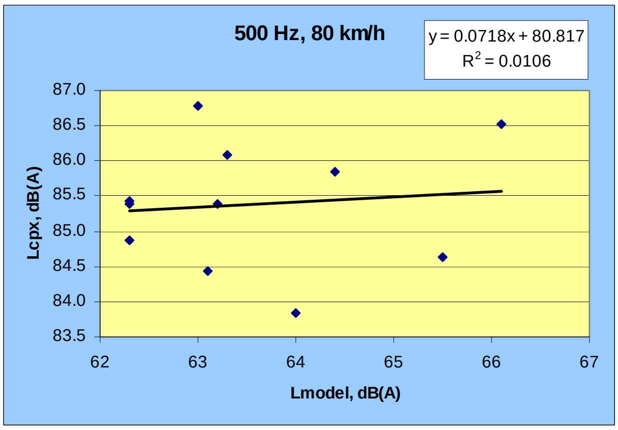

***Figure A21**: SMA11 2005, 500 Hz*

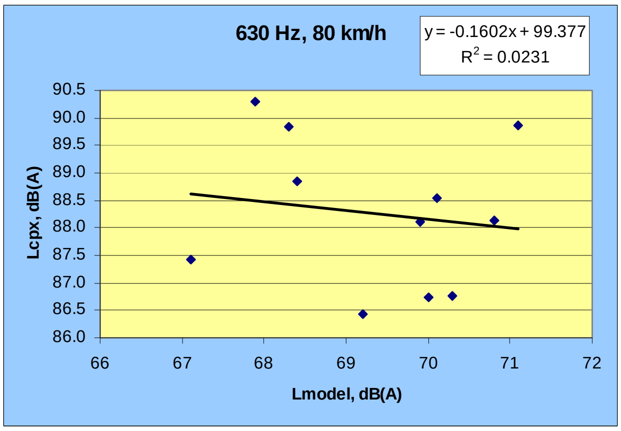

***Figure A22:** SMA11 2005, 630 Hz*

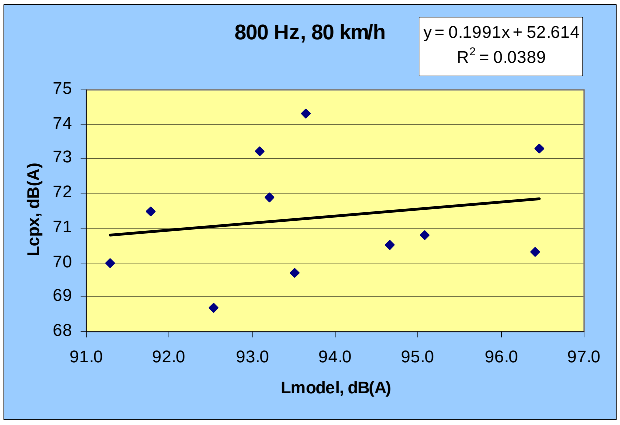

***Figure A23**: SMA11 2005, 800 Hz*

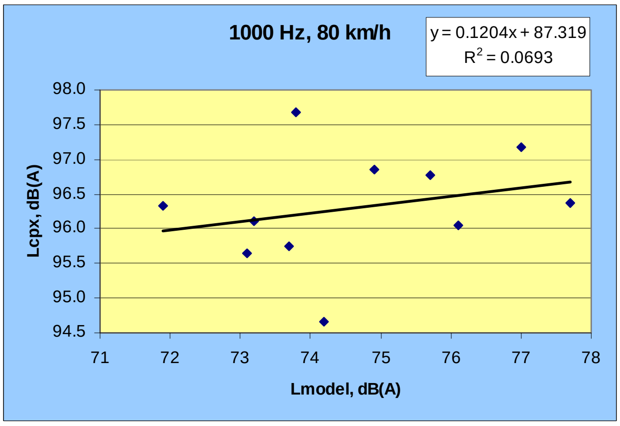

***Figure A24:** SMA11 2005, 1000 Hz*

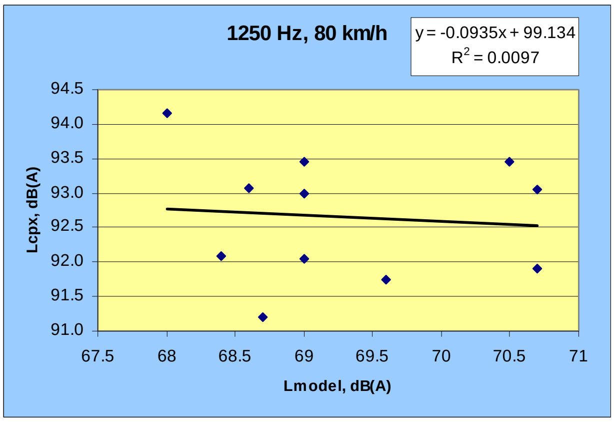

***Figure A25**: SMA11 2005, 1250 Hz*

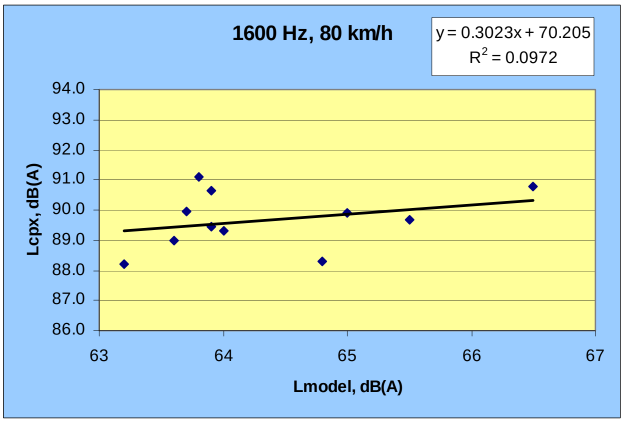

***Figure A25:** SMA11 2005, 1600 Hz*

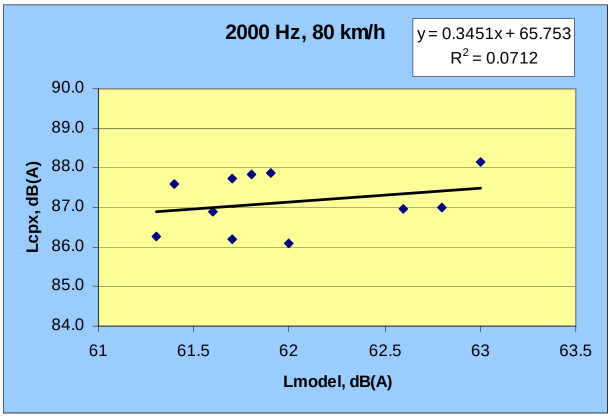

Figure A26: *SMA11 2005, 2000 Hz*

In figures A27-A44, the correlation is shown between ***measured*** CPX-levels on the ISO surface at Kloosterzande and ***measured*** CPX-levels on the SMA11 2007 surface (not exposed to winter conditions).

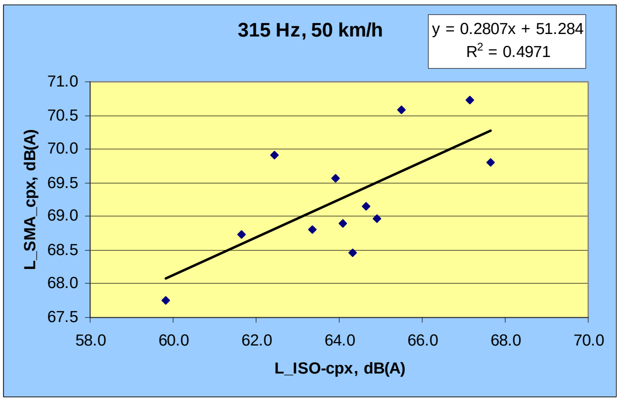

Figure A27*: ISO vs SMA11 2007, 315 Hz 50 km/h*

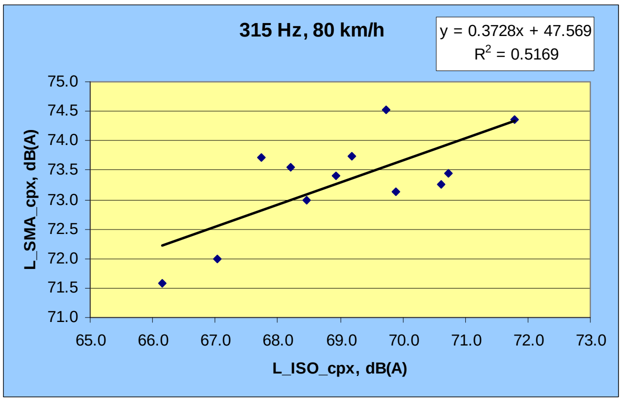

Figure A28: *ISO vs SMA11 2007, 315 Hz 80 km/h*

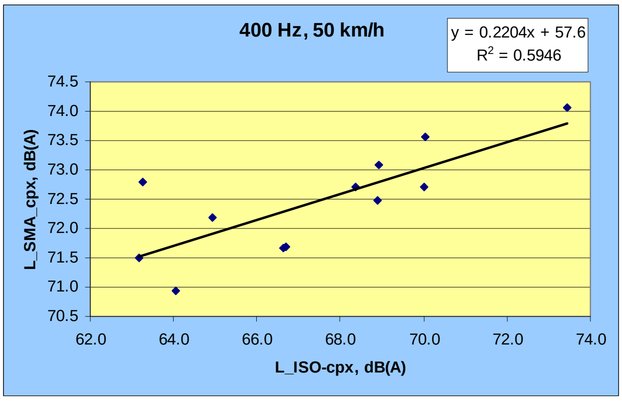

Figure A29*: ISO vs SMA11 2007, 400 Hz 50 km/h*

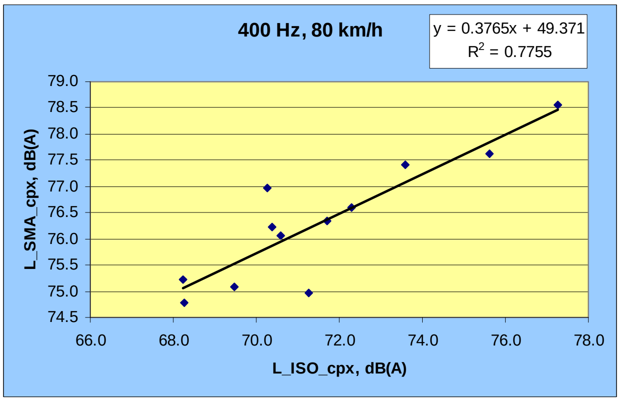

Figure A30: *ISO vs SMA11 2007, 400 Hz 80 km/h*

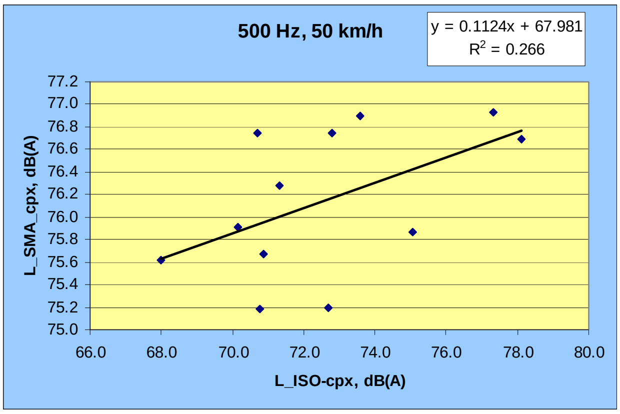

***Figure A31**: ISO vs SMA11 2007, 500 Hz 50 km/h*

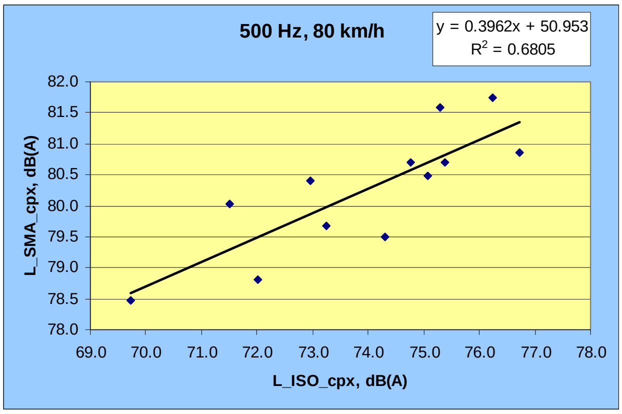

***Figure A32:** ISO vs SMA11 2007, 500 Hz 80 km/h*

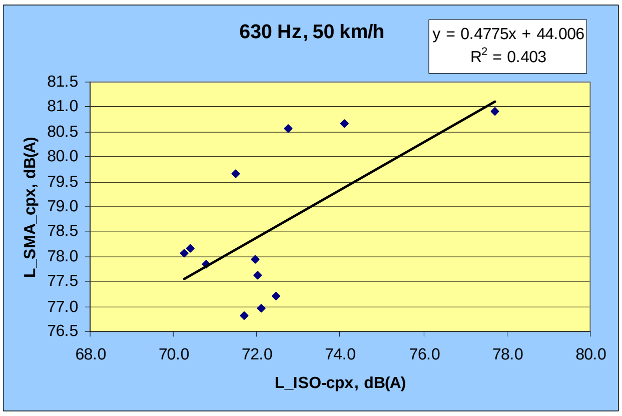

***Figure A33:** ISO vs SMA11 2007, 630 Hz 50 km/h*

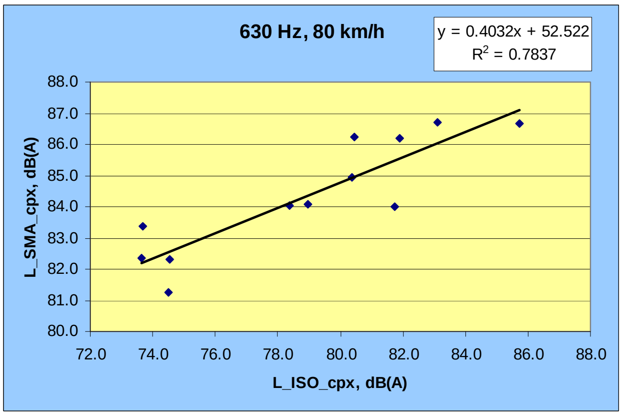

***Figure A34:** ISO vs SMA11 2007, 630 Hz 80 km/h*

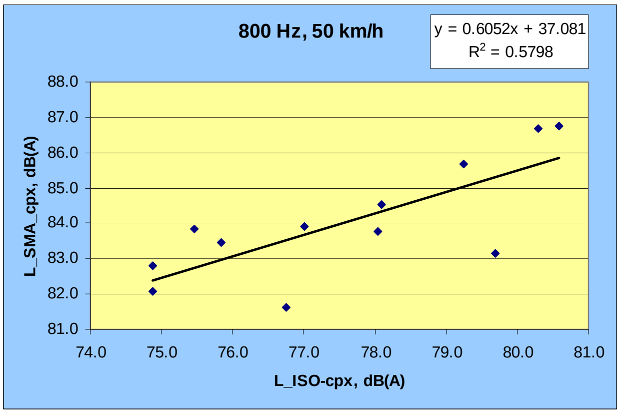

***Figure A35:** ISO vs SMA11 2007, 800 Hz 50 km/h*

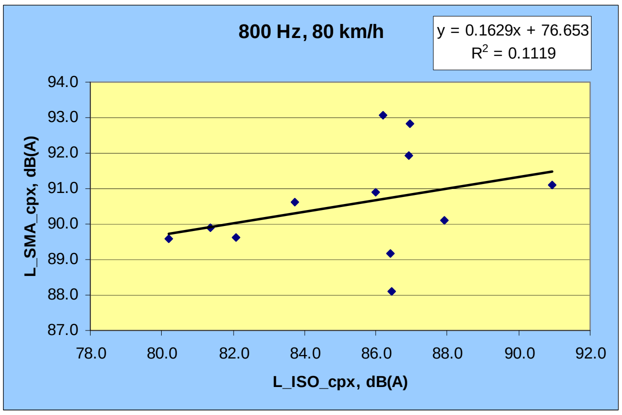

***Figure A36:** ISO vs SMA11 2007, 800 Hz 80 km/h*

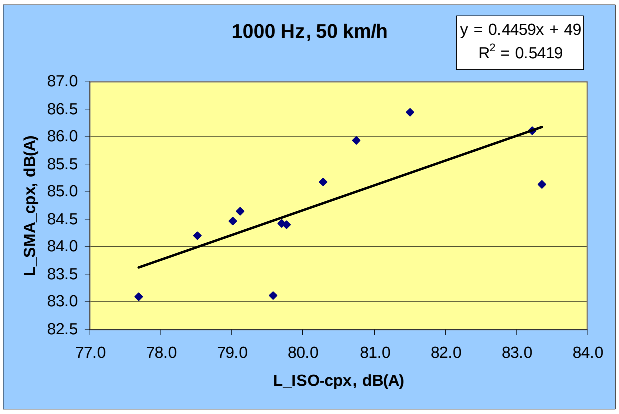

Figure A37: *ISO vs SMA11 2007, 1000 Hz 50 km/h*

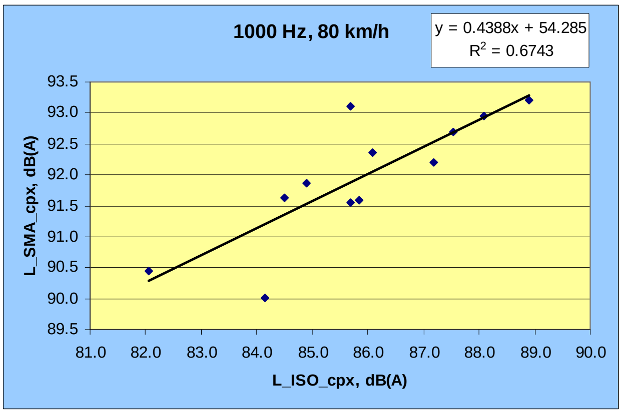

Figure A38: *ISO vs SMA11 2007, 1000 Hz 80 km/h*

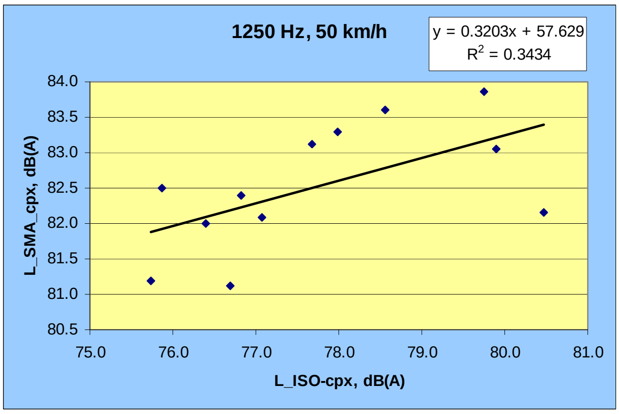

Figure A39: *ISO vs SMA11 2007, 1250 Hz 50 km/h*

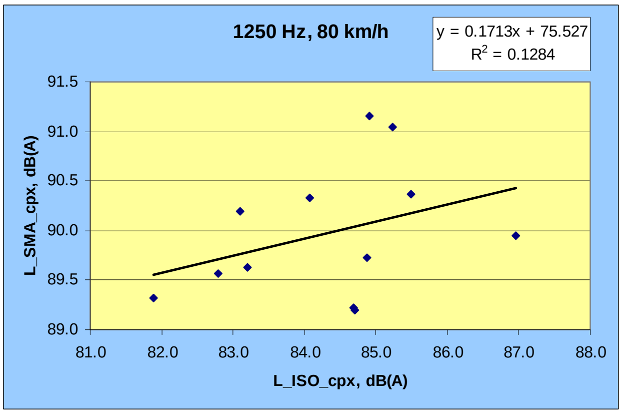

Figure A40: *ISO vs SMA11 2007, 1250 Hz 80 km/h*

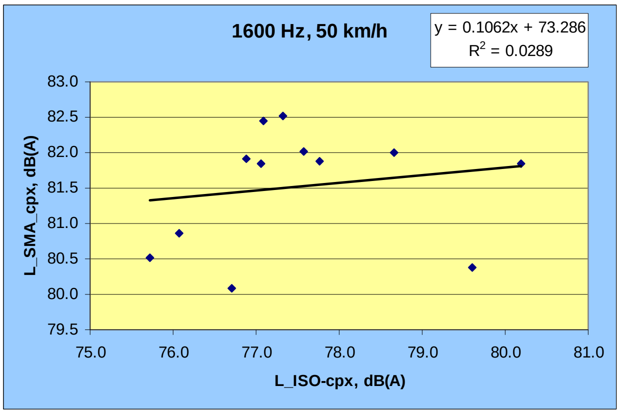

Figure A41: *ISO vs SMA11 2007, 1600 Hz 50 km/h*

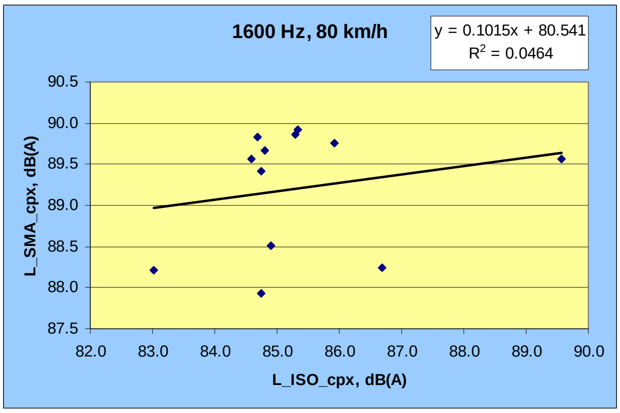

Figure A42: *ISO vs SMA11 2007, 1600 Hz 80 km/h*

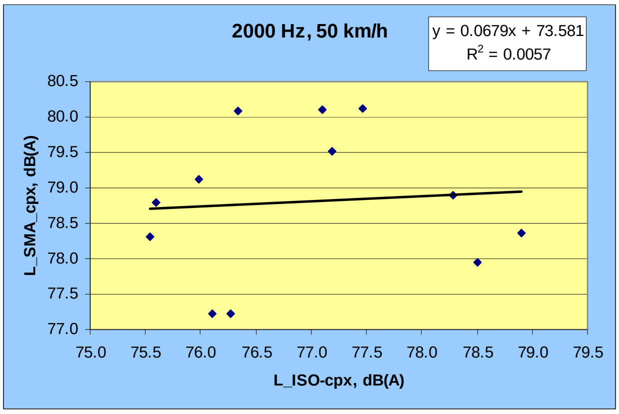

Figure A43: *ISO vs SMA11 2007, 2000 Hz 50 km/h*

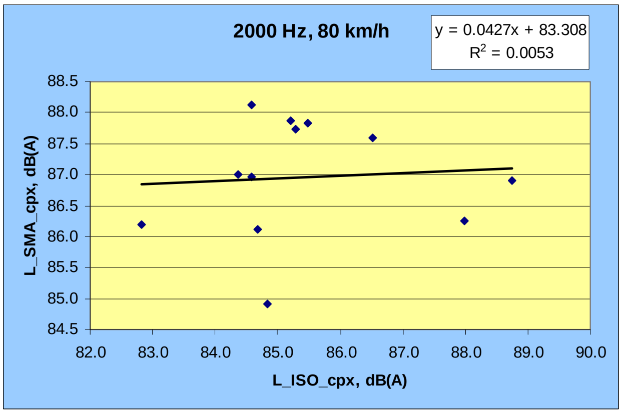

Figure A44: *ISO vs SMA11 2007, 2000 Hz 80 km/h*