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NordTyre - Tyre labelling and Nordic traffic noise

3rd Draft Final Report - Analysis of data on passenger car tyres

Kolofon:

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NordTyre - Tyre labelling and Nordic traffic noise

Preface

The NordTyre project was funded by NordFoU with contributions from

- Danish Road Directorate, (DRD) (Vejdirektoratet)
- Norwegian Public Roads Administration (NPRA) (Vegdirektoratet)
- Swedish Transport Administration (Trafikverket)
- Norwegian Climate and Pollution Control Agency (KLIF)

The Project Steering Group consisted of

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- Jakob Fryd, Danish Road Directorate (Vejdirektoratet)
- Kjell Strömmer (up to Dec-13); Peter Smeds (from Jan-14), Swedish Transport Administration (Trafikverket)
- Martin Hellung-Larsen, Danish Transport Authority (Trafikstyrelsen)
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- Jan Bo Kielland, Norwegian Climate and Pollution Agency, KLIF
- Ingunn Milford (from May -13), Norwegian Defence Estates Agency (Forsvarsbygg futura)
- Panu Sainio, Aalto University
- Ulf Sandberg, Swedish National Road and Transport Research Institute, VTI

The work was carried out by

Danish Road Directorate, DRD, as a project leader, assisted by
Jannicke Sjøvold, Norwegian Public Roads Administration (Statens vegvesen, Vegdirektoratet)

The following subcontractors contributed to the project:

SINTEF; Testworld Ltd; Technical University of Gdansk

Forord

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Summary

The main objectives of the project were:

- To establish a platform based on scientific evidence on the tyre/road contribution to traffic noise emission from roads in the Nordic countries, clarifying which combinations of tyres and pavements would yield the lowest noise emission throughout their lifetime, influencing the environment along roads and highways. This knowledge shall be the basis for qualified decision making concerning actions to mitigate traffic noise in the Nordic countries
- To clarify the noise emission from tyres, including Nordic winter tyres (Tyre Directive classes C1, C2 and C3) and its possible correlation with rolling resistance, wet grip, snow grip and ice grip. These results may be used to define realistic new tyre noise level limits that could be used in a future revision of the EU tyre labelling, Reg (EC) No1222/2009, and the tyre noise limits in Reg (EC) No 661/2009, including rolling resistance and supplementing the labelling of wet grip with labels of snow grip and ice grip

A group of passenger car tyres were procured which were believed to represent the tyre on the Nordic vehicle fleet. CPX trailer noise measurements were performed during the summer of 2012 on selected pavements in Denmark, Norway and Sweden, including one ISO test track. Measurements were made in 2013 on a supplementary test track.

Rolling resistance and noise measurements were performed on a drum facility. Tyre braking performance on ice and snow was measured for nine sets of winter and all-year tyres.

The total range of noise levels encountered between the quietest tyre on the quietest pavement (excluding the ISO test tracks) and the noisiest tyre on the noisiest pavement was almost 11 dB. No correlation was found between tyre manufacturers' noise labels and the noise levels measured on ISO test tracks. The reasons for this are discussed in the report. No final conclusions are drawn concerning the lack of correlation but the findings indicate a need for improving the tyre noise labelling system.

Replacing a traditional Nordic SMA 16 pavement with a quieter SMA 6 pavement was found to yield a potential reduction in tyre road noise levels from passenger cars of slightly more than 4 dB. The range of tyre/road noise levels measured on a given pavement was in the order of 4 dB. Regulating tyre noise so that only the quietest tyres were used could potentially reduce the average tyre/road noise levels from passenger cars by approximately 1.5 dB.

A regulation of tyre use in combination with a change from SMA 16 to a noise reducing thin asphalt layer SMA 8 could reduce the traffic noise level from passenger cars by up to 4.3 dB.

If road administrations can

- replace existing rough pavement, such as SMA 16 in Norway and SMA 11 in Denmark, by quieter pavement such as SMA 8
- regulate the use of car tyres so that only the 25 % quietest of the tyre population are in use

then the annoyance experienced by the Norwegian population can be reduced by about 13 % (as expressed by the Norwegian indicator Støyplageindeks, SPI) and the annoyance experienced by the Danish population can be reduced by about 35% (as expressed by the Danish indicator Støjbelastningstal, SBT), respectively.

Measured rolling resistance coefficients were found to be uncorrelated with measured tyre/road noise levels, and a trend was found for less good braking performance on ice and snow the better the labelled wet grip.

Resume

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Abbreviations

Abbreviation	Meaning
AC	Asphalt concrete
CB	Coast-By Method, UNECE R117
CEDR	Conference of European Directors of Roads
CPB	Controlled pass-by method
CPX	Close-Proximity method, ISO/DIS 11819-2
DRD	Danish Road Directorate, DK
ERGA	Evolution of Regulation – Global Approach (EU Commission ad hoc group on a method for measuring tyre/road noise)
EU	European Union
L_{Acpx}	A-weighted CPX noise level per one-third octave-band
L_{Aspb}	A-weighted SPB noise level per one-third octave-band
L_{ME}	Megatexture level
L_{veh}	Vehicle sound level, ISO 11819-1
L_{tx}	Surface texture level
MFA	Multiple Factor Analysis
MPD	Mean profile depth
Nord2000	Nordic prediction method for road traffic noise
P1	CPX reference test tyre proxy for light vehicles according to ISO/TS 11819-3
PA	Porous asphalt
PMA	Porous mastic asphalt, i.e. mastic asphalt EN 13108-6 (Gussasphalt) with an open graded texture at the top to avoid air pumping noise
SINTEF	Foundation for scientific and industrial research, Noeway
SMA	Stone mastic asphalt
SPB	Statistical Pass-By method according ISO 11819-1
SPL2000	Software developed by DELTA for calculation according to Nord2000
SRS	Noise reducing wearing course system
SRTT	Standard Reference Test Tyre, P1
TLPA	Two-layer porous asphalt
UNECE	United Nations. Economic Commission for Europe
VTI	Swedish National Road and Transport Research Institute, SE

1. BACKGROUND AND AIM

The steadily increasing traffic noise has caused administrations in Denmark, Norway and Sweden to set national targets for reducing noise annoyance, including working internationally to influence decision-making in CEDR/EU/ERGA on noise from vehicles and tyres.

A new Directive has come into force [1] and labelling of new vehicle tyres by November 2012 became mandatory in all EU and EEC countries. The tyre label includes classes or values of three parameters: wet grip, rolling resistance and noise. Nordic road administrations work on reducing traffic noise exposure by applying noise reducing pavement and by building and maintaining noise barriers which require significant economic resources. There is a need to know how “low noise” tyres could contribute to traffic noise mitigation and to clarify how this contribution can be optimized.

The objectives of the NordTyre project are to:

- clarify the “real” influence of the new tyre noise labelling
- establish scientific evidence on the tyre/road contribution to traffic noise emission from roads in the Nordic countries
- identify combinations of tyres and pavements which yield the lowest noise emission throughout their lifetime and thereby influencing the environment along roads and highways as little as possible
- generate a basis for qualified decision making concerning actions to mitigate traffic noise in the Nordic countries
- to define realistic new tyre noise limits for use in a future revision of the EU tyre labelling and the tyre noise limits, including rolling resistance and supplementing the labelling of wet grip with labels of snow grip and ice grip
- demonstrate the usefulness or necessity of a second “roughly textured” ISO reference test track for tyre noise testing and labelling, hence creating scientific arguments for a short term revision of EU tyre noise regulation

2. METHOD APPLIED

The NordTyre project was initiated by producing a report on the State-of-Art concerning the testing of tyre/road noise on various road surfaces [2]. Then a representative set of car tyres was selected and these tyres were run on selected representative pavements. Noise levels were measured using CPX-trailers. These measured noise levels were compared with the noise labels issued by tyre manufacturers and with noise levels measured on ISO test tracks.

The measurement results were used to derive potential noise reductions that could be obtained by replacing existing pavements with quieter pavement and by regulating the use of noisy car tyres. These potentials were used to calculate the potential effects on the annoyance experienced by the populations in Denmark and Norway.

3. LIMITATIONS

Only new car tyres were considered in the present part of the project. It has been decided to extend

Figure 1

The Danish Road Directorate CPX trailer 'deciBellA' having another set of tyres mounted at Höör

the project to also look into truck tyre noise and into the noise from worn car tyres, but these investigations are not dealt with in the present report. See also Section 16.

A number of passenger car tyres were selected among tyres which were available "here and now" (in May 2012) in Denmark. These tyres are believed to be reasonably representative for vehicle fleet tyres in all Nordic countries, but we cannot prove that they in fact are the most representative tyres.

4. SELECTED TYRES

The overall intention was to select an appropriate number of passenger car tyres to represent the tyres applied on Nordic cars. Based on interviews and on the availability of tyres from different tyre lines at the beginning of the project a total of 31 tyre lines were procured representing a cross-section of

1) Small / Medium / Large tyres

2) Summer / All-year / Winter tyres

3) Premium / Medium / Low price tyres

The finally selected tyres and their primary characteristics are summarised in Appendix 1, Table 15 and Table 16 on p. 39 - 40: tyre brand, dimensions, labels etc. The tyre price ranged between 54 € and 139 € per tyre, excluding V.A.T and rim. The sizes investigated were:

1) "Small" (typically 175 mm wide on 14" rim)

2) "Medium" (205 mm wide on 16" rim) and

3) "Large" (225 mm wide on 16" rim)

The range of labelled noise levels was 66 – 75 dB. The labelled rolling resistance classes were B – F, and the labelled wet grip classes were A – E.

5. SELECTED PAVEMENTS

The intention was to select a suitable number of pavements representing the spectrum of wearing courses encountered on Nordic roads, with slightly higher representation of quieter pavements than of pavements known to be associated with high traffic noise levels. Descriptions of the pavements can be found in Appendix 2. Some pavement characteristics are listed in Table 17 - Table 22 on p. 42 - 45, i.e. pavement designation, construction year, mean profile depth (MPD) and mega texture level (L_{ME}).

Road sections built in 2010 at Igelsø in Denmark were selected to represent typical Danish noise reducing thin asphalt layers: five SRS1) and one reference pavement. Six sections of highway M64 (Herning-I) were selected among 12 sections constructed in 2006, and three sections were selected among eight test sections and a reference pavement built in 2008 on highway M68 (Herning-II).

Five Norwegian sections built in 2005 at Mastemyr with SMA pavement having different maximum aggregate sizes were selected as were five sections at Hønefoss with dense asphalt concrete, also having various maximum aggregate sizes. The latter were built in 2005 except for one section with AC 11d built in 2002. All Norwegian road sections had been worn by vehicles with studded tyres.

Four Swedish road sections built in 2010 at Höör in southern Sweden were selected, i.e. SMA 11, SMA 8, AC 11d and AC 8d. These were supplemented by a section of SMA 16 built in 2006 at Hörby, also in Southern Sweden. Also these sections had been trafficked by vehicles having studded tyres.

6. MEASUREMENT RESULTS

The following measurement results were collected during the summer 2012, except for the braking performance tests which were made in February 2013 and supplementary CPX noise levels measured in July 2013 on a second ISO test track. In all these CPX noise measurements, the tyre load was 300 kN (326kg) and the tyre inflation pressure was 200 kPa.

Noise levels were measured on a laboratory drum, primarily to find out whether there was a difference between tyre/road noise levels on the right and left side of the tyre [3], see Appendix 3 on p. 46. This turned out to be the case for several tyres and the tyres were “turned” on their rims before and after measuring with the M+P trailer in Norway.

CPX noise measurements were made by DRD on pavements in Denmark and Sweden [4] whereas SINTEF/SVV made the CPX measurements on pavements in Norway [5].

TUG measured rolling resistance coefficients on its drum facility [6], see Appendix 4 on p. 48, and TestWorld Ltd measured snow and ice grip for winter and all-year tyres [7], see Appendix 5 on p. 50.

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1) SRS is a Danish abbreviation used for noise reducing wearing courses

7. DATA ANALYSIS

Initially a Multiple Factor Analysis (MFA) was carried out to identify patterns in the noise data, such as “clusters” of noise-wise similar pavements. This was mentioned in an early draft of this report. At a project workshop in December 2012 it was decided to give priority to looking at “pavement families” rather than at “pavement clusters” when determining the potential change in tyre/road noise, that a road administration can obtain by replacing an existing pavement with a quieter type. This is dealt with in Section 10.4 and in Appendix 6 on p. 52.

8. RELATION BETWEEN CPX NOISE LEVELS AND TYRE NOISE LABELS

Labelled tyre/road noise levels from the tyre manufacturers’ websites have been used as an independent variable (X-axis) in three of the diagrams in Figure 2 where the dependent variable (Y-axis) is the noise level measured with the DRD trailer on the 1) ISO test track #1, DRD20; 2) ISO test track #2, DRD32; and 3) SMA 11 pavement, DRD22. The latter is an example of a “real” road surface.

The fraction R^2 of explained variance in the results from the two ISO tracks is 2 % and 7 %, respectively (R^2 =0.023 and 0.0706), and only 1 % (R^2 = 0.0098) of the variation in noise levels on SMA 11 is explained by the noise labels. Very little of the variation in the dependent variable is explained by the variation of the independent variable, or in other words: the variables are not correlated.

The label values used in Figure 2 were read by DRD from manufacturer’s websites and then double checked by comparing with label values tabled by the Swiss Federal Office of Energy SFOE (Bundesamt für Energie BFE) [8]. Labels for the following tyre lines could not be identified: Tyre #13 - Klebér Dynaxer HP2, Tyre #30 - Uniroyal Tigerpaw SRTT and Tyre #31 - Michelin Primacy LC.

The quietest according to the noise label (Tyre #20: 66 dB; summer tyre Dunlop SP Sport 01 MO) was among the noisiest tyres when measured on the ISO test track #1; DRD20. Another tyre which according to its label is the noisiest (Tyre #18: 75 dB; summer tyre Marshal Matrac XM) was in the middle of the crowd when measured with the trailer on ISO test track #1; DRD20. Removing these two extremes would cause R^2 to increase to 0.097 and 0.013, respectively, in the upper two graphs in Figure 2.

The fourth diagram (bottom right) in Figure 2 shows the relation between CPX noise levels measured on the two ISO test tracks. There is a fair correlation (R^2 = 0.73), with a trend for lower noise levels from winter tyres and all-year tyres on the Volvo test track (#1) than on the IKA test track (#2) and the opposite trend for Summer tyres. The test track mean profile depths (MPD) and megatexture levels were 0.86 mm / 49.6 dB at Hällered and 0.44 mm / 43.3 dB at IKA.

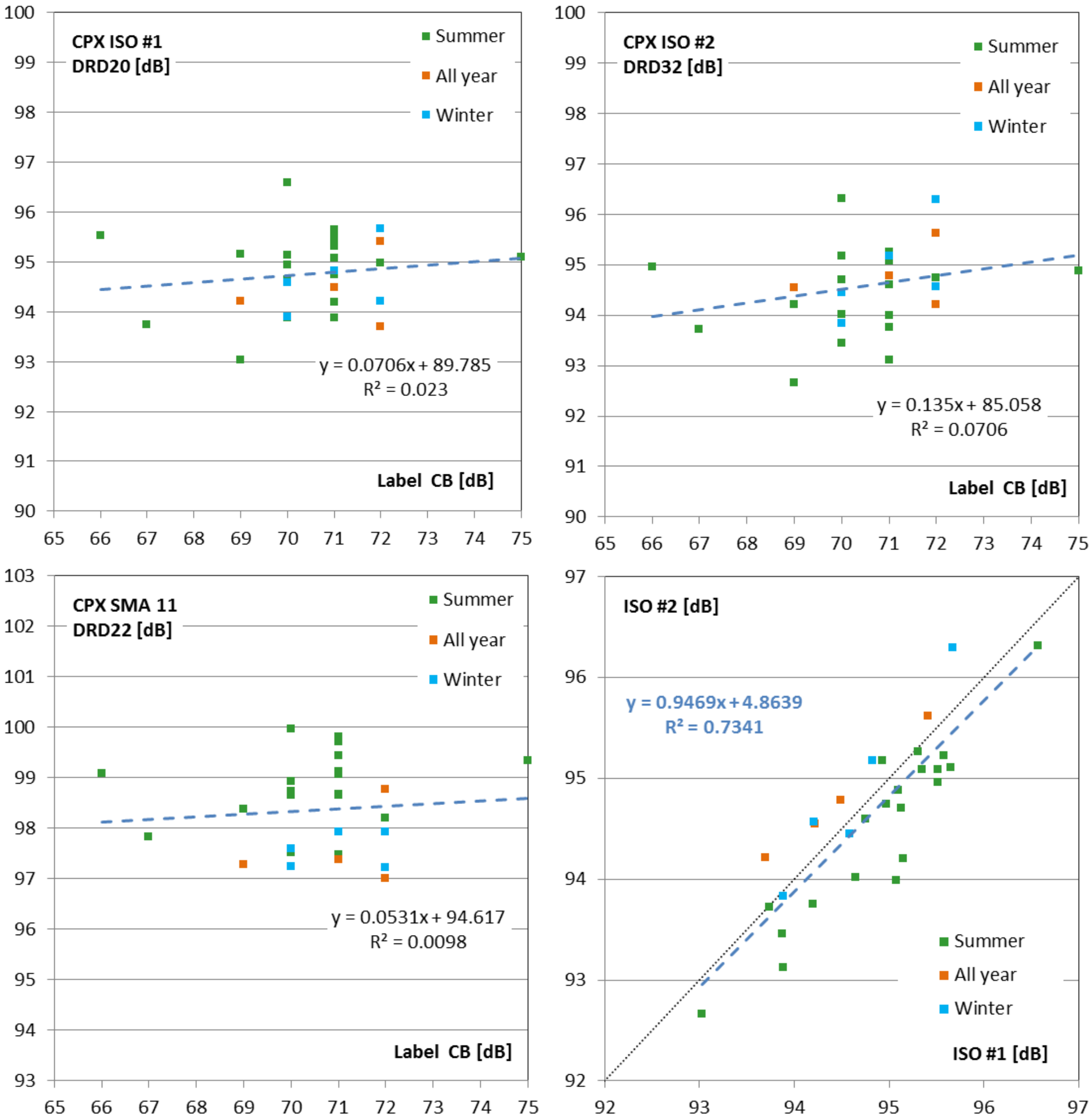

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Figure 2

Measured CPX noise level as a function of the noise label issued by the tyre manufacturer. Top left: ISO track #1 (DRD20); Top right: ISO track #2 (DRD32); Bottom left: SMA 11 (DRD22). Bottom right: relation between noise levels measured on ISO tracks # 1 and #2

9. CORRELATION BETWEEN NOISE LEVELS ON DIFFERENT PAVEMENTS

Scatter plots

Scatter plots are shown in Appendix 11 and a few examples are shown in Figure 3. Each diagram in the figure represents one of the 33 pavements. It shows the CPX noise level from each of the 31 tyres as a function of either the noise level measured on 1) DRD20 (the ISO track #1 at Hällered) or on 2) DRD22 (SMA 11 at Höör). The noise levels on pavement DRD22 were found to be a god representative of a group of pavements which were not so well represented by the ISO track (DRD20) noise levels, see the following section.

Each graph shows a scatter of data points and the value of the determination coefficient R^2 from a linear regression analysis, i.e. percentage of variance in the data explained by the independent variable.

> Note: In the scatterplots the determination coefficient R^2 is expressed as the percentage rather than as the fraction of explained variance.

The top part of Figure 3 shows results for the pavement denoted STF11, SMA 16 at Mastemyr. Data from this surface display the lowest value of R^2 = 37 % in the data set when looking at the relation with the noise levels measured on the ISO test track DRD20. The “real” noise levels are on the average about 7 dB higher on the SMA 16 than on the ISO track, and a label value for the tyre determined on this ISO track should be expected to explain little more than one-third of the variation in noise levels on the SMA 16. If only summer tyres are considered R^2 = 57 %. Had classification instead been based on measurements on DRD22 (SMA 11 at Höör) the “real” noise levels would have been 1 - 2 dB higher on the average and the label values would have explained more than two-thirds of the variation in noise levels (R^2 = 71 %).

The bottom part of Figure 3 shows the same relations for DRD 21, SMA 16 at Hörby, which in the Multiple Factor Analysis was identified as the noisiest surface. The “real” noise levels were 5 - 6 dB higher on an average than on the ISO track and about half of the variation in real noise levels would be explained by a noise label based on results from this track (R^2 = 46 %; or 68 % for summer tyres only). Had the DRD22 surface (SMA 11 at Höör) been used for the labelling the “real” noise levels would have been about 1.5 dB higher than the labelled values and more than 90 % of the variance would have been explained by the noise label.

It may be noted that there is a trend for winter and all-year tyres, when measured in summer conditions, to yield lower noise levels than summer tyres. This trend is better predicted by the measurements on SMA 11 (DRD22) than by the measurements on the ISO test track (DRD20).

Tables of R^2

The values of R^2 for any combination of the 33 pavements can be found in Table 26 on p. 55 while Table 27 and Table 28, respectively, shows the corresponding values of the slope and intercepts of the regression lines. These tables are based on data for all tyres, i.e. including winter tyres. Based on the percentage of explained variance (R^2) in Table 26 it was decided to divide the pavements into groups, see Table 1 and Table 25.

One group of pavements is well represented by the ISO test track (DRD20), i.e. the Igelsø sections with thin noise reducing asphalt layers, including the reference section with AC 11d at Igelsø. Also the supplementary test track in Aachen belongs to this group. Another group is better represented by SMA

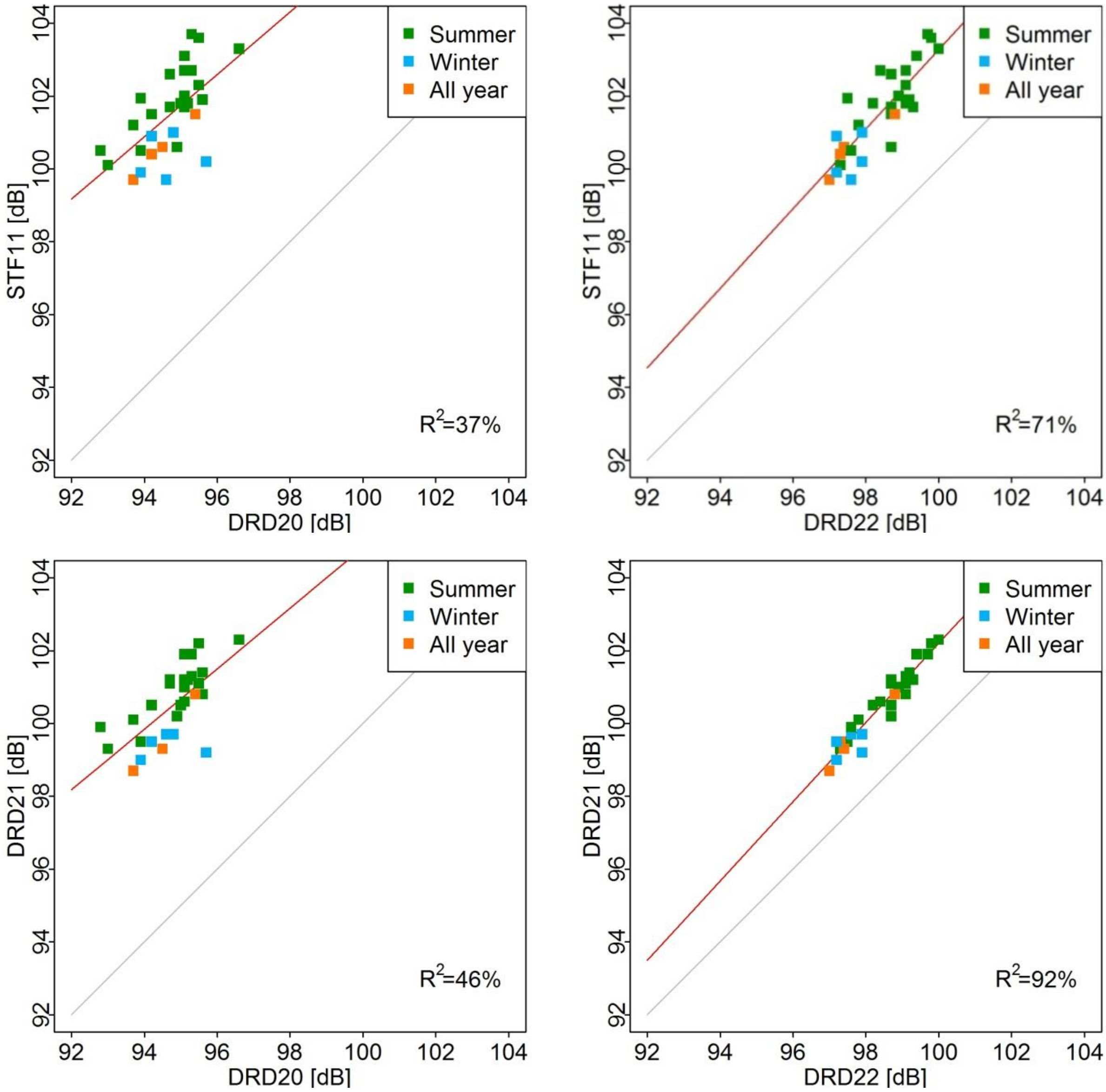

Figure 3

Examples of scatterplots: Noise levels from 31 tyres measured on selected surfaces as a function of the noise level from the same tyre measured on the ISO test track DRD20 (left) or the SMA 11 surface DRD22 (right). Top: on STF11 (SMA16 at Mastemyr); Bottom: on DRD21 (SMA 11 at Höör)

11 (DRD22), while the TUG drum pavements cannot be considered well represented by any of these two pavements. Table 1 shows the grouping of pavements based on the noise from summer and all-year tyres, i.e. excluding winter tyres, and represents the tyre population included in the regulation scenarios in Section 10.4. Minor differences are seen between the groupings of pavements in Table 1 and Table 25, but overall the correlations are slightly better for the summer/all-year tyres than for the noise levels from all tyres.

Table 1 also shows the slope and explained variance using the data from the Aachen test track (DRD32) as an independent variable. The noise levels measured on this test track are less representative of the noise levels measured on real roads than those measured on DRD20 in Hällered. In this respect the Hällered test track noise levels are more representative.

Most of the Nordic pavements selected for the present project would be better represented by a SMA 11 test track than by the ISO test tracks DRD20 or DRD32, while the ISO test tracks represent the newest sections with thin noise reducing asphalt layers better than a test track with SMA11 would do.

Table 1

Pavements sorted according to correlation (R^2 expressed in %) with DRD20, DR22, and DRD32, respectively, based on noise levels from summer and all-year tyres

Pavement			DRD20 ISO #1		DRD22 SMA 11		DRD32 ISO #2	
ID	Designation	Site	R^2	Slope	R^2	Slope	R^2	Slope
DRD20	ISO 10844	Hällered	100.0	1.00	74.2	0.9	77.3	0.9
DRD31	AC8o	Igelsø	94.5	0.95	81.8	1.0	74.0	0.9
DRD29	SMA6+8	Igelsø	93.4	0.98	71.5	0.9	82.7	1.0
DRD26	AC11d	Igelsø	92.5	0.96	72.9	0.9	84.4	0.9
DRD28	SMA6+11	Igelsø	92.3	0.91	67.7	0.9	83.3	0.9
DRD30	SMA8	Igelsø	92.1	0.93	82.3	1.0	68.5	0.8
DRD27	AC6o	Igelsø	89.6	0.89	58.5	0.8	77.5	0.9
DRD19	SMA6+8	M68 Herning 2	87.9	0.84	80.8	0.9	51.1	0.7
DRD32	ISO 10844	Aachen	77.3	0.85	43.5	0.7	100.0	1.0
DRD22	SMA11	RV13 Höör	74.2	0.79	100.0	1.0	43.5	0.6
DRD21	SMA16	E22 Hörby	67.8	0.67	92.8	0.9	34.8	0.5
DRD23	SMA8	RV13 Höör	76.4	0.80	92.5	1.0	48.2	0.7
DRD12	AC8o	M64 Herning1	80.3	0.80	92.2	0.9	46.6	0.6
DRD11	AC6o	M64 Herning1	82.8	0.85	91.9	1.0	52.7	0.7
DRD13	AC11d	M64 Herning1	76.1	0.74	91.7	0.9	51.0	0.6
DRD16	SMA11	M64 Herning1	71.5	0.68	91.1	0.9	32.6	0.5
DRD15	SMA6+8	M64 Herning1	78.8	0.78	90.1	0.9	49.8	0.6
DRD14	SMA6	M64 Herning1	79.7	0.78	89.0	0.9	49.3	0.6
DRD18	PA6	M68 Herning 2	81.7	0.83	87.8	0.9	47.0	0.7
DRD25	DAC8	RV13 Höör	67.0	0.65	87.2	0.8	42.9	0.5
STF18	DAC8	E16 Hønefoss	78.8	0.68	86.1	0.8	52.4	0.6
DRD17	AC11d	M68 Herning 2	80.5	0.82	86.0	0.9	63.2	0.8
DRD24	DAC11	RV13 Höör	68.7	0.75	85.9	0.9	51.1	0.7
STF20	DAC11	E16 Hønefoss	78.8	0.67	85.0	0.8	43.7	0.5
STF19	DAC11	E16 Hønefoss	76.9	0.67	84.5	0.8	43.5	0.5
STF16	DAC11	E16 Hønefoss	76.9	0.64	83.9	0.7	46.2	0.5
STF17	DAC6	E16 Hønefoss	74.3	0.74	83.8	0.9	57.7	0.7
STF15	SMA11	E18 Mastemyr	64.0	0.64	78.0	0.8	37.4	0.5
STF11	SMA16	E18 Mastemyr	58.0	0.54	75.7	0.7	23.5	0.3
STF12	SMA11	E18 Mastemyr	61.0	0.56	73.8	0.7	33.5	0.4
STF13	SMA8	E18 Mastemyr	65.3	0.63	72.5	0.7	47.7	0.5
STF14	SMA6	E18 Mastemyr	66.9	0.70	68.6	0.8	49.7	0.6
TUG12	DAC12	TUG Drum	44.7	0.69	49.0	0.8	41.1	0.7
TUG11	ISO 10844	TUG Drum	46.1	0.58	27.3	0.5	47.0	0.6

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10. SCENARIOS ON NOISE REDUCTION

10.1 PRINCIPLE AND PROCEDURE

Scenarios were generated by modifying the tyre/road noise component of the passenger car noise and estimating the consequent changes in overall vehicle pass-by noise levels.

The tyre/road noise and the propulsion noise contributions to the overall passenger car noise level were calculated in the following reference cases 1) Norway and Sweden: SMA 16 pavement and 2) Denmark: SMA 11 pavement. This was done by applying the Nord2000 prediction method.

To illustrate the process, Figure 4 shows the pass-by noise levels at 7.5 m distance, 1.2 m above the road surface, from a light vehicle on a stone mastic asphalt pavement (SMA 16) as a function of the (constant) vehicle speed, according to Nord2000. The total noise level is composed of the tyre/road noise and the propulsion system noise. If we modify the tyre/road noise by selecting another pavement or another population of tyres this will result in a change in the overall noise level. The "balance" between tyre/road noise and propulsion system noise depends on the sound propagation from source to receiver and hence scenarios were calculated for different propagation situations.

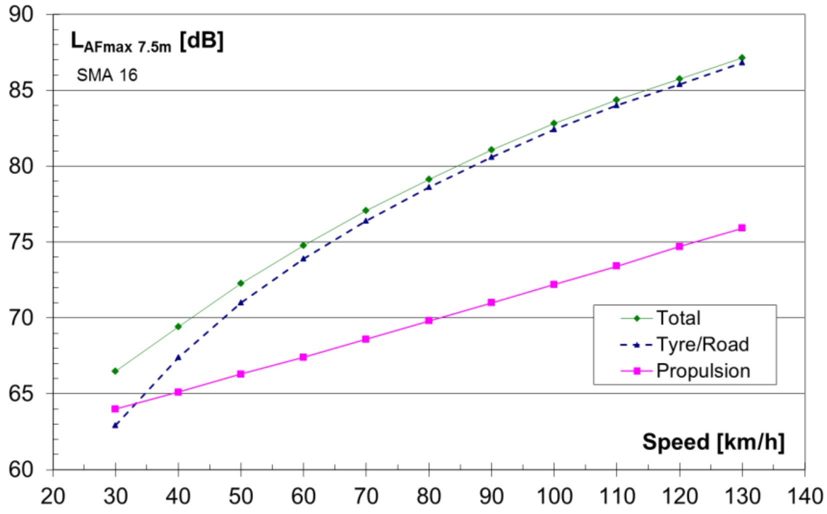

Figure 4

Light vehicle pass-by noise level at 7.5 m as a function of the (constant) speed calculated with Nord2000 for SMA 16: total noise and its components of tyre/road and propulsion system noise

10.2 LIMITATIONS

Only tyre/road noise from new passenger car tyres are dealt with in this part of the NordTyre project.

Winter tyres were excluded from scenario simulations of the effect of regulating the tyre use, because it would not make sense to assume the exclusion of all summer and all-year tyres and then have a vehicle fleet equipped with only winter tyres characterised by their noise levels measured during the summer.

10.3 DEFINITION OF SCENARIOS

Table 2 is an attempt to illustrate the scenarios. First, the average tyre road noise level from all tyres on all pavements in each "pavement family" was determined, see Section 10.4, and based on these the effects on tyre/road noise, denoted *x* – *z* and *a* – *c* in the table, of replacing the standard pavement with another pavement family. This reduced tyre/road noise level combined with the propulsion noise level gives a reduction ΔL_P of the total vehicle noise level which depend on the vehicle speed.

Then the effect ΔL_T on the total noise level obtained by removing all but the quietest tyres was determined, see Section 10.4. Finally the combined tyre/road and propulsion noise levels were determined presupposing different propagation conditions a) – d) defined in Table 3. Figure 5 shows the “balance” at 80 km/h between tyre/road noise and propulsion system noise in the reference case with SMA 16. In scenarios b) and d) this balance is in practice the same. The effects of replacing the pavement or regulating the use of tyres were expressed as the change ΔL_{PT} in overall noise level relative to the reference case: all summer and all all-year tyres on SMA 16 or SMA 11, respectively.

Table 2

Illustration of noise reduction scenarios for one propagation scenario

Pavement family [-]	Tyre/road noise: Effect of replacing pavement [dB]	Avg. of all tyres			With quietest tyre(s) only					
		Total noise reduction by replacing pavement [dB] Speed [km/h]			Total noise reduction by removing tyres [dB] Speed [km]			Total noise reduction [dB] by pavement and tyre regulation Speed [km/h]		
		50	80	110	50	80	110	50	80	110
SMA 16	0	**Ref**	**Ref**	**Ref**	ΔL_T	ΔL_T	ΔL_T	ΔL_{PT}	ΔL_{PT}	ΔL_{PT}
SMA 11	-*x*	ΔL_P	ΔL_P	ΔL_P	ΔL_T	ΔL_T	ΔL_T	ΔL_{PT}	ΔL_{PT}	ΔL_{PT}
SMA 8	-*y*	ΔL_P	ΔL_P	ΔL_P	ΔL_T	ΔL_T	ΔL_T	ΔL_{PT}	ΔL_{PT}	ΔL_{PT}
SMA 6	-*z*	ΔL_P	ΔL_P	ΔL_P	ΔL_T	ΔL_T	ΔL_T	ΔL_{PT}	ΔL_{PT}	ΔL_{PT}
AC 11d	-*a*	ΔL_P	ΔL_P	ΔL_P	ΔL_T	ΔL_T	ΔL_T	ΔL_{PT}	ΔL_{PT}	ΔL_{PT}
AC 8d	-*b*	ΔL_P	ΔL_P	ΔL_P	ΔL_T	ΔL_T	ΔL_T	ΔL_{PT}	ΔL_{PT}	ΔL_{PT}
AC 6d	-*c*	ΔL_P	ΔL_P	ΔL_P	ΔL_T	ΔL_T	ΔL_T	ΔL_{PT}	ΔL_{PT}	ΔL_{PT}

Table 3

Starting points for calculations of scenarios a) – d). Pavement: SMA 16

Passenger car	**Constant speed:**	**50, 80 and 110 km/h**	**Air temperature:**	**10 ºC**
a)	**7.5 m** from vehicle centre line; 1.2 m or 4 m above hard terrain (at SPB measurement position or dwelling close to a road); dense asphalt: flow resistivity G = $2 \cdot 10^{7}$ Nsm^{-4}			
b)	**100 m** from vehicle centre line; 1.5 m or 4 m above terrain; no wind; 1 m hard terrain: flow resistivity G = $2 \cdot 10^{7}$ Nsm^{-4}; the rest grassland: flow resistivity D = $2 \cdot 10^{5}$ Nsm^{-4}			
c)	As b) but moderate downwind ≈ yearly average noise as used in Denmark			
d)	As b) but moderate inversion (downward curvature): temperature gradient 1ºC/100 as used in Norway for noise mapping			

Note 1: For Scenario a) a speed of 110 km/h is unlikely to occur

Note 2: An air temperature of 10 ºC was selected to represent a yearly average temperature, even though all noise measurement results in the project have been normalized to 20 ºC. The temperature has marginal effect on the “balance” in Nord2000 between tyre/road noise and propulsion system noise.

Note 3: 4 m receiver height was chosen to represent the conditions for EU noise mapping

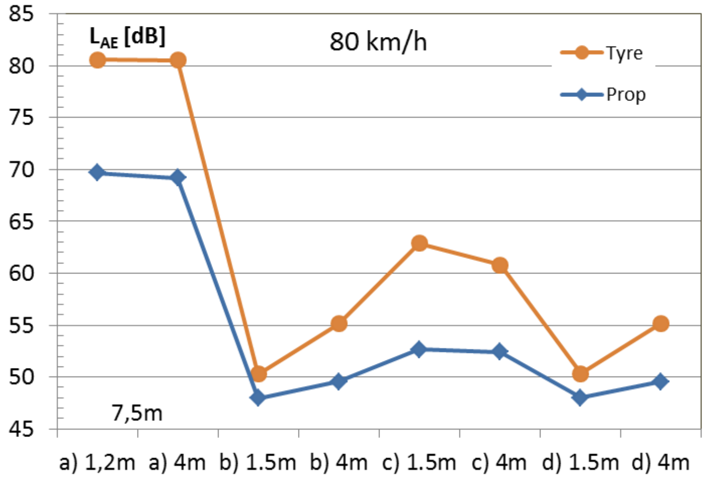

Figure 5

Calculated tyre/road noise level and propulsion system noise level at 80 km/h on SMA 16 according to Nord2000 for scenarios a) – d) defined in Table 3

10.4 EFFECTS OF REGULATION ON TYRE/ROAD NOISE

Effect of replacing the pavement

This section presents the effect of replacing a reference pavement (SMA 16 or SMA 11) by another pavement, grouped into various “pavement families”. The average tyre/road noise levels from all summer tyres and all-year tyres on each member of the pavement family were calculated. The selected families and the average noise levels from all the summer tyres and all-year tyres are shown in Table 24 on p. 52. Winter tyre data were not included in these calculations.

Table 4 lists the calculated average noise levels, the number of pavements included in each family and the standard deviations of the average noise levels per pavement family member. The variation in noise levels within each family is due to a mix of factors such as mix recipe, construction procedures, pavement age and exposure to traffic. The average effect of replacing the pavement is given in the rightmost table columns, one with SMA 16 and the other with SMA 11 as a reference. The mean values and standard deviations are also shown in Figure 6.

Table 4

Average tyre/road noise levels for each family of pavements, the number *N* of pavements in the family, standard deviation of the family mean noise level and reduction of tyre/road noise by replacing SMA 16 or SMA 11 by a member of another pavement family

Pavement family [-]	**Average *tyre/road noise* level [dB]**	***N*** [-]	**St. dev. [dB]**	**Reduction re SMA 16 [dB]**	**Reduction re SMA 11 [dB]**
SMA 16	101.2	2	-	**0.0**	**-1.5**
SMA 11	99.7	4	1.0	**1.5**	**0.0**
SMA 8	97.8	3	1.1	**3.4**	**1.9**
SMA 6	97.1	7	1.2	**4.2**	**2.6**
AC 11	98.3	7	1.1	**3.0**	**1.5**
AC 8	98.2	4	1.1	**3.1**	**1.5**
AC 6	97.0	3	1.8	**4.2**	**2.7**

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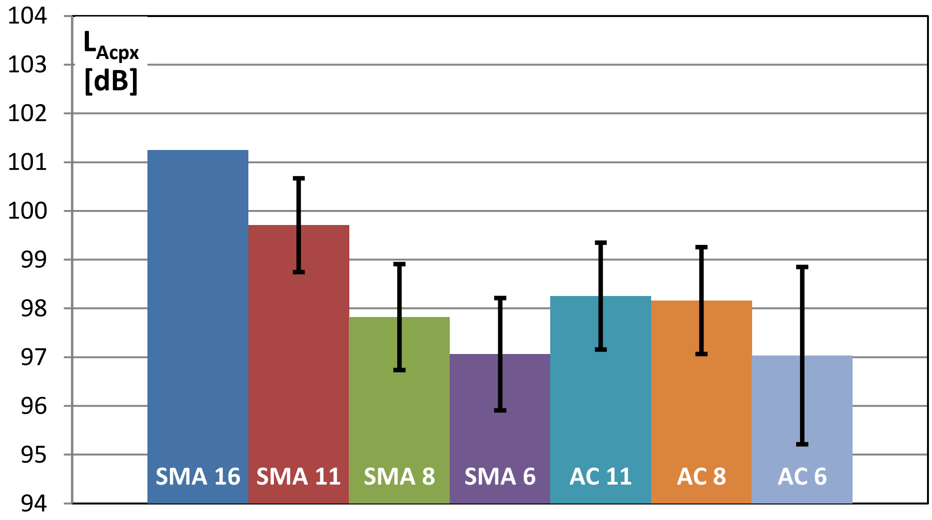

Figure 6
Average tyre/road noise levels and standard deviation from Table 4 per pavement family

Similar results are given in Table 5. The pavement families in this table were defined by their maximum aggregate size, while asphalt concrete and stone mastic asphalt were considered the same pavement family. A bit surprisingly, the standard deviations of noise levels within these larger pavement families are not a lot larger than the standard deviations in Table 4. As an overall result, replacing SMA 16 as represented among the selected pavements by a pavement having 6 mm nominal maximum aggregate size would imply a 4.2 dB reduction of passenger car tyre/road noise levels. This is based on the average noise levels from all summer and all-year tyres.

Table 5
Average tyre/road noise levels for each family of pavements, the number *N* of pavements in the family, standard deviation of the family mean noise level, and reduction of tyre/road noise by replacing SMA 16 or SMA 11 by a pavement family member. Numbers have been rounded to the nearest decimal place

Maximum aggregate size [mm]	**Average *tyre/road noise* level [dB]**	***N* [-]**	**St. dev. [dB]**	***Tyre/road noise* reduction re.**	
				SMA 16 [dB]	**SMA 11 [dB]**
16	101.2	2	-	0.0	-1.5
11	98.8	11	1.2	2.5	0.9
8	98.0	7	1.0	3.2	1.7
6	97.1	10	1.3	4.2	2.7

Effect of regulating tyre use

The estimation of the effect on tyre/road noise obtained by regulating tyre use is illustrated in Figure 8. The figure shows for each of the selected 24[2] summer tyres or all-year tyres the labelled noise level, which is presumed to represent the tyre/road noise emission, see the note below Figure 7. The range from the noisiest tyre (No. 18) to the quietest tyre (No. 20) is wide, namely 9 dB. This must, a. o. be due to erroneous labels for a few tyres. The right part of Figure 7 shows the distribution of noise labels

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[2] There are actually only 23 label values because the label of tyre #13 could not be identified

on 0.5 dB wide noise level classes. The figure also displays the energy average noise of the label values for all 24[3] tyres: 70.8 dB.

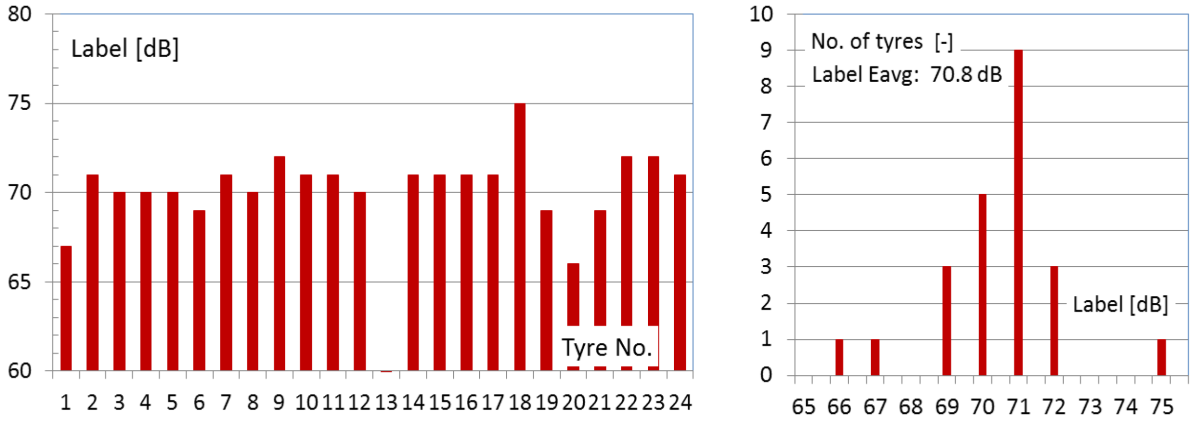

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Figure 7
Labelled noise levels for each summer or all-year tyre and their distribution on 0.5 dB wide noise level classes

Figure 8 shows how the energy average of the tyre noise labels in Figure 7 develops when the tyres are removed one by one from the set of 24 tyres, beginning with the noisiest tyre as ranked by the tyre manufacturers' labels. Data labels in Figure 8 show the ID number of the latest tyre which has been removed to reach at the energy average noise level shown by that data point. The first point with label "#13" is the energy average of all 23 noise label values. The range of noise levels in Figure 7 is 9 dB and the change in energy average noise level in Figure 8 after having removed all but the quietest tyre is 4.8 dB. After having removed all but the six quietest tyres the reduction would be 2.8 dB.

If two tyres having extreme label values (tyres #18 and #20) were removed from the tyre population the corresponding changes would be 3.9 dB and 1.7 dB, respectively. For the scenarios described in the following, it was assumed that only tyres labelled 69 dB remain in the tyre population. This implies a tyre/road noise reduction of 1.4 dB.

Note: Similar simulations made earlier in the project were based on results of NordTyre CPX measurements. These simulations have been abandoned for the time being. See Section 14.

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[3] See footnote 1)

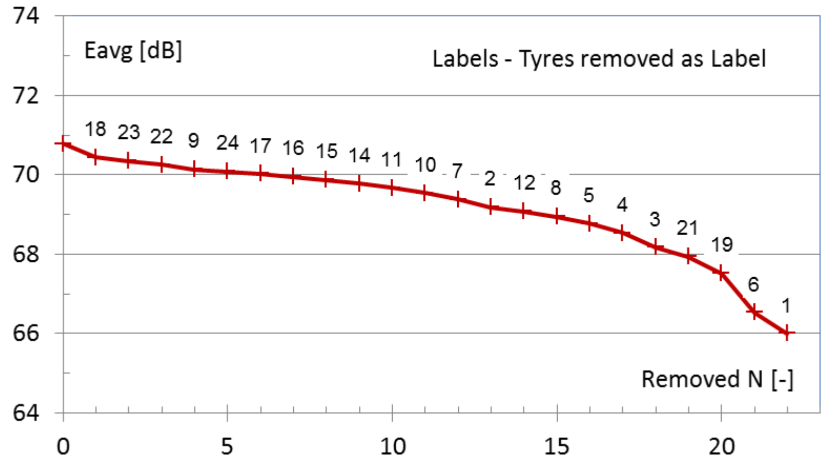

Figure 8

Energy average of the tyre noise labels in Figure 7 as a function of the number of tyres removed, beginning with the noisiest tyre (No. 18) when ranked according to manufacturers' labels File: < K:\AD\BBM\BEF\Støj\Projekter\Nordtyre\Scenarios\ Simulering_Label_only.xlsx; Sheet: Labels>

Combined effect of replacing pavement and regulating tyre use

Table 6 combines the reductions from Table 4 with the reduction found when simulating tyre noise regulation. Table 6 gives estimates of the total effect on passenger car tyre/road noise of first

- replacing the pavement and then
- removing all tyres but the tyres labelled 69 dB by manufacturers

the latter resulting in 1.4 dB reduction of the tyre/road noise from a passenger car.

Table 6

Summary of tyre/road noise reductions obtained by replacing the pavement and by excluding all but the tyres labelled 69 dB
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***Tyre/road noise* reduction [dB]**					
Pavement selection			**Tyre** regulation -	**Total** re.	
Re.	**SMA 16**	**SMA 11**	ranking as labels	**SMA 16**	**SMA 11**
SMA 16	0,0	-1,5	1,4	1,4	-0,1
SMA 11	1,5	0,0		3,0	1,4
SMA 8	3,4	1,9		4,9	3,3
SMA 6	4,2	2,6		5,6	4,1
AC 11	3,0	1,5		4,4	2,9
AC 8	3,1	1,5		4,5	3,0
AC 6	4,2	2,7		5,7	4,1

10.5 EFFECTS OF REGULATION ON TOTAL NOISE LEVELS

The combined effect on passenger car pass-by noise levels of replacing the pavement and regulating tyres as described in Section 10.4 are shown in Table 7 and Table 8 for traffic speed 80 km/h in scenario c). Table 7 gives the noise reduction relative to the average noise level from all tyres on Norwegian SMA 16, while Table 8 has Danish SMA 11 as a reference.

Table 7

Noise reductions at 80 km/h roads in Scenario c) with Norwegian SMA 16 as a reference
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Scenario c) 80 km/h	**Replace pavement** [dB]	**Regulate tyres as label** [dB]	**Total reduction** [dB]
SMA 16	0.0	1.2	1.2
SMA 11	1.3	1.2	2.5
SMA 8	2.8	1.2	4.0
SMA 6	3.4	1.2	4.6
AC 11	2.5	1.2	3.7
AC 8	2.5	1.2	3.8

Table 8

Noise reductions at 80 km/h roads in Scenario c) with Danish SMA 11 as a reference

Scenario c) 80 km/h	**Replace pavement** [dB]	**Regulate tyres as label** [dB]	**Total reduction** [dB]
SMA 16	-1.4	1.2	-0.1
SMA 11	0.0	1.2	1.2
SMA 8	1.6	1.2	2.9
SMA 6	2.2	1.2	3.5
AC 11	1.3	1.2	2.5
AC 8	1.3	1.2	2.6

Table 9 gives an overview of the traffic noise reduction which can be obtained in various scenarios by 1) replacing the noisiest pavement by SMA 8 and 2) regulating tyres as described in Section 10.4. Slightly higher reductions could be obtained if the existing pavements were replaced by SMA 6. The left part of the table shows the potentials with Danish SMA 11 as a reference, the right part with Norwegian SMA 16 as a reference. The noise reductions shown in parentheses are probably not relevant since very few residences are situated at 7.5 m from a road with a speed limit of 110 km/h.

Table 9

Reduction [dB] of the total noise levels from various types of road in Scenarios a) – d) by replacing standard pavements by SMA 8 and removing all tyres but those labelled 69 dB by the tyre manufacturer

Scenario	Danish - ref. - SMA 11			Norwegian - ref. SMA 16		
	50 km/h	80 km/h	110 km/h	50 km/h	80 km/h	110 km/h
a)	2.4	2.9	(3.1)	3.8	4.4	(4.6)
b) or d)	0.7	1.7	2.2	2.2	3.5	3.9
c)	2.2	2.9	3.0	2.9	4.0	4.3

11. SCENARIOS ON NOISE ANNOYANCE

This section describes the effects one would expect on the annoyance experienced by the populations if the noise reduction scenarios mentioned in the previous sections became reality. Based on available data on the present noise exposure of the population, changes in the value of overall noise exposure indicators to be expected as a consequence of implementing the noise reduction scenarios were calculated as described in the following.

11.1 NOISE ANNOYANCE INDICATORS

In Table 10 the definitions of various noise indicators are summarised and references are given to the documents defining them. Figure 11 shows their value as a function of the noise exposure. The Danish indicator (SBT) increases exponentially with increasing noise levels while the Norwegian indicator (SPI) increases linearly, and the percentage of highly annoyed persons (%HA) following a polynomial expression increases at a rate in between those of the two other indicators. In Sweden no particular indicator is applied for aggregating noise exposure. The overall noise exposure is expressed as the number of persons exposed to $L_{Aeq,24h} \geq 55$ dB (and $L_{Amax} \geq 70$ dB), [13].

Table 10
Definitions of noise indicators used in Denmark and Norway, and the percentage of highly annoyed persons according to the an EU position paper

Country	Indicator / Acronym	Definition	Reference
Denmark	Noise annoyance number (Støjbelastningstal) / SBT	$SBT = N_{dwellings} \cdot G$ $G = 0.01 \cdot 4.22^{0.1 \cdot (L_{den} - 44)}$	[9]
Norway	Noise annoyance index (Støyplageindeks) / SPI	$SPI = N_{per} \cdot G_{pvei}$ $G_{pvei} = 1.58 \cdot (L_{den} - 39.4)$	[10]
EU	Percent Highly Annoyed / %HA	$\%HA = 9.868 \cdot 10^{-4} \cdot (L_{den} - 42)^3 - 1.436 \cdot 10^{-2} \cdot (L_{den} - 42)^2 + 0.5118 \cdot (L_{den} - 42)$	[11]

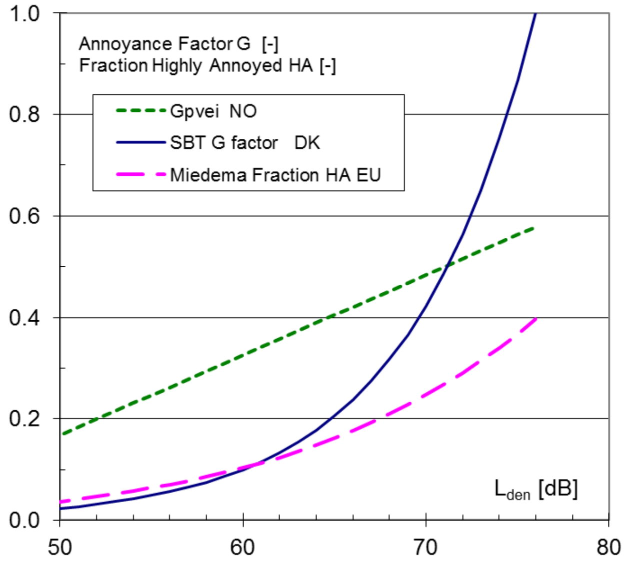

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Figure 9
Noise indicators as a function of the day-evening-night noise level L_{den}

11.2 NOISE MAPPINGS

Denmark

The results of the Danish noise mapping were reported in [12] in which results of mappings made by the Danish Road Directorate and by a number of municipalities have been merged. The total number of mapped dwellings was 1.5 million, 723,000 of which were exposed to L_{den} = 58 dB or more. Tables are given in [12] specifying the number of dwellings per 1 dB exposure class. The results are illustrated in Figure 10 and mentioned in more detail in Appendix 12

Norway

The Norwegian data extracted from the “Støybygg” data base were sorted by DRD into 1 dB wide noise level classes. The received data cover five regions of Norway and they are complete for four of these five regions. The data contains information on 223,824 dwellings, out of which 146,728 was supplied with information on the traffic speed limit. After limiting data to noise exposures exceeding 55 dB, the total number of dwellings was approximately 126,000. See Figure 10 and Appendix 12, for information on the data and their distribution.

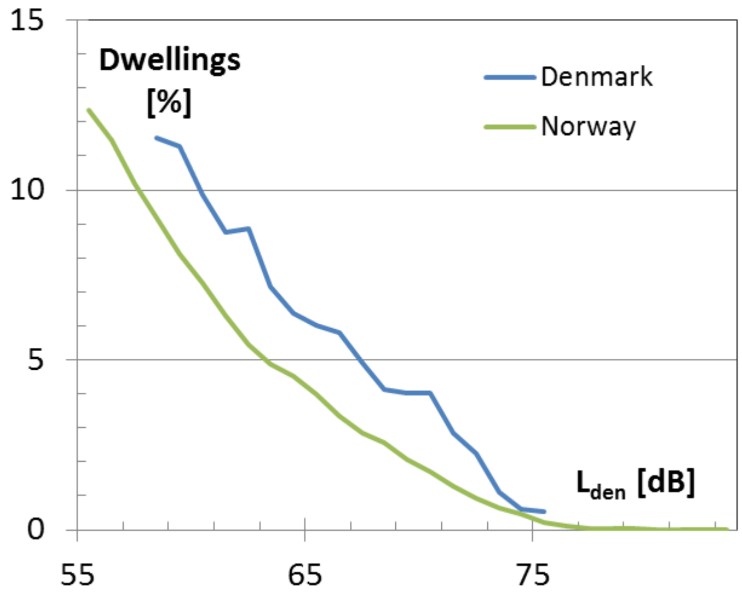

Figure 10

Distribution of mapped Danish and Norwegian dwellings on 1 dB wide classes of noise exposure

Sweden

The less detailed Swedish mapping results [13] were not analysed further; see also Appendix 12.

11.3 EFFECT OF REGULATION ON ANNOYANCE

Based on the data on population exposure to different noise level classes, the contributions from each noise level class to the overall noise indicators for the population as a whole were calculated. These calculations are described in Appendix 12. The results are illustrated in Figure 11 and the final results are given in Table 12.

Figure 11 shows the contributions from each decibel class to the overall noise indicators: Støjbelastningstal (SBT), Støyplageindeks (SPI) or Number of highly annoyed citizens (NHA). They are all based on the Norwegian population exposure data. The examples shown are for scenario c) in the “Before” situation and in an “After” situation where Norwegian SMA 16 has been replaced by SMA 8, and all but the tyres labelled 69 dB have been removed.

- All dwellings having $L_{\mathrm{den}} \geq 55.0$ dB[4] in the “Before” situation have been included
- All dwellings having $L_{\mathrm{den}} \geq 55.0$ dB “Before" have also been included in the “After”[5] situation

The assessments of the reduced annoyance made by means of the three indicators differ. SBT gives higher weight to improvements at the dwellings having the highest exposure than the two other indicators.

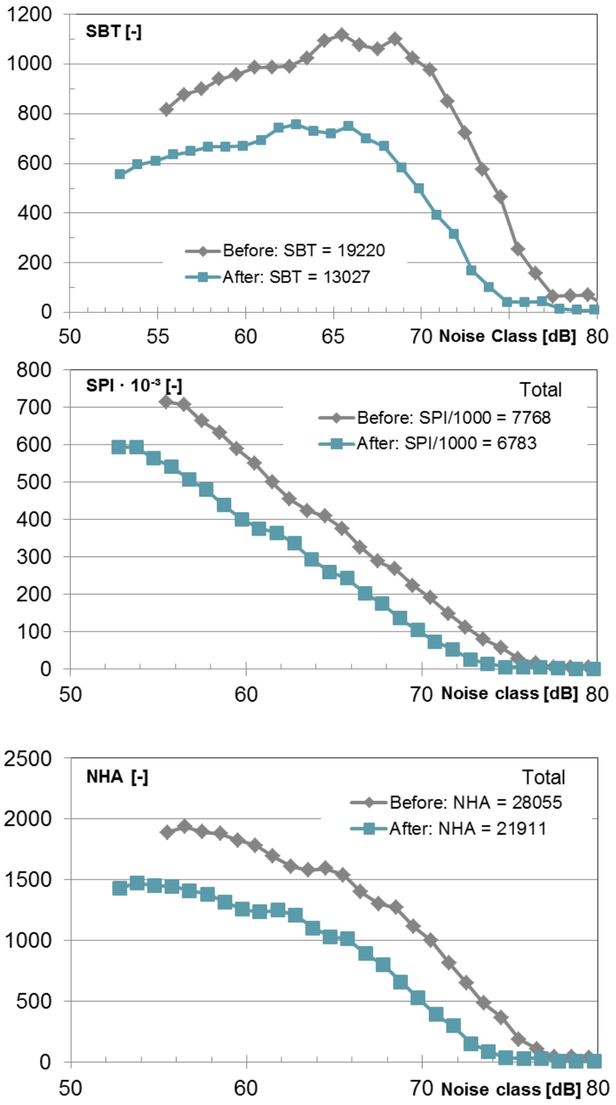

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Figure 11
Illustrations of the contributions from different noise level classes to (Top): Støjbelastningstal (SBT); Mid: Støyplageindeks (SPI); and Bottom: Number of highly annoyed persons (NHA). Based on Norwegian population exposure data and scenario c) “Before” and “After” replacing Norwegian SMA 16 by SMA 8 and removing all tyres but those labelled 69 dB

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[4] This has also been done for SBT to enable a direct comparison of the “behaviour” of the indicators, even though the Danish procedure normally excludes all dwellings having $L_{\mathrm{den}} < 58.0$ dB

[5] See footnote 4)

Table 11 shows the contributions from dwellings in different noise exposure ranges to the change in overall annoyance indicator. Almost equal contributions to the changes in SBT come from the dwellings exposed to the highest and lowest noise levels while an essentially larger part of the contribution to the changes in SPI originates from dwellings exposed to the lower noise level classes. The changes in NHA are intermediates.

Table 11

Contributions to the total annoyance indicator values from dwellings exposed to different ranges of noise exposure

Noise exposure range		Reduction in total noise indicator [%]		
[dB]		SPI	SBT	NHA
High	65.5 - 74.5	9.3	31.8	20.3
Low	55.5 - 64.5	14.0	32.3	22.8
Difference Low/High		50%	2%	12%

Table 12 shows the results of SBT-computations made for the Danish noise mapping data and SPI-computations made for the Norwegian noise mapping data. These computations of SBT only comprise contributions from dwellings exposed to noise levels ≥ 58.0 dB both before and after replacing pavements and regulating tyre noise. The computations of SPI comprise contributions from dwellings exposed to noise levels ≥ 55 dB before regulation, irrespective of their noise exposure in the “After” situation. The Danish annoyance indicator SBT is reduced by 35 % and the Norwegian indicator is reduced by 13 %.

Table 12

Change ΔSBT in SBT for Denmark and change ΔSPI in SPI for Norway calculated for Scenario c) replacing standard pavement (SMA 11 in Denmark and SMA 16 in Norway) by SMA 8 and by removing all other tyres than those labelled 69 dB

Speed	Denmark				Norway			
	SBT 10^{-3}		ΔSBT 10^{-3}		SPI		ΔSPI	
[km/]	Before	After	[-]	[%]	Before	After	[-]	[%]
50	135.4	90.5	-44.8	-33	4,749	4,265	-484	-10
80	5.8	3.3	-2.5	-43	2,570	2,154	-416	-16
110	14.4	6.7	-7.8	-54	449	364	-85	-19
Total	155.6	100.5	-55.1	-35	7,768	6,783	-985	-13

12. MEASURED ROLLING RESISTANCE

Table 23 in Appendix 4 shows the measured Rolling Resistance Coefficients (RRC). The measurements were carried out by TUG on “the large drum” in its facility in Gdansk [6]. The tyres were tested at 50 km/h and 80 km/h, respectively, both on an ISO 10844 replica surface and on an AC 16d replica. The measurements were performed at a temperature of approximately 20 ºC. All tyres were inflated with a pressure of 210 kPa and loaded with 4000 N. These conditions are not the same as those required in ISO 28580 [14] but the deviations from the standard are not likely to affect the outcome of the present project. See also Appendix 4. The results are illustrated in Figure 12. The rolling resistance coefficient on AC 16d on the average was about 3 % higher than the rolling resistance coefficient on the ISO replica, while the tyre having the highest rolling resistance coefficient had a 50 % higher rolling resistance coefficient than the tyre having the lowest value.

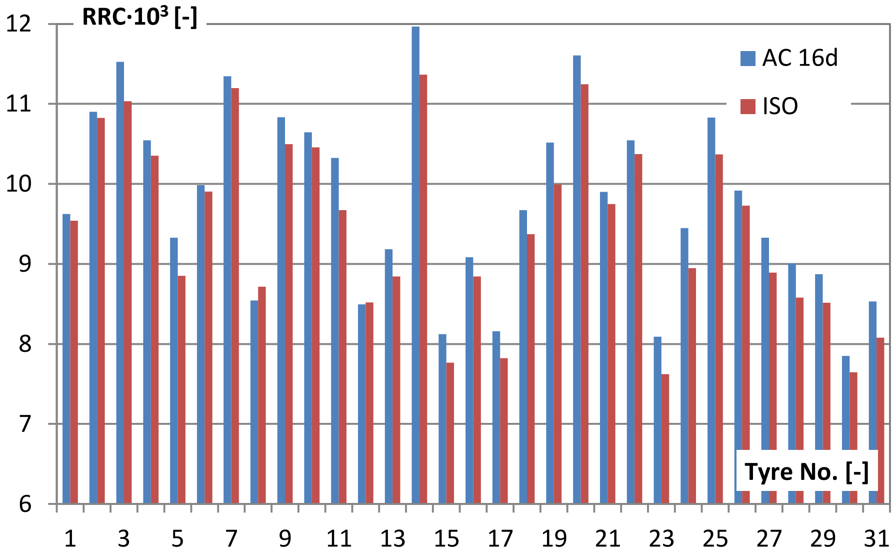


Figure 12 - Figure 15 in File: < K:\AD\BBM\BEF\Støj\Projekter\Nordtyre\Måleresultater\TUG data\RR\ResultsRR_kragh_15jan14.xlsx >

Figure 12

Rolling Resistance Coefficients (times 10^3) for tyres No. 1 – 31 measured at 80 km/h on ISO and on AC 16d replica surfaces

In Figure 13 the CPX noise levels measured on the ISO test track at Hällered (DRD20) and the noise levels measured on SMA 11 at Höör (DRD22), which is noise-wise an average of the pavements looked at in NordTyre, are shown as a function of the rolling resistance measured at 80 km/h on the ISO and AC 16d replica surfaces, respectively, on the TUG drum. There is no correlation between the RRC and the noise levels.

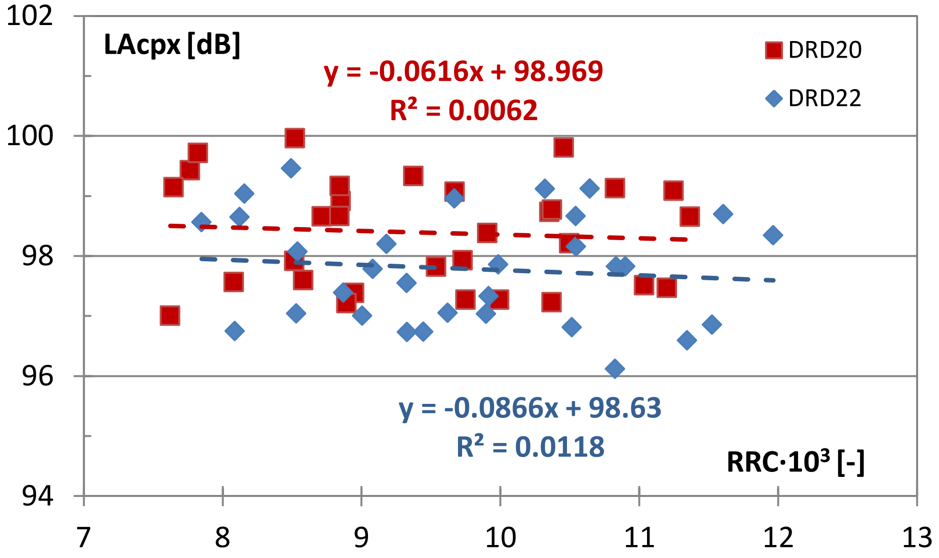


Figure 13

Noise level on the ISO test track (DRD20) as a function of the Rolling Resistance Coefficient (RRC) measured at 80 km/h on ISO replica surface and noise levels on SMA 11 (DRD22) as a function of RRC measured on AC 16d replica surface

Figure 14 shows the RRC measured on the TUG ISO replica surface as a function of the fuel efficiency class labelled by tyre manufacturers. Assuming each RRC value to be the same as the mid-point of the fuel efficiency class defined in [1] there is some correlation (R^2 = 0.57) but not a fine correlation between labels and TUG measurement results. See also textbox next to Table 23.

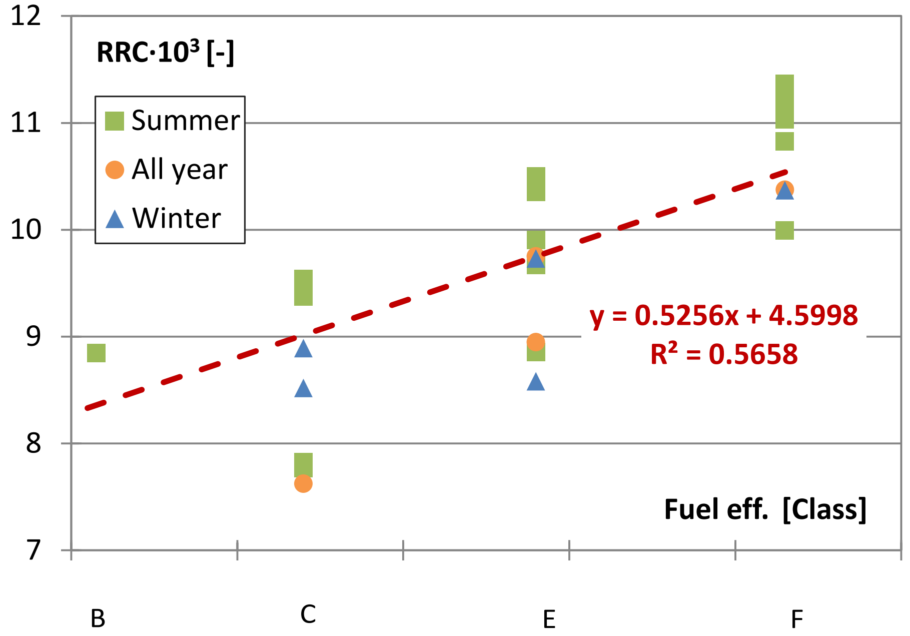


Figure 14

Measured rolling resistance coefficients on an ISO replica surface as a function of the labelled fuel efficiency class

The prices of the tyres are shown in Figure 15 as a function of the rolling resistance coefficient (RRC) measured by TUG on its ISO replica. There is poor correlation with an overall trend for lower prices the higher the rolling resistance.

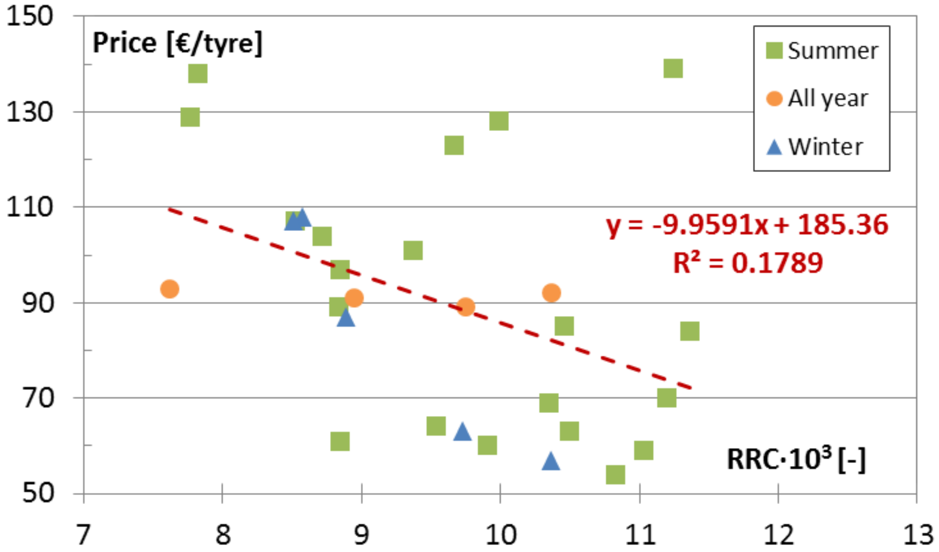


Figure 15

Tyre price as a function of rolling resistance coefficient measured on ISO replica (DRD21)

13. MEASURED ROAD GRIP

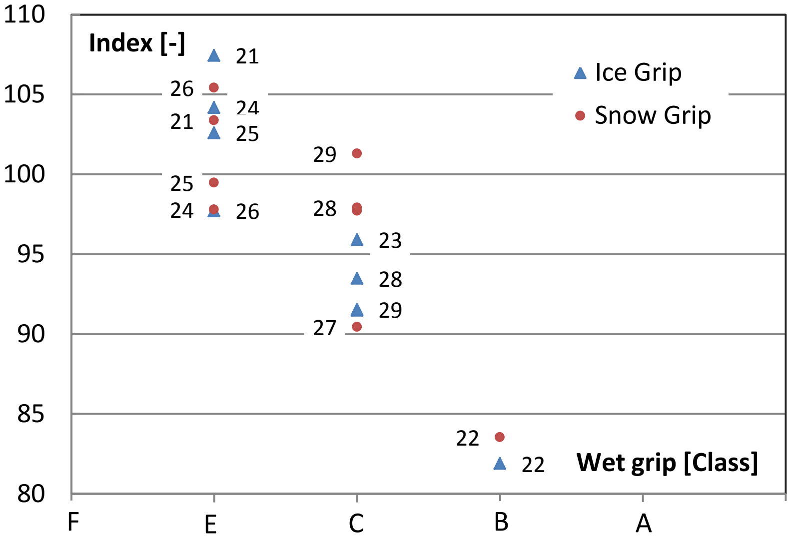
Table 13 shows the ice and snow grip indices measured by Test World Ltd in its facility at Ivalo, Finland [7]. The braking distance of a car equipped with each set of winter and all-season tyres was measured in a standardised way and compared to a reference measurement. The reference tyre (SRTT) has an index of 100 [-]. An increase in index equals better performance. Wet grip labels show ratings from A to F, where A is better and F is worse. Also the average trailer noise levels L_{Acpx} measured on all 31 pavements are given in the table.

Table 13

Measured ice and snow grip for the all-year and winter tyres and label values

No. #	Ice Grip Index [-]	Snow Grip Index [-]	Wet grip [Label]	L_{Acpx} [dB]
All-year tyres				
21	107.4	103.4	E	97.0
22	81.9	83.5	B	98.5
23	95.9	97.7	C	96.6
24	104.2	97.8	E	97.3
Winter Tyres				
25	102.6	99.5	E	96.4
26	97.7	105.4	E	97.3
27	91.5	90.4	C	97.2
28	93.5	97.9	C	97.1
29	91.5	101.3	C	97.5

The relations between road grip and measured noise levels are shown in Appendix 5. The general trend was that the noise level did not vary systematically with the road grip. The only exception was that for tyre No. 22 which yielded noise levels around 1.5 dB higher than the rest of the tyres also gave the best wet grip and the poorest snow and ice grip. This is also illustrated in Figure 16 which shows the relation between the measured ice and snow grip and the labelled wet grip values. Note that wet grip labels according to the Directive [1] only encompass classes A, B, C, E and F, not class D.



Labels:
Snow = left; Ice = right
Ice: 29 on top of 27
Snow: 28 on top of 23

Figure 16

Relations between measured ice and snow grip indices and labelled wet grip

14. DISCUSSION

14.1 NOISE LABELS VS “REAL NOISE LEVELS“

An important aim of NordTyre is to determine the relation between the number on the noise label issued by the tyre manufacturer and the noise level during the pass-by of a car on a Nordic road. The possibility of identifying such relations is hampered by the observation that trailer measurements may not distinguish correctly between noise levels from different tyres in real traffic because of differences in tyre load and tyre inflation pressure. With this in mind, an attempt has been made in the following to discuss different findings and their validity.

Representativity of measured noise levels

A preliminary conclusion of the NordTyre project stated that no correlation could be seen between noise levels measured on ISO test tracks in the project and the noise labels declared by tyre manufacturers. This was met by the comment that such a correlation should not at all be expected for reasons mentioned below. This came as an unpleasant surprise to project participants.

It was argued by tyre manufacturer representatives that Close-Proximity (CPX) noise levels cannot be expected to represent labelled noise levels. Such label values shall be measured during vehicle coast by (CB) while meeting requirements concerning tyre load and tyre inflation pressure. For most of the tyres in NordTyre these requirements differ from those required for CPX trailer measurements and applied in NordTyre.

Such deviations in tyre load/inflation pressure may cause tyres to have a different “foot print”6) during the CPX measurements made in NordTyre from the footprint they have during CB measurements made for labelling purposes. A short version of these comments is that while it may be appropriate to compare road surfaces by means of CPX measurement, even when applying other tyres than specified in the draft CPX standard, it is not possible to make meaningful comparisons of the noise emission from different car tyres based on CPX results. As a consequence it was decided to base the scenarios in this report on the labelled noise levels, assuming that label values represent a valid estimate of the range of noise emission on dense asphalt with small aggregate.

Recent measurements made in the Norwegian – Polish project LEO, however, indicate that CPX trailer noise levels may actually have better correlation with CB noise levels than claimed by tyre manufacturers, see Section A.10.4. This will hopefully be clarified in Part 4 of the NordTyre project.

Tyre manufacturers usually select one member of a “family” of tyre lines, often the one they expect is the noisiest family member, for noise labelling measurement, if it keeps within the Directive noise limit. The noise label is then issued for the entire family. Thus, if NordTyre procured another family member for the measurement, this may have contributed to the lack of correlation between labels and measured noise levels.

It could be argued that the load and inflation pressure prescribed in the labelling procedure are not necessarily be the conditions all tyres are driven with in the traffic, see Section A.10.1. A tyre line may be used for a range of car models having different weight, and for a given car model a range of tyre dimensions may be used. Such variation will contribute to make the label value less representative for the noise emission on real roads.

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6) This “foot print” is defined by the size and the shape of the tyre/road contact patch

Test track variations

It is known that noise levels from the same tyres measured on different ISO 10844 test tracks may vary significantly, [2] referring to [15]. For example, in [15] a set of Pirelli summer tyres were reported to yield a CB noise level of 75.9 dB on one test track (denoted ISO 2) and 68.6 dB on another test track (denoted ISO 7), i.e. a range of more than 7 dB. For a set of Goodyear winter tyres the corresponding range exceeded 3 dB. But to state that one surface was louder than another would be too simple because noise level differences between tracks varied from tyre to tyre. The relations between surface properties such as texture and sound absorption on one hand and the noise generation on the other are complex [15].

In Figure 2 the correlation is not perfect, and for a given CPX noise level on one of the two ISO tracks there could be a range exceeding 1 dB in CPX noise levels on the other ISO test track. Both test tracks were built according to the 1994 version of ISO 10844 and during the NordTyre measurements their MPD was measured to be 0.83 mm at Hällered and 0.44 mm at Aachen, see Section 14.2 The new version ISO 10844:2011 has stricter limits on pavement properties than the earlier version and track to track variability may eventually be smaller. This, however, will have to be proved.

Until it becomes certain that track to track variability has been controlled, inter-calibration between test tracks with subsequent issue of individual corrections could be a temporary solution. Such corrections could be based on results of a series of measurement made either by track owners themselves on the same set(s) of passenger car tyres and / or truck tyres which were circulated among test facilities or by measurements made by trailer team(s) and / or CB team(s) dispatched to measure on all tracks. Such effort would imply cost to test track owners but the outcome could be more meaningful noise labels.

Perhaps a further tightening of requirements on labelling measurements could also contribute, e.g. by narrowing the allowed intervals of ambient temperature during labelling measurements. At present measurements may be made if the air temperature is above 5 °C and below 40 °C and a temperature correction is applied using correction coefficients -0.03 dB per ºC above 20 ºC and -0.06 dB per ºC below 20 ºC. This correction is prescribed for all tyres even though the values have been shown to vary from tyre line to tyre line.

14.2 NEED FOR A SECONDARY TEST TRACK

The results in Table 1 show that the small group of results from new Danish pavements would be very well represented by the test track at Hällered (DRD20) and somewhat less well represented by the test track at Aachen (DRD32) or by SMA 11 at Höör (DRD22). The group of other Nordic pavements would be best represented by SMA 11 (DRD22) and somewhat less well but not too badly represented by the test track at Hällered (DRD20), while the noise level measured on the Aachen test track correlated poorly with the noise levels measured on the group of Nordic roads.

Table 14 shows average values of the determination coefficients R^2 and average slopes of the regression lines, respectively. The latter is a measure of the ability to estimate differences between tyres based on test track noise levels. In particular, the results from the test track at Aachen correlate poorly with the results from the Nordic roads and the regression line slope is rather small. These data indicate that by introducing SMA 11 as a second test track could improve the agreement between the value of a second noise label and noise levels on Nordic roads. This finding is based on the noise levels from 24 sets of summer and all-year tyres, i.e. excluding the results for winter tyres as it was also done in the simulations described in Section 10, because it was judged irrelevant to include noise levels from winter tyres measured at summer temperatures.

Table 14

Average slope and average percentage R^2 of explained variance in linear regressions of *y* = noise levels on NordTyre pavements on *x* = noise levels on different test tracks. Winter tyre results were not included

	Average slope [-]			Average R^2 [%]		
Test track candidate	**DRD20**	**DRD22**	**DRD32**	**DRD20**	**DRD22**	**DRD32**
New Danish pavements	0.92	0.90	0.86	92	74	75
Other pavements	0.71	0.84	0.58	73	86	46

Figure 17 shows the surface texture spectra measured on the two test tracks in Hällered and Aachen and the reference spectrum given in ISO 10844:2011. This figure demonstrates that the test track at Hällered had a “rougher” surface than the test track at Aachen, and that the test track at Aachen would fit better with the new version of the standard than the test track at Hällered even though both tracks were built to fulfil the older standard.

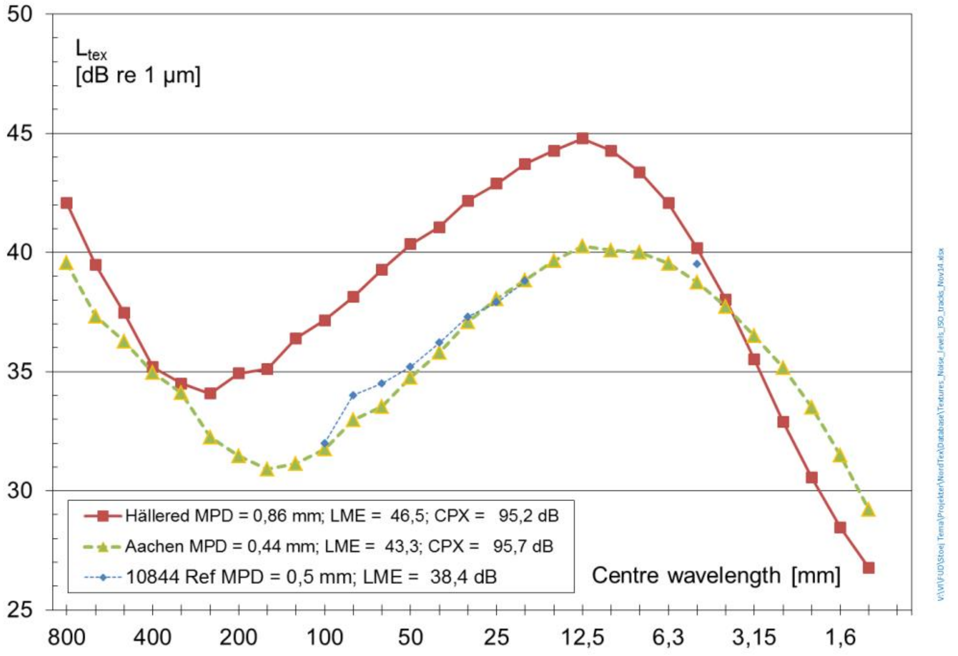

Figure 17

Surface texture spectra measured on the two ISO test tracks compared with the reference spectrum given in an informative annex in ISO 10844:2011

14.3 NOISE REDUCTION POTENTIALS

The final version of the scenarios on potential noise reduction were based on the tyre noise label values under the assumption that these do in fact reflect the noise emission from tyres on SMA 8. In a draft version of the present report, the noise levels measured with the CPX trailer were instead assumed to represent the noise levels on SMA 8. Under this assumption the results illustrated in Figure 18 were found. The figure shows the result of simulations as described in connection with Figure 7 and Figure 8. In Figure 18 the resulting tyre/road noise levels on SMA 16 are shown after having removed individual tyres in an order determined by the labelled noise levels, by the noise levels measured with the trailer on the ISO test track at Hällered and by the noise levels measured with the trailer on SMA 11 at Höör. Estimated in this way the tyre/road noise reduction would be slightly higher when removing tyres according to the CPX measurement results than the finally decided potential of 1.4 dB.

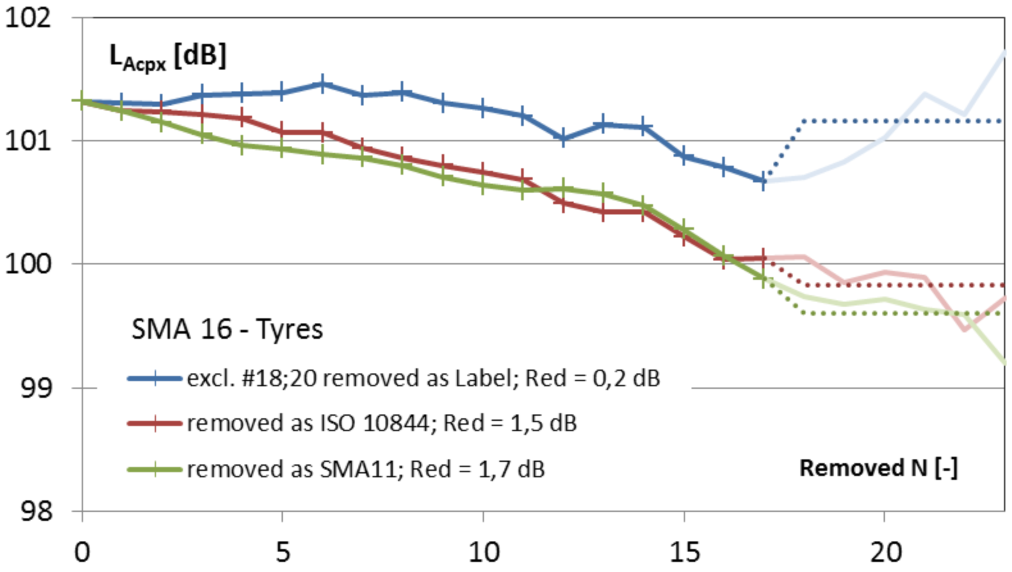

Figure 18

Development of the energy average tyre/road noise level L_{Acpx} when removing the noisiest tyres one by one according to different measures: 1) the label values, or 2) the CPX-noise levels measured on ISO 10844 test track at Hällered and on 3) the CPX-noise levels measured on SMA11 at Höör. Tyres #18 and #20 have been removed from the group of tyres in the simulation based on label values. The dotted lines show the average noise level from the quietest 25 % of the tyres

14.4 SCENARIOS

The calculated effects of regulating pavements and tyres on the annoyance indicators used in Denmark and Norway are rather different; see Section 11.3 and Section A.12.2. Even though a Norwegian change from SMA 16 to SMA 8 gives more reduction of traffic noise levels than a change in Denmark from SMA 11 to SMA 8, the change in the Danish annoyance indicator value is larger than the change in the Norwegian indicator value. The main explanation is that the Danish SBT puts extra emphasis on very high noise exposure levels compared to the Norwegian SPI.

Also the fact that in the SBT calculation, dwellings having a noise exposure of 58.0 dB or more in the “Before situation” contribute to SBT while the same dwellings are disregarded in the “After situation” if their noise exposure drops below 58 dB. A very small improvement in noise exposure may cause such dwellings to vanish completely from the calculation even though the improvement may be insignificant. The reasons for this approach are unknown to the authors, and the procedure should be reconsidered. When calculating the value of the Norwegian SPI all dwellings exposed to 55.0 dB or more ”Before” are included in the calculation for the situation “After”. If such a procedure was applied the change in the Danish SBT would be to 28 % rather than 35 %, see Table 36.

To obtain the annoyance reductions given above both pavements and tyres were regulated. If only the pavements are changed the percentages would be in the order of three quarters of the numbers given.

14.5 OTHER PARAMETERS

The measured rolling resistance coefficients were found not to be correlated with measured tyre/road noise levels, see Section 12, and the same applied to the relations between noise level and rod grip, see Section 13. There was some correlation but not a fine correlation between the measured rolling resistance coefficients and the labelled fuel efficiency classes. This lack of a fine correlation may or may not be explained by the fact that measurement conditions at TUG did not exactly match the standard for such measurements. Also, TUG does not participate in laboratory inter-calibration. However, these deviations are not essential to the main aim of the NordTyre project, which is traffic noise reduction.

15. CONCLUSIONS AND RECOMMENDATIONS

The total range of noise levels encountered between the quietest tyre on the quietest pavement (excluding the ISO tracks) and the noisiest tyre on the noisiest pavement was almost 11 dB.

No correlation was found between tyre manufacturers' noise labels and the noise levels measured on the ISO test track. The reasons for this lack of correlation are discussed in the report, and the authors believe that the main reason is variation in test track properties although it cannot be ruled out that differences in test conditions during labelling measurements and the measurements carried out in the NordTyre project also contribute to this unfortunate fact. Hopefully this can be clarified in a continuation of the NordTyre project.

A few years ago a new international standard for test track properties was issued. This may contribute to reducing variation from test track to test track in measured tyre/road noise levels from a given tyre. Further improved reproducibility in tyre noise labelling measurements could be obtained by limiting the allowed temperature intervals but perhaps the best action to take would be to request test track owners to participate in regular inter-calibration to obtain correction factors to be applied to measurement results from each test track. Such inter-calibrations could be carried out in various ways mentioned in the report and they would imply extra cost for noise labelling measurements but could potentially provide valuable improvement of the reliability of noise label values.

If a second test track could be introduced into the labelling procedure and a second noise label could be added which better represent the noise emission from tyres running on the rough surfaces of Nordic roads, then an efficient regulation of the use of noisy tyres would be easier to implement than is the case with the present smooth test tracks. On the other hand, if pavements are regulated by replacing rough textured surfaces by smoother wearing courses then the need for a rougher test track disappears.

Replacing noisy pavements with quieter pavements was found to potentially yield more reduction in traffic noise levels than the noise reduction obtained by regulating tyre use, but the additional noise reduction which could be obtained by using quieter tyres is by no means insignificant.

If successful regulation of the use of noisier tyres can be implemented in combination with a change from SMA 16 to a noise reducing thin asphalt layer the traffic noise level from passenger cars can be reduced by up to 5 dB. If all pavements in Denmark and Norway could be changed from standard pavement to stone mastic asphalt with 8 mm maximum aggregate size and all but the quietest 25 % of the tyres could be removed from the vehicle fleet, then annoyance from passenger car noise could be reduced by estimated 35 % in Denmark (Danish SBT) and by estimated 13 % in Norway (Norwegian SPI).

Measured rolling resistance coefficients were found to be uncorrelated with measured tyre/road noise levels. The same applied to most data on road grip, and a trend was found for less good braking performance on ice and snow the better the labelled wet grip. The one all-season tyre having the best road grip yielded the highest noise level of all-season and winter tyres.

The procedure for calculating the Danish annoyance indicator SBT should be reconsidered. The authors recommend a change so that all dwellings exposed to L_{den} = 58.0 dB or more before a noise reduction measure is taken and exposed to less than 58 dB after the traffic noise has been reduced shall no longer be discarded from the after-calculation. This would reduce the change in annoyance indicator SBT.

16. PERSPECTIVE

During the planning of Parts 1 and 2 of the NordTyre project reported on here, an urgent need was identified to demonstrate that the present limits for noise from truck tyres are too ineffective and to introduce stricter limit values. Among other things also the need were pointed out for

1. establishing procedures for testing winter traction and friction of tyres
2. producing, if possible, an objective procedure to identify/define winter tyres for heavy vehicles, to replace rather arbitrary definitions applied by individual tyre manufacturers
3. encouraging public organizations to require the use of quiet and safe tyres; e.g. publicly procured bus transportation, taxi approvals, and cooperate with large transportation companies to have them favour the use of quiet and safe tyres
4. introducing limits and labelling procedures for the noise from retreaded tyres (in particular for trucks and busses)

The NordTyre project steering committee requested VTI (Ulf Sandberg) to work out a proposal [17] for Part 3 of the NordTyre project to deal with the noise from truck tyres. Based on this NordTyre Part 3 was initiated in the spring of 2014.

By the end of 2014 plans exist to extend the NordTyre project a Part 4 dealing with tyre/road noise from car tyres which are worn and aged rather than the new tyres dealt with so far.

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APPENDIX 1 – SELECTED TYRES

General

The overall intention was to select an appropriate number of passenger car tyres to represent the tyres applied on Nordic cars. Based on various interviews and the availability of tyre lines at the project start a total of 31 tyre lines were procured representing a cross-section of 1) Small / Medium / Large tyres; 2) Summer / All-year / Winter tyres; and 3) Premium / Medium / Low price tyres. The tyres finally selected for the project and some tyre characteristics are listed in Table 15 and Table 16.

1) Cat = the tyre category: Summer; All-year; or Winter

2) Tyre tread hardness is the average value for outer and centre tread blocks on the left and right trailer wheel. The values given are averages of all Shore A values per tyre line measured during the measurement series from Apr-12 to Aug-12

3) The Load Index corresponds to a maximum permitted load given below. Linear regression yields: Permitted load = 15.978*(Load Index) – 831.13; R^2 = 0,99

Load Index [-]	75	82	84	87	91	92	95	96	98
Permitted load [kg]	387	475	500	545	615	630	690	710	750

6. The tyre Speed Index: T; H; V; or W is

Speed Index [-]	T	H	V	W
Permitted speed [km/h]	190	210	240	270

9. The tyre age is its age by mid Jul-12, in the middle of the measurement series, [weeks]

10 – 11. RRC is the rolling resistance coefficient at 80 km/h on drum surface ISO and AC 12d, [-]

Table 15

List of procured tyres and their primary characteristics

#	Brand	Tyre Line	Dimension	Noise label [dB]	Fuel eff [Class]	Wet grip [Class]	Price [€/tyre]
Summer tyres							
1	Goodyear	DuraGrip	185/60 R14	67	C	C	64
2	Firestone	Multihawk	175/65 R14	71	F	C	54
3	Continental	ContiEcoContact3	175/65 R14	70	F	C	59
4	Uniroyal	Rain Expert	175/65 R14	70	E	B	69
5	Michelin	Energy Saver	175/65 R14	70	E	B	61
6	Klebér	Dynaxer HP3	175/65 R14	69	E	C	60
7	Nankang	Ultra Sport NS II	155/65 R14	71	F	C	70
8	Bridgestone	Turanza ER300 Ecopia	205/60 R16	70	E	A	104
9	Firestone	Multihawk	195/65 R15	72	E	E	63
10	Continental	ContiPremiumContact2	205/55 R16	71	E	B/C	85
11	Uniroyal	RainSport2	205/50 R16	71	E	B	123
12	Michelin	Energy Saver	205/60 R16	70	E	A	107
13	Klebér	Dynaxer HP2	205/60 R16	-	-	-	97
14	Nankang	Ultra Sport NS II	195/45 R16	71	F	C	84
15	Bridgestone	Turanza T001	225/55 R16	71	C	B	129
16	Hankook	Kinergy ECO K425	215/65 R15	71	B	B	89
17	Continental	PremiumContact5	225/55 R16	71	C	A	138
18	Marshal	Matrac XM	225/60 R16	75	C	C	101
19	TOYO	Proxes C1S	225/60 R16	69	F	C	128
20	Dunlop	SP Sport 01 MO	225/50 R16	66	F	A	139
All-season tyres							
21	Goodyear	Vector 4 Seasons	185/65 R14	69	E	E	89
22	Bridgestone	A001	205/55 R16	72	F	B	92
23	Hankook	Optimo 4S	205/65 R15	72	C	C	93
24	Klebér	Quadraxer	205/55 R16	71	E	E	91
Winter tyres							
25	Firestone	Winterhawk 2 EVO	175/65 R14	70	F	E	57
26	Klebér	Krisalp HP2	175/65 R14	72	E	E	63
27	Hankook	Winter i*cept evo	205/60 R15	72	C	C	87
28	Michelin	Alpin A4	205/60 R16	70	E	C	108
29	Nokian	WR D3	205/60 R16	71	C	C	107
Special tyres							
30	Uniroyal	Tigerpaw SRTT	225/60 R16	-	-	-	
31	Michelin	Primacy LC	205/60 R15	-	-	-	

Table 16

Further tyre characteristics

1	2	3	4	5	6	7	8	9	10	11
Tyre No.	**Cat**	**Width**	**Tread hardness**	**Load Index**	**Speed Index**	**Aspect ratio**	**Rim diam**	**Age**	**RRC [-] 80km/h**	
[-]	[-]	[mm]	[Shore A]	[-]	[-]	[-]	[”]	[weeks]	ISO	AC16d
1	S	185	70	82	H	60	14	127	0,0095	0,0096
2	S	175	66	82	T	65	14	31	0,0108	0,0109
3	S	175	70	82	T	65	14	17	0,0110	0,0115
4	S	175	67	82	T	65	14	32	0,0104	0,0105
5	S	175	65	82	T	65	14	82	0,0089	0,0093
6	S	175	70	82	T	65	14	24	0,0099	0,0100
7	S	155	66	75	V	65	14	37	0,0112	0,0113
8	S	205	67	92	H	60	16	111	0,0087	0,0085
9	S	195	65	91	T	65	15	17	0,0105	0,0108
10	S	205	71	91	H	55	16	64	0,0105	0,0106
11	S	205	65	87	V	50	16	16	0,0097	0,0103
12	S	205	68	92	H	60	16	20	0,0085	0,0085
13	S	205	71	92	H	60	16	16	0,0088	0,0092
14	S	195	65	84	V	45	16	32	0,0114	0,0120
15	S	225	69	95	V	55	16	27	0,0078	0,0081
16	S	215	67	96	H	65	15	15	0,0088	0,0091
17	S	225	68	95	W	55	16	16	0,0078	0,0082
18	S	225	69	98	W	60	16	32	0,0094	0,0097
19	S	225	61	98	W	60	16	33	0,0100	0,0105
20	S	225	70	92	V	50	16	23	0,0112	0,0116
21	A	185	62	86	H	65	14	15	0,0097	0,0099
22	A	205	68	91	V	55	16	111	0,0104	0,0105
23	A	205	62	94	H	65	15	43	0,0076	0,0081
24	A	205	64	91	H	55	16	18	0,0089	0,0094
25	W	175	61	82	T	65	14	21	0,0104	0,0108
26	W	175	65	82	T	65	14	32	0,0097	0,0099
27	W	205	65	91	H	60	15	53	0,0089	0,0093
28	W	205	62	92	H	60	16	77	0,0086	0,0090
29	W	205	61	92	H	60	16	37	0,0085	0,0089
30	S	225	64	97	S	60	16	62	0,0076	0,0078
31	S	205	65	91	V	60	15	120	0,0081	0,0085

APPENDIX 2 – SELECTED PAVEMENTS

The intention was to select a suitable number of different pavements representing the spectrum of wearing courses encountered on Nordic roads, with slightly higher representation of quieter pavements than pavements known to be associated with high traffic noise levels. The Danish so-called SRS have been optimised for low noise levels by having small maximum aggregate and an open surface structure. AC 6o, for example, is open graded asphalt concrete modified to obtain lower traffic noise levels, by optimizing the texture and void structure (semi-open pores) without comprising the durability. SMA 6+11 means stone mastic asphalt having 6 mm nominal maximum aggregate size but with a small fraction of oversized (8/11 mm) aggregate added to obtain a more open structure.

The main selection criteria were that the pavements should

1. represent pavements used in regions of Nordic countries where studded tyres are not used
2. have been exposed to traffic for at least 6 months prior to measurements
3. be in good condition without significant signs of wear and tear
4. include standard pavements not designed for noise reduction
5. include noise reducing pavements, so-called SRS, thin asphalt layers with small maximum aggregate and an open surface structure
6. include pavements with higher noise reduction potential, e.g. optimized thin layers with higher built-in air void content
7. be located in groups with short driving distance between the pavements

DANISH PAVEMENTS

Igelsø

The road sections built in August 2010 at Igelsø to demonstrate typical Danish noise reducing pavements (SRS) were selected; see Table 18. There are five SRS and one reference pavement, each around 500 m long. The speed limit is 80 km/h. Yearly SPB and CPX measurements are being performed by DRD in local Danish projects.

Herning-I

Six sections of highway M64 were selected among 12 sections constructed in 2006, see Table 19. The speed limit is 90 km/h. The length of each section is between 150 m and 200 m. Yearly SPB and CPX measurements are being performed by DRD in local Danish projects.

Herning-II

Three sections were selected among eight test sections and a reference pavement built in 2008 on highway M68, see Table 20. The speed limit is 90 km/h. The length of each section is between 250 m and 300 m. Yearly SPB and CPX measurements are being performed by DRD in local Danish projects.

Table 17

Pavement characteristics

Pavement No.	Site	Type	Constr. year	Pavement ID	MPD	Mega texture level L_{ME}
					[mm]	[dB re 10^{-6} m]
1	M64 Herning-I	AC 6o	2007	DRD11	0.97	49.6
2	M64 Herning-I	AC 8o	2007	DRD12	1.09	50.8
3	M64 Herning-I	AC 11d	2007	DRD13	0.85	47.5
4	M64 Herning-I	SMA 6	2007	DRD14	1.05	49.2
5	M64 Herning-I	SMA 6+8	2007	DRD15	1.01	48.5
6	M64 Herning-I	SMA 11	2007	DRD16	1.23	51.9
7	M68 Herning-II	AC 11d	2008	DRD17	0.73	45.6
8	M68 Herning-II	PA 6	2008	DRD18	1.21	45.2
9	M68 Herning-II	SMA 6+8	2008	DRD19	1.12	49.5
10	Hällered	ISO 10844	2004	DRD20	0.86	46.5
11	E22 Hörby	SMA 16	2006	DRD21	0.93	51.7
12	RV13 Höör	SMA 11	2010	DRD22	0.82	49.4
13	RV13 Höör	SMA 8	2010	DRD23	0.77	46.9
14	RV13 Höör	AC 11d	2010	DRD24	0.55	42.8
15	RV13 Höör	AC 8d	2010	DRD25	0.70	44.2
16	Igelsø	AC 11d	2010	DRD26	0.54	44.8
17	Igelsø	AC 6o	2010	DRD27	0.72	45.2
18	Igelsø	SMA 6+11	2010	DRD28	0.69	45.3
19	Igelsø	SMA 6+8	2010	DRD29	0.73	45.9
20	Igelsø	SMA 8	2010	DRD30	1.03	50.0
21	Igelsø	AC 8o	2010	DRD31	0.89	48.9
22	Aachen	ISO 10844	-	DRD32	0.44	43.3
23	E18 Mastemyr	SMA 16	2005	STF11	1.40	54.7
24	E18 Mastemyr	SMA 11	2005	STF12	1.03	50.1
25	E18 Mastemyr	SMA 8	2005	STF13	0.78	46.5
26	E18 Mastemyr	SMA 6	2005	STF14	0.94	48.0
27	E18 Mastemyr	SMA 11	2005	STF15	0.88	48.1
28	E16 Hønefoss	AC 11d	2005	STF16	0.90	45.2
29	E16 Hønefoss	AC 6d	2005	STF17	0.58	43.2
30	E16 Hønefoss	AC 8d	2005	STF18	0.71	42.6
31	E16 Hønefoss	AC 11d	2005	STF19	0.95	46.5
32	E16 Hønefoss	AC 11d	2002	STF20	0.99	46.9
33	TUG drum	ISO 10844	-	TUG21	-	48.0
34	TUG drum	AC 12d	-	TUG22	-	49.2

Table 18

Properties of Danish pavements at Igelsø selected for the project

Designation	Comment	Max aggregate size [mm]	Specified air void [%]	Avg car noise red 1st year [dB] *)	MPD Oct 2010[7] [mm]
AC 11d	Normal dense graded asphalt concrete	11	2.8	2.4	0.57
AC 6o **)	Open graded asphalt concrete	6	11.7	6.7	0.78
AC 8o **)	Open graded asphalt concrete	8	12.2	4.0	0.89
SMA 8 **)	Stone Mastic Asphalt	8	8.3	3.7	1.04
SMA 6+8 **)	Stone Mastic Asphalt modified with 8 mm extra aggregate	6 + 8	8.0	4.2	0.75
SMA 6+11 **)	Stone Mastic Asphalt modified with 11 mm extra aggregate	6 + 11	8.3	5.9	0.75

Table 19

Properties of Danish pavements at Herning-I selected for the project

Pavement	Comment	Max aggregate size [mm]	Specified air void [%]	Avg. car noise red. over first 4 years [dB] *)	MPD 2010[1] [mm]
SMA 11	Standard stone mastic asphalt	11	-	-0.4	1.24
AC 11d	Normal dense graded asphalt concrete	11	2.3	2.5	0.82
AC 6o **)	Open graded asphalt concrete	6	-	5.3	1.08
AC 8o **)	Open graded asphalt concrete	8	-	4.0	1.14
SMA 6 **)	Stone Mastic Asphalt	6	8.9	3.3	1.02
SMA 6+8 **)	Stone Mastic Asphalt modified with 8 mm extra aggregate	6 + 8	6.0	3.4	0.90

Table 20

Properties of Danish pavements at Herning-II selected for the project

Pavement	Comment	Max aggregate size [mm]	Specified air void [%]	Avg. car noise red. over first 3 years [dB] *)	MPD 2010[7] [mm]
AC11d	Normal dense graded asphalt	11	-	3.1	0.69
DA6 **)	Thin semi porous asphalt	6	12.3	7.6	0.91
SMA 6+8 **)	Stone Mastic Asphalt modified with 8 mm extra aggregate	6 + 8	12.5	4.6	0.75

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[7] Newest available data at the time of pavement selection

*) Noise reductions relative to Nord2000 default value = for AC 11d

**) Optimised for low noise levels (SRS)

NORWEGIAN PAVEMENTS

Selection criteria #5 and #6 are not applicable to Norwegian conditions. No pavements have been built to be noise reducing except for a few experimental sections constructed in the project "Environmentally friendly roads - EFR" (2005-2008). These were mainly porous asphalt and thin layer asphalt. Monitoring has shown that none of these sections have maintained their noise reduction.

Some wearing courses built in the EFR project were dense asphalt concrete surfaces with maximum aggregate sizes between 6 mm and 16 mm, see Table 21. Two of these locations were on E18 at Mastemyr near Oslo (five pavements), and on E16 near Hønefoss (five surfaces). All these were constructed in 2005, except for one AC 11d built in 2002 at Hønefoss.

CPX noise measurements in 2011 with 10 different passenger car tyres showed a 5 dB difference at Mastemyr between a "low-noise" tyre on the pavement with 6 mm maximum aggregate and a "noisy" tyre on the SMA 16 pavement. On E16 at Hønefoss, the largest differences were 3.5 - 4 dB.

At these two locations the pavements are grouped together and noise levels and the surface texture have been monitored for several years. Table 21 summarises basic data for the two test locations. E18 is a 4 lane highway, with a speed limit of 80 km/h. E16 is a two-lane rural road with a speed limit of 80 km/h.

Table 21

Norwegian road surfaces selected for the NordTyre project

Pavement No.	County	Location	Road No.	Hp/Lane	Chainage [km]	Length [m]	Pavement	Constr. year
1	Oslo	Mastemyr	E18	1, Lane 2	1.577-1.294	283	SMA 16	2005
2	Oslo	Mastemyr	E18	1, Lane 2	1.294-1.024	270	SMA 11	2005
3	Oslo	Mastemyr	E18	1, Lane 2	1.024-0.754	269	SMA 8	2005
4	Oslo	Mastemyr	E18	1, Lane 2	0.754-0.510	244	SMA 6(4)	2005
5	Oslo	Mastemyr	E18	1, Lane 2	0.510-0.017	493	SMA 11	2005
6	Buskerud	Hønefoss	E16	6, Lane 1	1.512-2.066	554	AC 11d	2005
7	Buskerud	Hønefoss	E16	6, Lane 1	2.066-2.379	313	AC 6d	2005
8	Buskerud	Hønefoss	E16	6, Lane 1	2.379-2.661	282	AC 8d	2005
9	Buskerud	Hønefoss	E16	6, Lane 1	2.661-3.659	328	AC 11d	2005
10	Buskerud	Hønefoss	E16	6, Lane 1	3.656-4.0	344	AC 11d	2002

Road surface No.4 was originally constructed as an SMA 6. However, a bore core test and analysis performed during the spring 2012 revealed that the grading curve was closer to a 4 mm surface, than a 6 mm. The grading curve is shown in Figure 19.

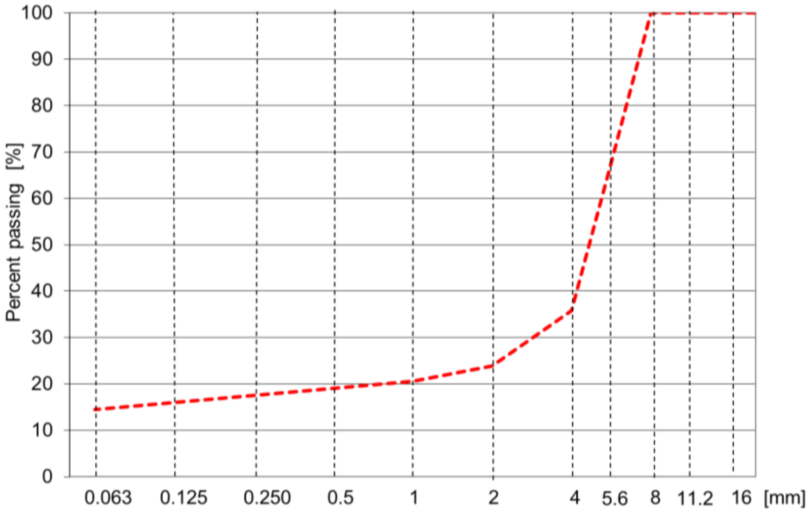


Figure 19

Grading curve for pavement No. 4 on E18 at Mastemyr. Bore core sample taken in 2012

SWEDISH PAVEMENTS

Four Swedish road sections denoted HO-1111 built in 2010 at Höör in Southern Sweden were selected, i.e. SMA 11, SMA 8, AC 11d and AC 8d. These were supplemented by a section with SMA 16 built in 2006 on E22 Southwest of Hörby, also in Southern Sweden. These sections had all been trafficked by vehicles having studded tyres. Data on the pavements are given in Table 22.

Table 22

Swedish pavements selected for the NordTyre project

ID #	Pavement designation		Site	Construction	Chainage	Length	MPD
	International	Swedish		year [-]	[m]	[m]	[mm]
RV13-1	AC 8d	ABT 8	RV13 West of Höör	2010	1,601 – 2,155	500	0.35
RV13-2	SMA 8	ABS 8	RV13 West of Höör	2010	954 – 1,601	500	0.79
RV13-3	AC 11d	ABT 11	RV13 West of Höör	2010	2,155 – 10,773	800	0.37
RV13-4	SMA 11	ABS 11	RV13 West of Höör	2010	10 - 954	800	0.76
RV13-Ref	SMA 16	ABS 16	E22 Southwest of Hörby	2006	-	800	0.99

APPENDIX 3 - NOISE LEVELS ON THE LEFT AND RIGHT SIDE OF THE TYRES

Measurements were made on two surfaces on the (small-) drum in the facility of TUG; see Figure 20. The results are summarized in Figure 21 and Figure 22. This led to the conclusion that in order to avoid introducing extra uncertainty in the measurement results, the tyres had to be remounted on their rims before the wheels were shipped to Norway for measuring with the SINTEF/SVV trailer. In this way the microphones would be on the same side of the tyre on the Norwegian trailer as they were on the Danish trailer. After the measurements in Norway, the tyres were again “turned” before the measurements were made with the Danish trailer in Sweden.

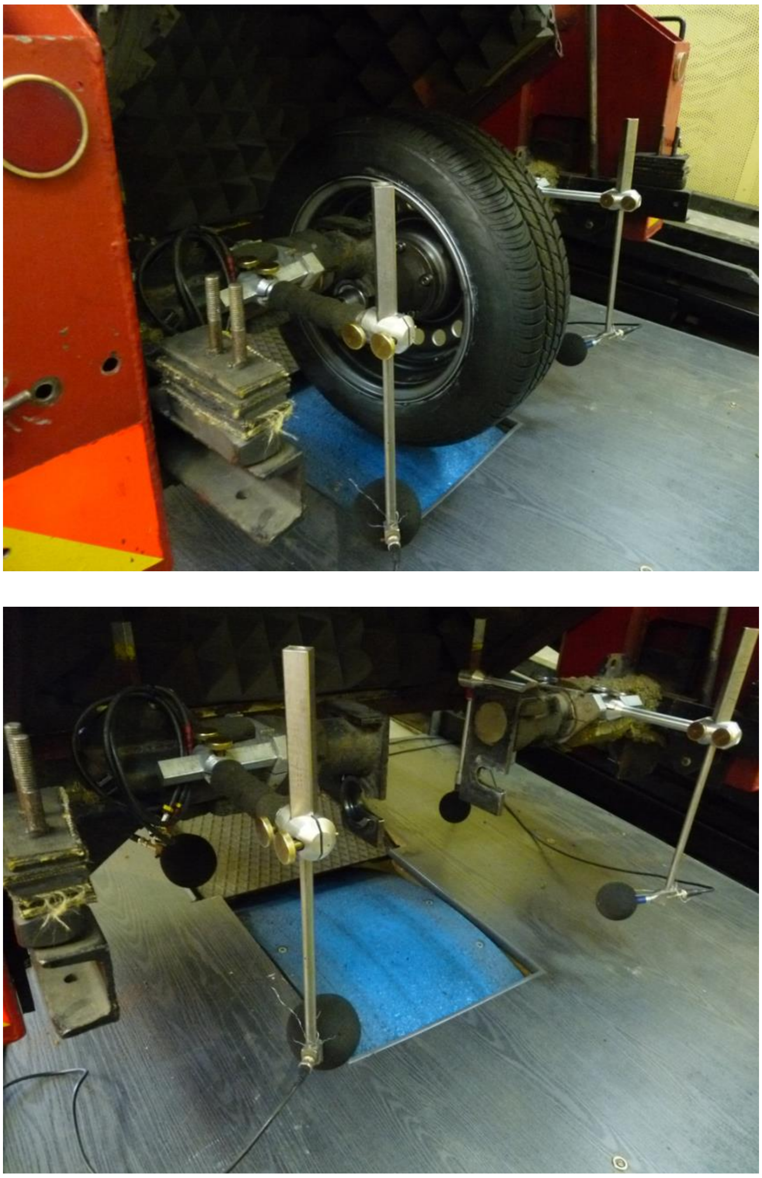
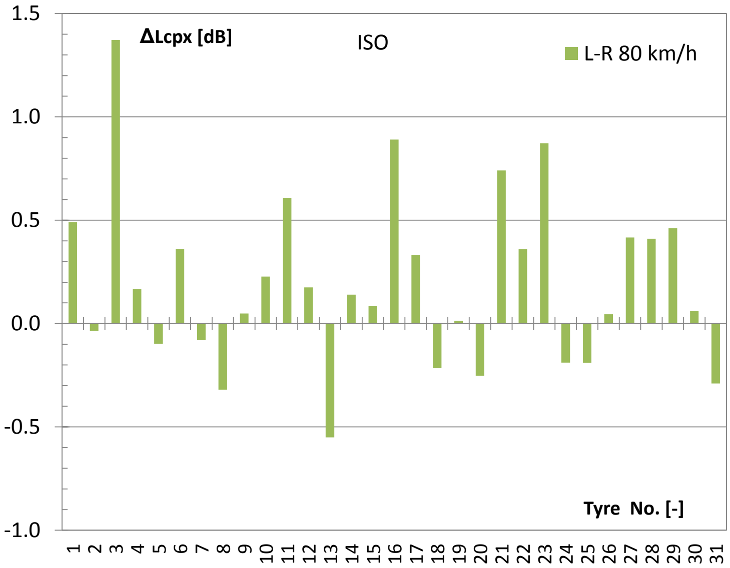


Figure 20

Trailer wheel and microphones on the ”small-drum” facility at TUG



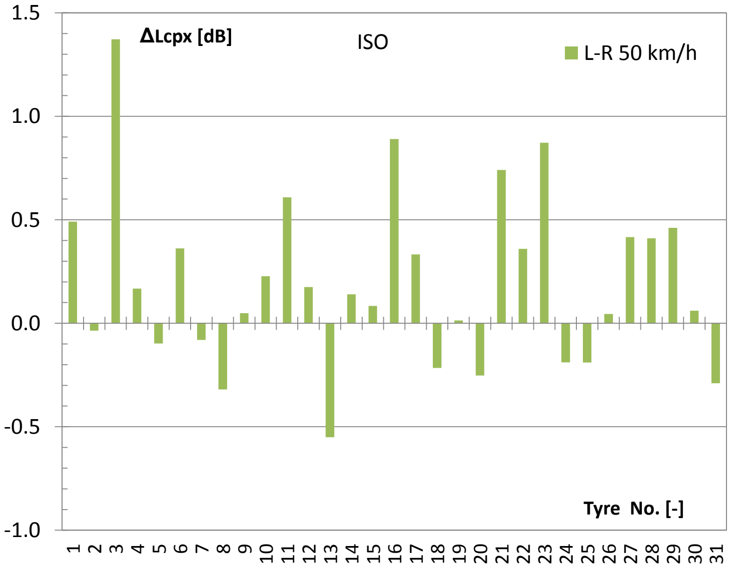
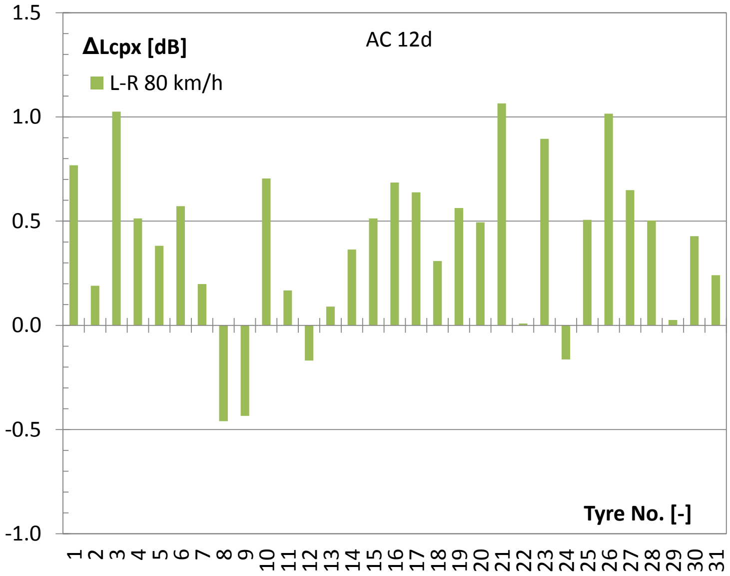


Figure 21

Difference L-R between noise levels measured on the left and right side of the tyres on a drum with ISO replica surface. Top: 80 km/h: Bottom: 50 km/h

In particular, the measurement results in Figure 22 from the AC 12d replica surface indicate systematically higher noise levels on the left side than on the right side of the tyres. This is not as clearly the case in the results in Figure 21. The reason for having more systematic differences on the AC 12d could be differences in a) microphone distances from the tyre, b) reflections from the trailer enclosure, c) surface texture at the two sides of the wheel, or d) other measurement errors. This has not been further investigated.



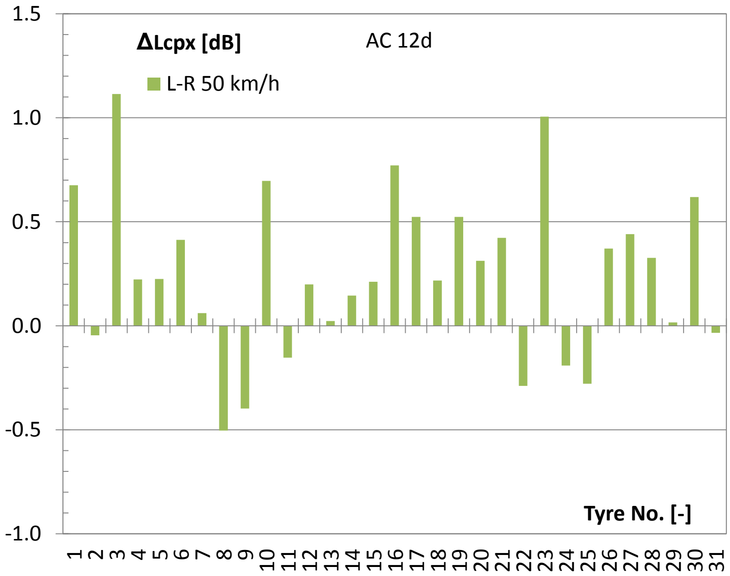


Figure 22

Difference L-R between noise levels measured on the left and right side of the tyres on a drum with AC 12d replica surface. Top: 80 km/h: Bottom: 50 km/h

APPENDIX 4 - MEASURED ROLLING RESISTANCE

Table 23 shows the measured Rolling Resistance Coefficients (RRC). See also Section 12. In the European project SILENCE, TUG measured RRC with both the TUG and the ISO methods. The correlation between results obtained by means of the ISO and TUG methods was rather high, within each surface, but the TUG method gave approx. 40 % greater RRC than the ISO method on the rough surface due to the higher inflation pressure applied when using the ISO method.

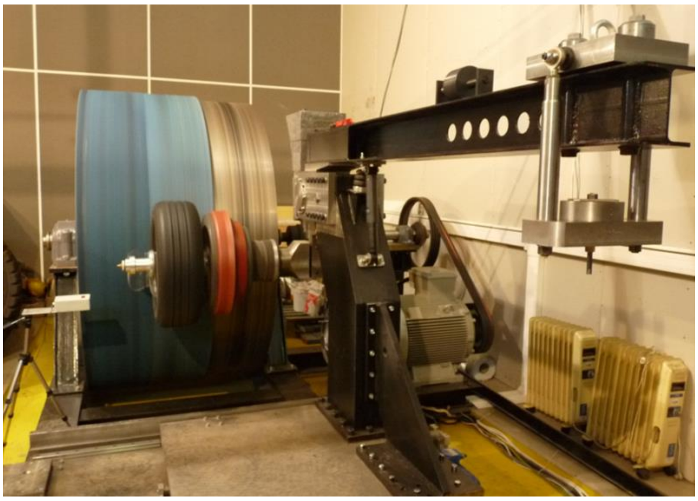


Figure 23 The large drum at TUG

Table 23 Rolling Resistance Coefficients (·10^3) measured on two surfaces at to speeds (left) and fuel efficiency classes defined in [1] (right)

		RRC·10^3 [-]			
No.	Tyre ID	ISO		AC 16d	
		50 km/h	80 km/h	50 km/h	80 km/h
1	1A	8.8	9.5	9.0	9.6
2	2A	10.8	10.8	10.6	10.9
3	3A	10.6	11.0	10.9	11.5
4	4A	9.8	10.4	9.9	10.5
5	5A	8.3	8.9	8.7	9.3
6	6A	9.4	9.9	9.5	10.0
7	7A	10.6	11.2	10.9	11.3
8	8A	8.5	8.7	8.1	8.5
9	9A	10.5	10.5	10.7	10.8
10	10A	10.4	10.5	10.6	10.6
11	11A	9.1	9.7	9.6	10.3
12	12A	8.3	8.5	8.2	8.5
13	13A	8.7	8.8	8.9	9.2
14	14A	10.9	11.4	11.2	12.0
15	15A	7.6	7.8	7.9	8.1
16	16A	8.7	8.8	9.0	9.1
17	17A	7.7	7.8	7.9	8.2
18	18A	9.3	9.4	9.7	9.7
19	19A	9.9	10.0	10.3	10.5
20	20A	11.1	11.2	11.6	11.6
21	21A	9.1	9.7	9.4	9.9
22	22A	10.1	10.4	10.3	10.5
23	23A	7.4	7.6	7.7	8.1
24	24A	8.5	8.9	8.9	9.4
25	25A	9.9	10.4	10.1	10.8
26	26A	9.0	9.7	9.2	9.9
27	27A	8.7	8.9	9.2	9.3
28	28A	8.2	8.6	8.6	9.0
29	29A	8.2	8.5	8.6	8.9
30	30A	7.4	7.6	7.7	7.8
31	31A	8.0	8.1	8.4	8.5

Fuel efficiency classes [1]		
Class [-]	RRC [-]	Mid-point [-]
A	≤ 6.5	-
B	6.6 – 7.7	7.15
C	7.8 – 9.0	8.4
D	Empty	-
E	9.1 – 10.5	9.8
F	10.6 – 12.0	11.3
G	≥ 12.0	-

APPENDIX 5 – MEASURED ROAD GRIP

Figure 24 - Figure 26 show the average of the noise levels L_{Acpx} measured on all 31 pavements as a function of the labelled wet grip class and the measured ice grip and snow grip index, respectively, for each all-year and each winter tyre. There is hardly any connection between noise level and road grip. The only exception is that tyre No. 22, having the hardest tread and yielding around 1.5 dB higher noise levels than the rest of the tyres, also had the best wet grip but the poorest snow and ice grip.

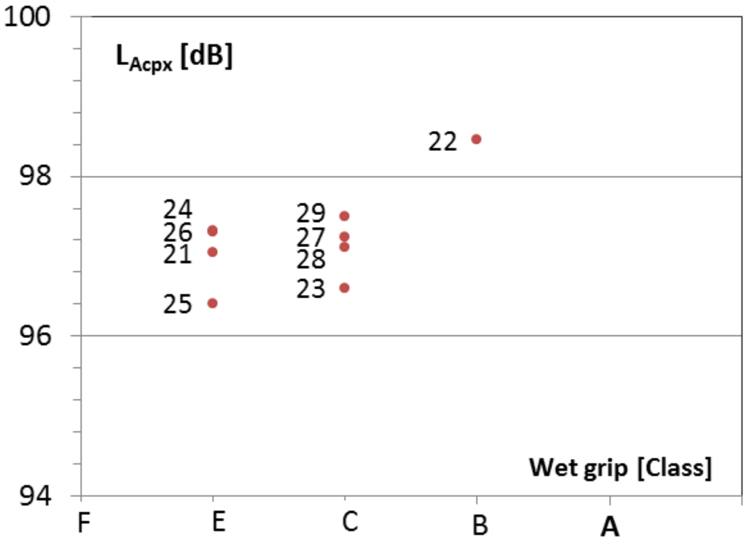


Figure 24

Average noise level as a function of the wet grip class for all-year and winter tyres

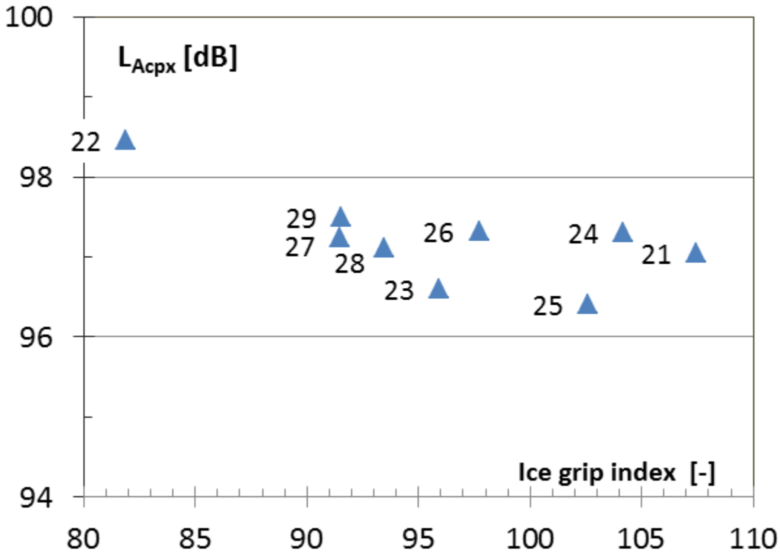


Figure 25

Average noise level as a function of the ice grip index for all-year and winter tyres

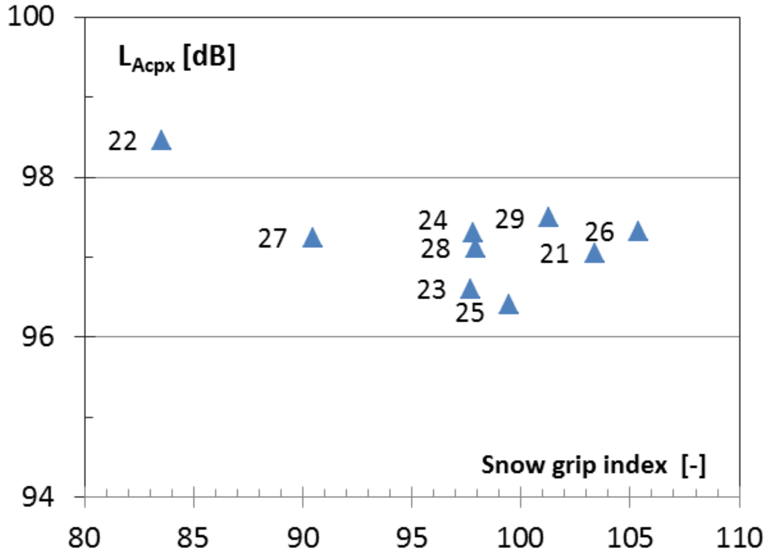


Figure 26

Average noise level as a function of the snow grip index for all-year and winter tyres

APPENDIX 6 - PAVEMENT FAMILIES

Table 24 shows the pavements, excl. ISO tracks and drum pavements, and some pavement characteristics. It may be discussed at length whether for example an open graded asphalt concrete should belong to the same “family” as a dense graded asphalt concrete or whether it would be more appropriate to group in with stone mastic asphalt. The spread in tyre/road noise levels due to differences in pavement age, exposure to traffic etc. in some cases is larger than the difference between the average noise level on noise-wise “neighbouring” families, and the grouping shown in the table was selected as a primary choice for the present project. See also Section 10.4 on p. 18.

Table 24

Average CPX noise levels for all summer tyres and all-year tyres per pavement, and some other pavement characteristics

Road surface ID	Family [-]	Type [-]	MPD [mm]	L_{ME} [dB re 10^{-6} m]	Average L_{Acpx} [dB]	Age [years]
DRD11	AC 6	AC 06o	0.97	49.6	98.5	5
DRD27		AC 06o	0.72	45.2	95.0	2
STF17		AC 06d	0.58	43.2	97.6	7
DRD12	AC 8	AC 08o	1.09	50.8	99.2	5
DRD25		AC 08d	0.70	44.2	97.6	2
DRD31		AC 08o	0.89	48.9	96.9	2
STF18		AC 08d	0.71	42.6	98.9	7
DRD13	AC 11	AC 11d	0.85	47.5	98.5	5
DRD17		AC 11d	0.73	45.6	97.2	4
DRD24		AC 11d	0.55	42.8	98.0	2
DRD26		AC 11d	0.54	44.8	96.5	2
STF16		AC 11d	0.90	45.2	98.9	7
STF19		AC 11d	0.95	46.5	99.4	7
STF20		AC 11d	0.99	46.9	99.3	10
DRD18	SMA 6	PA 06	1.21	50.2	94.8	4
DRD14		SMA 06	1.05	49.2	96.5	5
DRD15		SMA 06+8	1.01	48.5	98.1	5
DRD19		SMA 06+8	1.12	49.5	98.1	4
DRD28		SMA 06+11	0.69	45.3	96.9	2
DRD29		SMA 06+8	0.73	45.9	95.6	2
STF14		SMA 06	0.94	48.0	95.8	7
DRD23	SMA 8	SMA 08	0.77	46.9	98.4	2
DRD30		SMA 08	1.03	50.0	97.3	2
STF13		SMA 08	0.78	46.5	97.1	7
DRD16	SMA 11	SMA 11	1.23	51.9	99.1	5
DRD22		SMA 11	0.82	49.4	99.3	2
STF12		SMA 11	1.03	50.1	98.6	7
STF15		SMA 11	0.88	48.1	100.7	7
DRD21	SMA 16	SMA 16	0.93	51.7	100.3	6
STF11		SMA 16	1.40	54.7	100.7	7

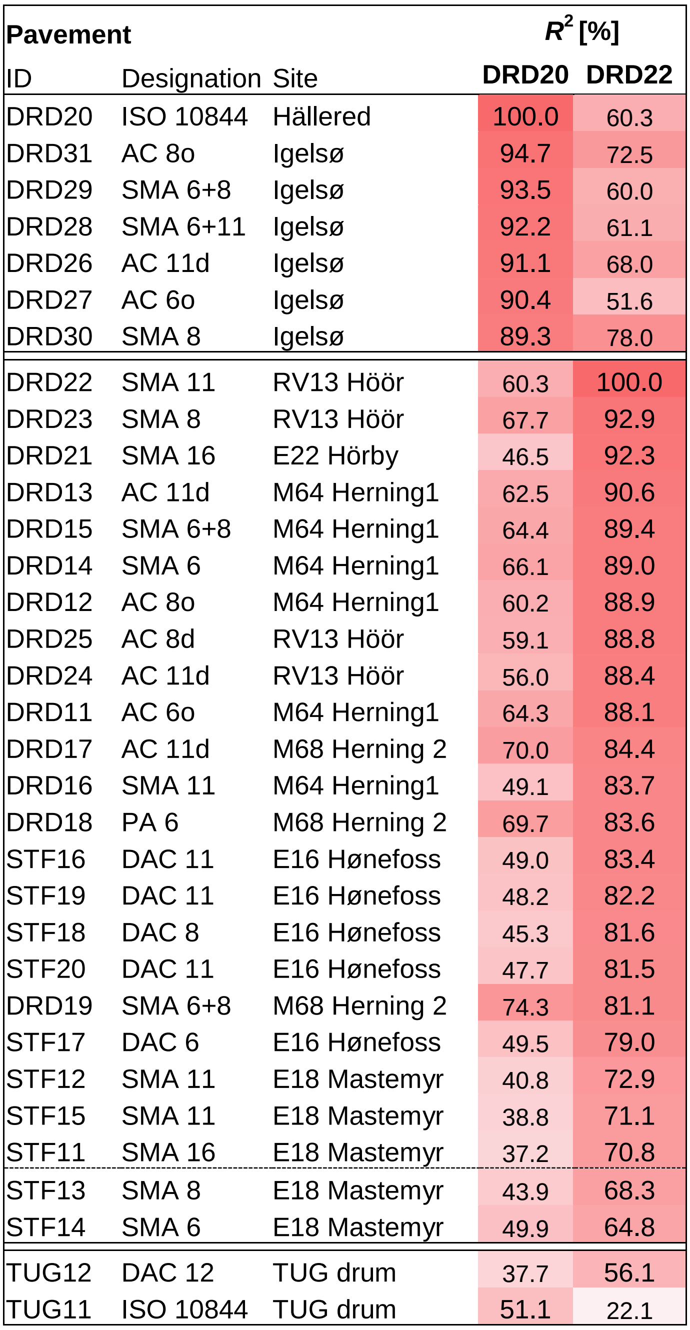
APPENDIX 7 - CORRELATION BETWEEN NOISE LEVELS ON DIFFERENT PAVEMENTS

Table 26 shows values of R^2 for any combination of the 33 pavements while Table 27 and Table 28 show the values of the slope and intercepts of the regression lines. These tables have been generated based on the noise levels measured with all tyres, i.e. winter tyre data have been included.
In Table 25 the columns dealing with the ISO test track at Hällered (DRD20) and the SMA 11 pavement at Höör (DRD22) have been extracted from Table 26 and the data have been sorted according to the value of R^2. This table differs from Table 1 in that the calculations leading to Table 1 excluded the winter tyre noise levels, so Table 1 represents the tyre population used in the regulation scenarios mentioned in Section 10, while Table 25 covers all tyres selected for the project. Overall the correlations in Table 1 are the same as or slightly better than those in Table 25 which are based on the noise levels from all tyres. Only minor differences are seen between the groupings of pavements in the two tables.

Both tables indicate that most of the Nordic pavements selected for the present project would be better represented by a SMA 11 test track than by the ISO test track DRD20. The ISO test track represents the newest Danish road sections with thin noise reducing asphalt layers better than a test track with SMA11 would do. Table 14 shows the average values of R^2 from Table 1 and Table 25 for each group of pavements and for each “candidate test track”, DRD20, DRD22 and DRD32, respectively.

Table 25

Pavements sorted according to correlation (R^2 expressed in %) with DRD20 and DR22, respectively, based on all tyres



Pavement			R^2 [%]	
ID	Designation	Site	**DRD20**	**DRD22**
DRD20	ISO 10844	Hällered	100.0	60.3
DRD31	AC 8o	Igelsø	94.7	72.5
DRD29	SMA 6+8	Igelsø	93.5	60.0
DRD28	SMA 6+11	Igelsø	92.2	61.1
DRD26	AC 11d	Igelsø	91.1	68.0
DRD27	AC 6o	Igelsø	90.4	51.6
DRD30	SMA 8	Igelsø	89.3	78.0
DRD22	SMA 11	RV13 Höör	60.3	100.0
DRD23	SMA 8	RV13 Höör	67.7	92.9
DRD21	SMA 16	E22 Hörby	46.5	92.3
DRD13	AC 11d	M64 Herning1	62.5	90.6
DRD15	SMA 6+8	M64 Herning1	64.4	89.4
DRD14	SMA 6	M64 Herning1	66.1	89.0
DRD12	AC 8o	M64 Herning1	60.2	88.9
DRD25	AC 8d	RV13 Höör	59.1	88.8
DRD24	AC 11d	RV13 Höör	56.0	88.4
DRD11	AC 6o	M64 Herning1	64.3	88.1
DRD17	AC 11d	M68 Herning 2	70.0	84.4
DRD16	SMA 11	M64 Herning1	49.1	83.7
DRD18	PA 6	M68 Herning 2	69.7	83.6
STF16	DAC 11	E16 Hønefoss	49.0	83.4
STF19	DAC 11	E16 Hønefoss	48.2	82.2
STF18	DAC 8	E16 Hønefoss	45.3	81.6
STF20	DAC 11	E16 Hønefoss	47.7	81.5
DRD19	SMA 6+8	M68 Herning 2	74.3	81.1
STF17	DAC 6	E16 Hønefoss	49.5	79.0
STF12	SMA 11	E18 Mastemyr	40.8	72.9
STF15	SMA 11	E18 Mastemyr	38.8	71.1
STF11	SMA 16	E18 Mastemyr	37.2	70.8
STF13	SMA 8	E18 Mastemyr	43.9	68.3
STF14	SMA 6	E18 Mastemyr	49.9	64.8
TUG12	DAC 12	TUG drum	37.7	56.1
TUG11	ISO 10844	TUG drum	51.1	22.1

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Table 26

Determination coefficients R^2 (in per cent) in linear regression analyses of the relations between noise levels on individual pavements

R^2	DRD11	DRD12	DRD13	DRD14	DRD15	DRD16	DRD17	DRD18	DRD19	DRD20	DRD21	DRD22	DRD23	DRD24	DRD25	DRD26	DRD27	DRD28	DRD29	DRD30	DRD31	STF11	STF12	STF13	STF14	STF15	STF16	STF17	STF18	STF19	STF20	TUG11	TUG12
DRD11	100.00	98.23	93.88	96.11	96.95	84.45	90.73	95.07	88.86	64.34	86.99	88.13	82.58	83.27	82.18	70.22	57.10	65.32	64.27	80.74	74.74	66.67	68.69	62.90	61.64	63.98	88.01	84.36	85.34	86.47	86.36	23.07	56.32
DRD12	98.23	100.00	94.30	95.27	95.85	89.19	89.06	92.62	89.03	60.17	89.27	88.92	82.77	83.62	80.11	65.18	52.77	60.61	59.57	78.47	71.34	70.74	71.22	64.46	62.01	66.21	87.99	82.29	84.32	86.14	85.86	24.39	59.65
DRD13	93.88	94.30	100.00	95.84	96.65	91.75	95.39	89.74	84.03	62.46	89.21	90.60	85.30	90.81	86.61	68.44	54.09	63.26	62.08	78.82	73.61	67.88	71.01	66.69	64.21	66.75	82.45	79.13	80.27	79.35	78.21	27.34	63.78
DRD14	96.11	95.27	95.84	100.00	99.37	89.00	90.96	94.47	90.88	66.06	89.96	88.95	84.58	85.70	85.47	67.84	58.22	64.43	63.47	81.13	75.75	73.01	75.19	68.30	67.47	69.20	87.44	78.70	81.10	85.29	84.57	24.17	56.40
DRD15	96.95	95.85	96.65	99.37	100.00	89.43	92.09	94.37	89.42	64.36	91.01	89.40	85.06	86.63	86.25	68.00	56.52	63.78	62.78	80.15	74.32	72.96	75.93	68.78	67.55	69.87	89.37	81.74	84.11	87.30	86.56	23.56	56.59
DRD16	84.45	89.19	91.75	89.00	89.43	100.00	82.59	80.94	82.71	49.13	88.67	83.72	74.98	81.01	74.02	53.30	43.09	49.17	47.31	69.80	62.22	76.88	73.43	67.70	60.77	69.32	81.16	70.07	77.01	78.43	77.10	25.53	63.09
DRD17	90.73	89.06	95.39	90.96	92.09	82.59	100.00	89.47	82.18	69.98	79.92	84.37	83.66	85.91	83.45	76.93	62.76	72.15	71.93	82.65	78.47	56.01	61.00	60.25	59.74	56.72	75.26	74.97	73.92	72.46	71.29	33.89	62.16
DRD18	95.07	92.62	89.74	94.47	94.37	80.94	89.47	100.00	91.37	69.69	81.79	83.56	79.28	76.76	79.62	70.65	61.71	67.29	66.96	81.73	76.49	68.28	68.10	61.73	63.39	63.69	81.37	74.99	76.54	80.93	81.08	27.56	55.65
DRD19	88.86	89.03	84.03	90.88	89.42	82.71	82.18	91.37	100.00	74.25	80.35	81.09	76.38	70.08	69.51	72.70	71.10	71.72	70.49	88.09	81.88	72.56	69.94	64.56	64.31	65.53	81.64	67.72	73.64	80.57	80.28	36.22	54.23
DRD20	64.34	60.17	62.46	66.06	64.36	49.13	69.98	69.69	74.25	100.00	46.46	60.30	67.65	55.97	59.09	91.11	90.43	92.23	93.54	89.34	94.69	37.19	40.78	43.91	49.88	38.75	49.01	49.49	45.33	48.19	47.72	51.08	37.74
DRD21	86.99	89.27	89.21	89.96	91.01	88.67	79.92	81.79	80.35	46.46	100.00	92.25	83.12	83.60	82.71	53.01	42.37	48.68	47.65	68.48	60.04	80.23	80.66	70.25	65.54	74.54	90.40	78.15	85.10	89.10	88.64	16.89	55.61
DRD22	88.13	88.92	90.60	88.95	89.40	83.72	84.37	83.56	81.09	60.30	92.25	100.00	92.94	88.35	88.81	67.97	51.60	61.14	60.05	78.00	72.53	70.79	72.87	68.26	64.81	71.07	83.43	79.03	81.57	82.24	81.46	22.10	56.06
DRD23	82.58	82.77	85.30	84.58	85.06	74.98	83.66	79.28	76.38	67.65	83.12	92.94	100.00	89.11	92.25	72.86	55.54	64.79	65.78	78.95	76.38	62.58	66.59	62.77	63.66	64.42	78.73	78.11	75.18	76.09	75.21	27.63	53.57
DRD24	83.27	83.62	90.81	85.70	86.63	81.01	85.91	76.76	70.08	55.97	83.60	88.35	89.11	100.00	89.83	65.93	46.61	57.00	55.10	68.73	67.36	62.69	69.47	67.93	65.68	66.39	79.42	83.66	81.26	76.85	76.06	22.60	66.74
DRD25	82.18	80.11	86.61	85.47	86.25	74.02	83.45	79.62	69.51	59.09	82.71	88.81	92.25	89.83	100.00	62.27	44.86	54.15	54.71	68.09	66.64	62.26	66.87	62.28	61.36	63.97	75.77	75.50	73.92	74.33	73.34	17.20	46.98
DRD26	70.22	65.18	68.44	67.84	68.00	53.30	76.93	70.65	72.70	91.11	53.01	67.97	72.86	65.93	62.27	100.00	89.27	96.43	95.68	92.27	94.26	35.72	41.54	46.57	50.25	40.71	58.29	66.32	59.91	56.84	56.51	53.60	50.09
DRD27	57.10	52.77	54.09	58.22	56.52	43.09	62.76	61.71	71.10	90.43	42.37	51.60	55.54	46.61	44.86	89.27	100.00	96.26	94.61	88.70	91.37	31.69	34.49	39.21	44.14	32.56	46.64	44.87	43.13	44.89	45.32	59.61	39.81
DRD28	65.32	60.61	63.26	64.43	63.78	49.17	72.15	67.29	71.72	92.23	48.68	61.14	64.79	57.00	54.15	96.43	96.26	100.00	97.70	92.08	94.06	33.29	37.73	42.73	46.93	35.90	51.74	55.21	50.73	49.91	50.21	55.75	43.44
DRD29	64.27	59.57	62.08	63.47	62.78	47.31	71.93	66.96	70.49	93.54	47.65	60.05	65.78	55.10	54.71	95.68	94.61	97.70	100.00	92.19	94.70	31.66	36.15	41.09	46.82	35.39	50.27	54.98	48.57	49.16	48.66	56.99	43.76
DRD30	80.74	78.47	78.82	81.13	80.15	69.80	82.65	81.73	88.09	89.34	68.48	78.00	78.95	68.73	68.09	92.27	88.70	92.08	92.19	100.00	97.01	51.21	53.20	54.29	56.35	50.91	69.33	67.66	65.30	67.24	67.08	51.00	54.17
DRD31	74.74	71.34	73.61	75.75	74.32	62.22	78.47	76.49	81.88	94.69	60.04	72.53	76.38	67.36	66.64	94.26	91.37	94.06	94.70	97.01	100.00	44.08	47.02	49.63	53.22	45.15	61.83	62.10	58.19	59.44	58.64	53.08	51.79
STF11	66.67	70.74	67.88	73.01	72.96	76.88	56.01	68.28	72.56	37.19	80.23	70.79	62.58	62.69	62.26	35.72	31.69	33.29	31.66	51.21	44.08	100.00	95.22	87.06	83.06	92.82	76.13	59.36	70.21	78.24	77.13	11.90	39.68
STF12	68.69	71.22	71.01	75.19	75.93	73.43	61.00	68.10	69.94	40.78	80.66	72.87	66.59	69.47	66.87	41.54	34.49	37.73	36.15	53.20	47.02	95.22	100.00	93.61	90.58	95.28	79.63	67.52	75.52	81.76	79.98	11.69	41.45
STF13	62.90	64.46	66.69	68.30	68.78	67.70	60.25	61.73	64.56	43.91	70.25	68.26	62.77	67.93	62.28	46.57	39.21	42.73	41.09	54.29	49.63	87.06	93.61	100.00	95.47	94.59	69.93	64.81	71.18	73.38	71.71	13.74	39.75
STF14	61.64	62.01	64.21	67.47	67.55	60.77	59.74	63.39	64.31	49.88	65.54	64.81	63.66	65.68	61.36	50.25	44.14	46.93	46.82	56.35	53.22	83.06	90.58	95.47	100.00	93.42	66.67	63.44	65.47	70.00	68.42	17.65	41.45
STF15	63.98	66.21	66.75	69.20	69.87	69.32	56.72	63.69	65.53	38.75	74.54	71.07	64.42	66.39	63.97	40.71	32.56	35.90	35.39	50.91	45.15	92.82	95.28	94.59	93.42	100.00	73.46	65.17	72.32	77.33	75.35	11.08	42.34
STF16	88.01	87.99	82.45	87.44	89.37	81.16	75.26	81.37	81.64	49.01	90.40	83.43	78.73	79.42	75.77	58.29	46.64	51.74	50.27	69.33	61.83	76.13	79.63	69.93	66.67	73.46	100.00	87.92	95.88	98.40	97.24	18.43	55.92
STF17	84.36	82.29	79.13	78.70	81.74	70.07	74.97	74.99	67.72	49.49	78.15	79.03	78.11	83.66	75.50	66.32	44.87	55.21	54.98	67.66	62.10	59.36	67.52	64.81	63.44	65.17	87.92	100.00	93.38	87.82	87.52	20.01	59.79
STF18	85.34	84.32	80.27	81.10	84.11	77.01	73.92	76.54	73.64	45.33	85.10	81.57	75.18	81.26	73.92	59.91	43.13	50.73	48.57	65.30	58.19	70.21	75.52	71.18	65.47	72.32	95.88	93.38	100.00	96.16	95.43	16.94	57.31
STF19	86.47	86.14	79.35	85.29	87.30	78.43	72.46	80.93	80.57	48.19	89.10	82.24	76.09	76.85	74.33	56.84	44.89	49.91	49.16	67.24	59.44	78.24	81.76	73.38	70.00	77.33	98.40	87.82	96.16	100.00	99.09	16.16	53.28
STF20	86.36	85.86	78.21	84.57	86.56	77.10	71.29	81.08	80.28	47.72	88.64	81.46	75.21	76.06	73.34	56.51	45.32	50.21	48.66	67.08	58.64	77.13	79.98	71.71	68.42	75.35	97.24	87.52	95.43	99.09	100.00	15.12	51.37
TUG11	23.07	24.39	27.34	24.17	23.56	25.53	33.89	27.56	36.22	51.08	16.89	22.10	27.63	22.60	17.20	53.60	59.61	55.75	56.99	51.00	53.08	11.90	11.69	13.74	17.65	11.08	18.43	20.01	16.94	16.16	15.12	100.00	44.54
TUG12	56.32	59.65	63.78	56.40	56.59	63.09	62.16	55.65	54.23	37.74	55.61	56.06	53.57	66.74	46.98	50.09	39.81	43.44	43.76	54.17	51.79	39.68	41.45	39.75	41.45	42.34	55.92	59.79	57.31	53.28	51.37	44.54	100.00

Table 27

Slopes of linear regression lines relating noise levels on individual pavements

Slope	DRD11	DRD12	DRD13	DRD14	DRD15	DRD16	DRD17	DRD18	DRD19	DRD20	DRD21	DRD22	DRD23	DRD24	DRD25	DRD26	DRD27	DRD28	DRD29	DRD30	DRD31	STF11	STF12	STF13	STF14	STF15	STF16	STF17	STF18	STF19	STF20	TUG11	TUG12
DRD11	1.00	0.94	0.92	0.97	0.98	0.86	0.97	0.96	0.94	0.90	0.87	0.99	0.98	0.93	0.85	0.95	0.84	0.89	0.93	1.02	0.98	0.67	0.70	0.72	0.80	0.72	0.76	0.82	0.72	0.76	0.74	0.50	0.83
DRD12	1.04	1.00	0.96	1.02	1.02	0.93	1.00	0.99	0.98	0.92	0.92	1.04	1.03	0.97	0.88	0.96	0.85	0.90	0.95	1.06	1.01	0.72	0.75	0.77	0.84	0.77	0.79	0.85	0.76	0.80	0.77	0.54	0.90
DRD13	1.03	0.98	1.00	1.03	1.04	0.95	1.05	0.99	0.97	0.94	0.93	1.06	1.05	1.02	0.92	0.99	0.86	0.93	0.97	1.07	1.03	0.72	0.75	0.78	0.86	0.78	0.78	0.84	0.75	0.77	0.74	0.57	0.93
DRD14	0.99	0.94	0.93	1.00	1.00	0.89	0.97	0.96	0.95	0.92	0.89	1.00	1.00	0.95	0.87	0.94	0.85	0.89	0.94	1.03	1.00	0.71	0.74	0.76	0.84	0.75	0.76	0.80	0.71	0.76	0.73	0.52	0.84
DRD15	0.99	0.94	0.93	1.00	1.00	0.89	0.98	0.96	0.95	0.91	0.89	1.00	1.00	0.95	0.87	0.94	0.84	0.88	0.93	1.03	0.98	0.71	0.74	0.76	0.84	0.75	0.77	0.81	0.72	0.77	0.74	0.51	0.84
DRD16	0.98	0.96	0.97	1.00	1.00	1.00	0.98	0.94	0.96	0.85	0.93	1.03	1.00	0.97	0.86	0.88	0.78	0.83	0.86	1.02	0.96	0.77	0.77	0.80	0.84	0.79	0.77	0.80	0.73	0.77	0.74	0.56	0.93
DRD17	0.94	0.89	0.91	0.94	0.94	0.85	1.00	0.92	0.89	0.93	0.82	0.96	0.97	0.93	0.84	0.98	0.86	0.92	0.97	1.02	0.99	0.61	0.65	0.70	0.78	0.67	0.69	0.76	0.67	0.69	0.66	0.59	0.86
DRD18	1.00	0.94	0.91	0.98	0.99	0.86	0.98	1.00	0.97	0.95	0.86	0.98	0.98	0.91	0.85	0.97	0.89	0.92	0.97	1.05	1.01	0.69	0.71	0.73	0.82	0.73	0.74	0.79	0.70	0.75	0.73	0.56	0.84
DRD19	0.95	0.91	0.88	0.96	0.95	0.86	0.93	0.95	1.00	0.97	0.84	0.96	0.95	0.86	0.79	0.97	0.94	0.94	0.99	1.08	1.03	0.70	0.71	0.74	0.82	0.73	0.74	0.74	0.68	0.74	0.72	0.62	0.82
DRD20	0.73	0.67	0.68	0.73	0.72	0.60	0.77	0.74	0.77	1.00	0.58	0.74	0.80	0.69	0.65	0.96	0.94	0.94	1.01	0.96	0.99	0.46	0.49	0.55	0.65	0.51	0.51	0.57	0.48	0.52	0.50	0.65	0.62
DRD21	1.01	0.97	0.96	1.01	1.02	0.95	0.98	0.96	0.96	0.83	1.00	1.09	1.06	1.00	0.91	0.89	0.78	0.83	0.87	1.02	0.95	0.79	0.81	0.82	0.88	0.83	0.82	0.85	0.78	0.83	0.80	0.47	0.89
DRD22	0.89	0.86	0.86	0.89	0.90	0.82	0.89	0.85	0.85	0.83	0.85	1.00	0.99	0.91	0.84	0.89	0.76	0.82	0.86	0.96	0.92	0.66	0.69	0.71	0.78	0.72	0.70	0.75	0.67	0.71	0.68	0.47	0.79
DRD23	0.85	0.81	0.81	0.85	0.86	0.76	0.86	0.82	0.81	0.86	0.79	0.94	1.00	0.89	0.83	0.90	0.77	0.82	0.88	0.94	0.92	0.61	0.64	0.67	0.75	0.67	0.67	0.73	0.63	0.67	0.64	0.51	0.76
DRD24	0.91	0.87	0.89	0.91	0.92	0.84	0.93	0.85	0.83	0.83	0.84	0.98	1.01	1.00	0.87	0.91	0.75	0.82	0.86	0.94	0.92	0.65	0.70	0.74	0.81	0.72	0.71	0.80	0.70	0.71	0.69	0.49	0.89
DRD25	0.98	0.92	0.95	0.99	0.99	0.87	1.00	0.94	0.89	0.93	0.91	1.07	1.11	1.03	1.00	0.96	0.80	0.87	0.93	1.01	1.00	0.70	0.74	0.77	0.85	0.77	0.76	0.83	0.73	0.76	0.73	0.48	0.82
DRD26	0.75	0.69	0.70	0.74	0.74	0.62	0.80	0.74	0.76	0.95	0.61	0.78	0.82	0.74	0.66	1.00	0.92	0.95	1.01	0.97	0.98	0.45	0.49	0.56	0.65	0.52	0.55	0.65	0.55	0.56	0.54	0.66	0.70
DRD27	0.70	0.64	0.64	0.70	0.69	0.58	0.74	0.71	0.77	0.97	0.57	0.70	0.74	0.64	0.58	0.97	1.00	0.98	1.03	0.98	0.99	0.43	0.46	0.53	0.62	0.48	0.51	0.55	0.48	0.51	0.50	0.71	0.65
DRD28	0.75	0.69	0.70	0.74	0.74	0.62	0.79	0.74	0.78	0.98	0.61	0.76	0.80	0.71	0.64	1.01	0.99	1.00	1.05	1.00	1.01	0.45	0.49	0.55	0.64	0.50	0.54	0.61	0.52	0.54	0.52	0.69	0.68
DRD29	0.70	0.64	0.65	0.69	0.69	0.57	0.75	0.70	0.73	0.93	0.57	0.71	0.76	0.66	0.60	0.95	0.92	0.93	1.00	0.94	0.95	0.41	0.45	0.51	0.61	0.47	0.50	0.58	0.48	0.50	0.49	0.66	0.64
DRD30	0.80	0.75	0.74	0.79	0.79	0.70	0.81	0.78	0.82	0.93	0.68	0.82	0.85	0.74	0.68	0.95	0.91	0.92	0.98	1.00	0.98	0.52	0.55	0.59	0.67	0.57	0.59	0.65	0.56	0.59	0.58	0.64	0.72
DRD31	0.77	0.72	0.72	0.77	0.76	0.66	0.80	0.76	0.80	0.96	0.65	0.80	0.84	0.74	0.68	0.96	0.93	0.94	1.00	0.99	1.00	0.49	0.52	0.57	0.66	0.54	0.57	0.63	0.53	0.56	0.54	0.65	0.71
STF11	1.01	0.99	0.96	1.05	1.05	1.01	0.94	1.00	1.04	0.86	1.03	1.09	1.05	0.99	0.91	0.85	0.78	0.80	0.83	1.01	0.94	1.00	1.01	1.03	1.13	1.05	0.86	0.85	0.81	0.89	0.86	0.47	0.87
STF12	1.00	0.96	0.95	1.03	1.04	0.96	0.95	0.97	1.00	0.87	1.00	1.08	1.05	1.01	0.91	0.88	0.79	0.82	0.85	1.00	0.94	0.95	1.00	1.04	1.14	1.03	0.86	0.87	0.81	0.88	0.85	0.45	0.86
STF13	0.89	0.86	0.86	0.92	0.92	0.86	0.88	0.86	0.89	0.84	0.87	0.97	0.96	0.93	0.82	0.87	0.78	0.81	0.84	0.94	0.90	0.85	0.90	1.00	1.09	0.96	0.75	0.80	0.74	0.78	0.75	0.45	0.78
STF14	0.79	0.75	0.76	0.82	0.82	0.74	0.79	0.78	0.80	0.80	0.76	0.85	0.86	0.82	0.73	0.80	0.74	0.76	0.80	0.86	0.83	0.74	0.80	0.88	1.00	0.86	0.66	0.71	0.64	0.68	0.66	0.45	0.72
STF15	0.91	0.88	0.88	0.94	0.94	0.89	0.87	0.89	0.91	0.80	0.91	1.00	0.98	0.93	0.85	0.82	0.73	0.76	0.80	0.93	0.87	0.89	0.92	0.99	1.09	1.00	0.78	0.81	0.75	0.81	0.78	0.42	0.82
STF16	1.17	1.11	1.07	1.16	1.17	1.06	1.10	1.10	1.12	0.99	1.10	1.20	1.19	1.13	1.01	1.08	0.95	0.99	1.04	1.18	1.11	0.89	0.94	0.94	1.03	0.95	1.00	1.04	0.95	1.01	0.97	0.57	1.03
STF17	1.04	0.98	0.95	1.00	1.02	0.89	0.99	0.96	0.93	0.90	0.93	1.06	1.08	1.05	0.92	1.04	0.84	0.92	0.98	1.06	1.01	0.72	0.78	0.82	0.91	0.82	0.85	1.00	0.85	0.86	0.84	0.53	0.96
STF18	1.19	1.12	1.09	1.15	1.17	1.06	1.12	1.10	1.09	0.98	1.10	1.22	1.20	1.17	1.03	1.12	0.94	1.01	1.05	1.18	1.11	0.88	0.94	0.98	1.05	0.97	1.01	1.10	1.00	1.02	0.99	0.56	1.07
STF19	1.14	1.09	1.04	1.13	1.14	1.02	1.06	1.08	1.10	0.96	1.08	1.17	1.15	1.09	0.99	1.05	0.92	0.96	1.01	1.15	1.08	0.89	0.93	0.95	1.04	0.96	0.98	1.02	0.94	1.00	0.96	0.53	0.99
STF20	1.18	1.12	1.06	1.16	1.17	1.05	1.09	1.12	1.13	0.99	1.11	1.21	1.19	1.12	1.01	1.08	0.95	0.99	1.04	1.19	1.11	0.91	0.95	0.97	1.06	0.98	1.00	1.05	0.97	1.03	1.00	0.53	1.01
TUG11	0.51	0.50	0.52	0.52	0.51	0.50	0.61	0.54	0.62	0.81	0.41	0.53	0.59	0.51	0.42	0.84	0.86	0.83	0.89	0.83	0.84	0.32	0.32	0.37	0.46	0.33	0.37	0.42	0.35	0.36	0.34	1.00	0.75
TUG12	0.70	0.68	0.70	0.69	0.69	0.69	0.74	0.68	0.68	0.64	0.64	0.73	0.73	0.76	0.59	0.74	0.65	0.67	0.71	0.77	0.75	0.48	0.51	0.53	0.61	0.54	0.56	0.63	0.55	0.55	0.53	0.62	1.00

Table 28

Intercepts of linear regression lines relating noise levels on individual pavements

inter-cept	DRD11	DRD12	DRD13	DRD14	DRD15	DRD16	DRD17	DRD18	DRD19	DRD20	DRD21	DRD22	DRD23	DRD24	DRD25	DRD26	DRD27	DRD28	DRD29	DRD30	DRD31	STF11	STF12	STF13	STF14	STF15	STF16	STF17	STF18	STF19	STF20	TUG11	TUG12
DRD11	0.00	4.84	8.37	3.06	2.47	12.76	4.71	6.22	7.79	13.01	11.07	1.02	3.23	7.89	15.84	7.20	18.96	13.59	8.84	-0.87	3.42	30.22	28.01	27.13	20.16	26.58	23.76	18.85	26.87	22.92	25.43	49.45	14.68
DRD12	-3.34	0.00	4.36	-0.60	-1.08	6.77	1.58	3.51	3.86	12.23	6.24	-3.60	-0.96	3.86	13.45	6.66	18.70	13.14	8.37	-3.73	1.55	25.45	23.89	23.38	16.70	22.45	20.72	16.55	24.41	19.97	22.67	46.43	8.78
DRD13	-2.79	1.14	0.00	-2.54	-3.15	3.90	-3.36	3.35	4.88	9.12	4.68	-6.22	-4.09	-1.64	8.63	2.89	16.28	9.83	4.99	-5.64	-1.57	25.48	22.57	20.70	13.81	20.70	21.69	16.60	24.74	21.59	24.60	42.46	4.27
DRD14	0.66	5.04	6.31	0.00	0.11	9.43	3.40	5.33	5.64	10.81	8.51	-0.64	0.92	5.47	13.16	7.54	17.15	13.03	8.22	-2.33	1.61	26.21	23.89	23.26	15.64	22.83	22.97	20.41	27.61	22.38	25.15	47.63	13.53
DRD15	0.44	4.94	6.12	0.48	0.00	9.40	3.03	5.56	6.53	12.05	8.18	-0.68	0.84	5.16	12.96	7.61	18.43	13.61	8.86	-1.56	2.67	26.38	23.69	23.17	15.76	22.64	22.33	19.15	26.51	21.69	24.47	48.29	13.56
DRD16	2.35	3.84	4.12	1.10	0.68	0.00	3.57	8.09	5.72	18.86	5.08	-2.24	2.17	3.82	15.32	13.71	24.78	19.94	16.37	0.33	6.24	21.25	21.57	20.36	16.19	19.51	22.50	21.44	26.44	22.25	25.36	44.49	4.88
DRD17	4.26	8.84	7.39	5.28	4.56	13.30	0.00	8.57	10.79	9.21	14.18	2.80	2.40	6.25	14.84	2.91	14.94	9.17	3.66	-2.17	0.96	34.99	31.28	28.03	20.85	29.99	28.61	22.75	31.05	28.50	31.25	39.66	10.36
DRD18	-1.60	3.58	6.50	-0.10	-0.24	10.75	1.42	0.00	2.68	5.88	9.87	-0.47	1.15	7.56	13.41	3.06	12.29	8.61	3.20	-5.51	-1.61	26.03	24.85	24.30	15.48	23.26	23.04	19.67	27.10	21.77	24.14	42.39	11.44
DRD19	2.99	6.74	10.66	3.14	3.69	11.22	6.63	5.53	0.00	4.54	11.96	2.37	4.27	12.68	19.87	3.23	7.84	7.31	2.36	-7.65	-3.33	25.15	25.13	23.97	16.23	23.48	24.13	24.51	29.51	23.15	25.67	36.38	13.80
DRD20	23.19	28.27	28.20	23.18	23.93	35.24	20.43	23.40	20.07	0.00	36.47	21.76	17.02	27.45	31.37	1.94	5.90	4.89	-1.53	1.13	-0.84	48.13	45.24	40.66	31.14	43.72	43.97	39.27	47.12	43.37	45.27	31.74	32.32
DRD21	1.49	4.36	5.98	1.13	0.37	6.16	5.64	8.24	7.60	21.66	0.00	-6.62	-2.23	2.93	11.39	14.59	26.14	21.04	16.78	1.76	8.40	20.37	18.72	19.68	13.83	17.40	19.14	17.99	23.64	18.10	20.99	54.38	10.95
DRD22	10.38	13.62	14.27	11.07	10.70	17.32	12.39	16.04	15.96	19.68	13.00	0.00	2.62	9.87	16.93	13.03	26.39	20.26	15.95	5.57	9.39	31.72	29.58	27.97	22.23	26.64	29.25	25.11	31.86	28.36	30.95	52.75	18.99
DRD23	13.62	16.95	17.12	13.69	13.30	21.84	13.27	18.52	18.71	15.75	17.61	4.15	0.00	10.11	15.91	10.75	24.16	18.51	12.85	5.73	7.81	35.57	32.59	30.88	23.20	30.09	31.29	25.79	34.49	31.07	33.58	47.84	21.04
DRD24	8.66	12.14	10.14	8.54	7.90	14.74	7.51	15.51	17.79	18.70	13.03	1.33	0.13	0.00	12.55	10.24	26.33	19.13	15.41	6.86	8.37	32.30	27.79	24.67	18.03	25.50	27.51	19.42	28.68	27.24	29.87	49.83	8.05
DRD25	1.30	6.36	4.45	0.68	0.07	11.11	0.79	6.55	10.94	9.37	5.91	-7.52	-10.36	-3.36	0.00	4.95	21.26	14.10	8.32	-0.83	0.87	26.59	22.83	21.29	13.62	20.35	22.86	16.46	25.75	22.07	25.00	51.10	14.87
DRD26	22.33	27.84	27.39	24.43	24.21	35.02	19.19	25.09	22.99	6.44	34.86	19.69	16.44	24.19	31.89	0.00	8.71	5.23	-0.26	1.97	1.68	50.97	46.83	41.22	33.02	44.58	41.71	33.16	42.52	41.29	43.23	32.41	25.73
DRD27	26.10	31.33	31.65	26.33	27.15	37.96	23.11	26.39	20.48	3.06	38.11	25.90	22.88	32.06	38.25	1.39	0.00	1.56	-3.60	-0.03	-0.70	50.82	48.28	42.70	33.78	46.97	44.44	40.99	47.58	44.34	45.78	25.97	29.82
DRD28	21.85	27.33	27.08	23.23	23.44	34.67	18.44	23.79	20.43	2.36	34.64	20.42	17.68	26.13	33.35	-1.99	1.91	0.00	-5.00	-1.59	-1.89	50.22	46.70	40.93	32.32	45.16	42.29	35.83	44.22	42.13	43.74	28.41	27.44
DRD29	26.89	32.04	31.85	28.13	28.35	39.46	23.24	28.34	25.60	7.41	38.97	25.61	21.90	31.43	36.90	4.24	8.31	6.78	0.00	4.23	3.70	54.04	50.65	45.25	36.28	48.61	46.28	39.63	48.40	45.82	47.68	31.87	31.40
DRD30	18.75	22.98	24.05	19.54	19.84	28.09	18.04	21.45	17.47	8.95	28.36	16.05	14.90	24.22	30.49	5.38	10.62	8.89	3.19	0.00	2.10	43.96	42.04	38.41	30.91	40.18	38.33	33.92	41.54	38.02	40.01	35.22	24.56
DRD31	21.00	25.70	25.83	21.45	21.99	31.21	19.38	23.23	19.61	5.77	31.97	18.21	15.57	24.34	30.62	3.75	8.73	7.33	1.27	0.72	0.00	47.07	44.64	40.32	32.12	42.78	40.93	35.91	44.00	40.87	43.04	33.52	25.50
STF11	2.18	3.53	7.02	-0.93	-1.10	1.13	10.24	5.08	0.70	20.45	-1.48	-6.00	-0.73	4.60	12.84	19.99	27.32	25.51	22.45	3.44	10.71	0.00	0.60	-0.53	-9.07	-3.68	16.16	19.04	21.64	13.31	16.77	55.88	14.32
STF12	2.50	4.88	6.59	-0.55	-1.22	4.98	8.06	6.81	4.15	18.23	0.07	-5.51	-1.91	1.53	11.27	15.49	25.49	22.21	18.81	3.39	9.49	4.07	0.00	-2.28	-11.62	-3.11	15.66	15.21	20.04	12.87	16.62	56.36	13.97
STF13	11.30	13.90	13.95	8.93	8.46	13.25	13.25	15.55	12.45	19.56	11.27	3.11	6.09	7.62	18.50	15.37	24.78	21.64	18.16	7.51	11.91	12.82	8.16	0.00	-8.29	2.67	24.59	20.94	26.00	21.35	24.69	55.09	19.78
STF14	20.47	23.44	23.45	18.07	17.87	25.31	21.78	22.59	20.90	22.79	22.25	14.48	14.50	17.74	26.68	20.67	28.07	25.92	21.36	14.89	17.68	22.81	18.19	11.57	0.00	12.51	33.13	29.07	35.45	30.27	33.20	54.73	25.95
STF15	10.68	12.93	14.04	8.42	7.83	12.39	15.80	14.45	11.93	24.26	8.82	1.22	4.95	8.68	17.64	20.63	31.14	27.88	23.75	10.31	15.81	10.20	7.43	2.60	-7.32	0.00	23.06	20.95	25.73	19.58	23.17	59.33	17.63
STF16	-16.36	-11.63	-6.47	-14.59	-16.00	-5.78	-7.81	-7.66	-9.48	5.29	-11.93	-19.25	-16.97	-11.32	-0.05	-5.12	8.86	4.22	-0.50	-16.08	-9.23	8.40	4.78	5.51	-2.27	3.34	0.00	-2.19	4.63	-1.18	2.63	43.44	-5.05
STF17	-4.89	0.47	3.84	-0.32	-2.30	9.03	0.94	4.60	7.64	12.26	3.81	-6.87	-7.16	-4.94	7.96	-2.73	17.33	9.03	3.54	-5.54	-0.72	24.61	18.64	15.85	7.92	15.67	13.24	0.00	13.13	11.61	14.54	45.48	0.25
STF18	-17.86	-12.44	-8.05	-13.63	-15.84	-6.06	-9.88	-7.49	-7.17	6.09	-11.78	-21.27	-17.63	-15.67	-1.63	-9.43	9.62	2.46	-1.66	-16.00	-9.13	9.38	4.56	2.07	-4.23	1.38	-0.74	-8.09	0.00	-2.86	0.82	43.86	-9.20
STF19	-13.22	-8.42	-2.55	-11.11	-12.56	-2.09	-3.88	-5.34	-6.73	7.87	-9.06	-16.23	-12.94	-7.52	2.78	-1.89	12.22	7.65	2.47	-12.28	-5.19	9.04	5.47	5.23	-2.64	2.89	2.69	-0.17	6.37	0.00	3.66	47.64	-0.74
STF20	-16.92	-11.86	-5.25	-14.35	-15.85	-4.65	-6.53	-8.95	-10.11	5.22	-12.42	-19.57	-16.07	-10.57	0.17	-5.01	8.88	4.30	-0.32	-15.88	-8.01	6.63	3.32	3.12	-4.94	0.87	0.01	-3.35	3.59	-2.89	0.00	47.30	-2.36
TUG11	47.05	47.92	46.23	46.66	47.12	47.70	37.83	45.15	37.42	20.15	55.51	45.43	39.62	47.27	56.38	16.46	15.64	18.03	12.07	16.87	15.94	65.08	64.73	60.68	52.36	63.64	60.45	55.81	62.69	61.71	63.79	0.00	21.73
TUG12	32.32	33.32	32.30	33.12	32.88	32.58	29.21	35.44	35.23	39.86	36.19	28.93	29.87	26.26	42.79	29.63	39.32	36.69	32.34	25.62	27.72	51.84	49.96	48.15	41.30	46.62	45.74	39.00	46.63	45.91	48.60	40.55	0.00

APPENDIX 8 – NOISE REDUCTIONS IN SCENARIOS A) - D)

Figure 27 shows the calculated tyre/road and propulsion noise levels at 110 km/h and 50 km/h in scenarios a) – d). The corresponding results for 80 km/h are shown in Figure 5. The balance between tyre/road and propulsion noise is in practice identical in scenarios b) and d).

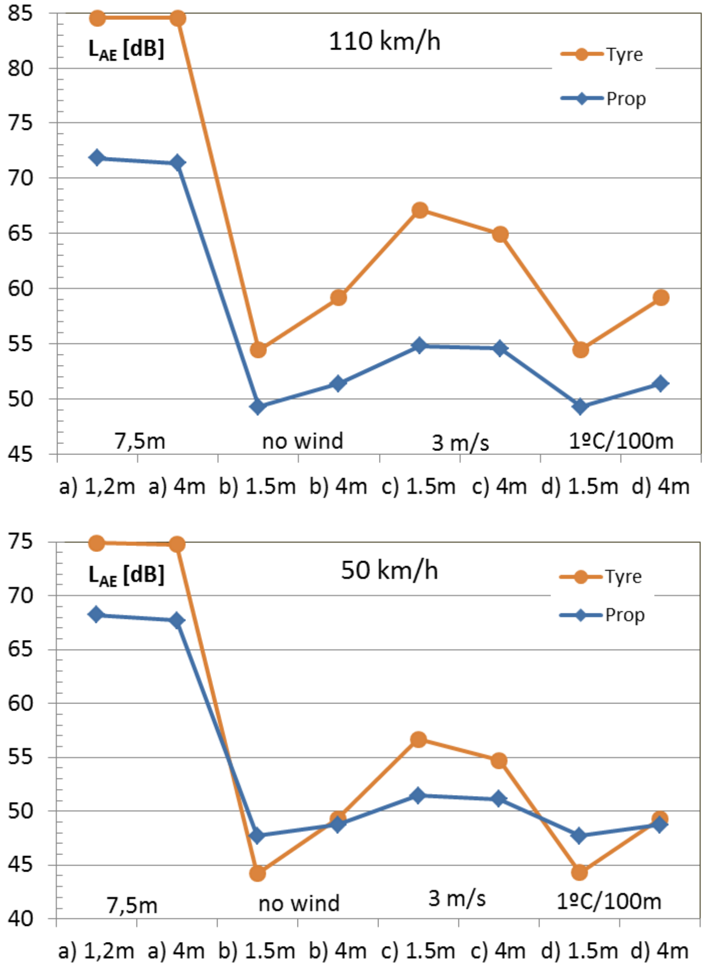


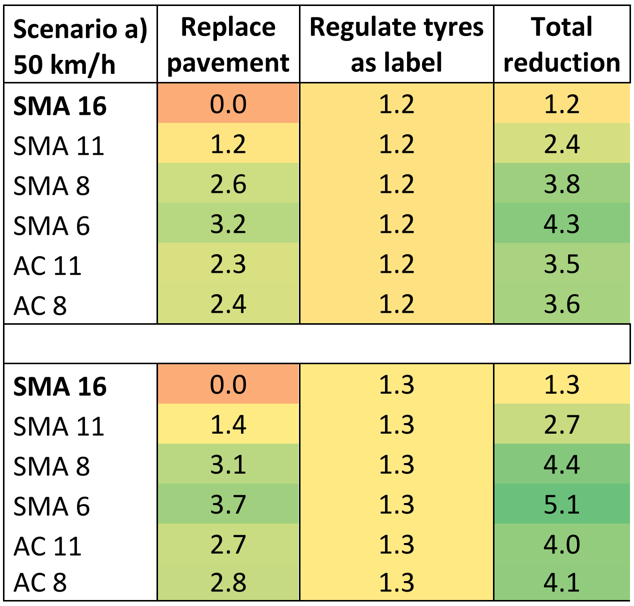
Figure 27

Tyre/road noise levels and propulsion noise levels at 110 km/h (top) and 50 km/h (bottom) in scenarios a) – d)

The combined effect of on passenger car pass-by noise levels of 1) replacing the pavement and 2) regulating the tyre use by removing all but the quietest tyre lines are shown in Table 29 - Table 31 for scenarios a), b) and c), respectively. The top parts of the tables give the noise reduction relative to the average noise level from of all tyres on SMA 16, while the bottom part has SMA 11 as a reference.

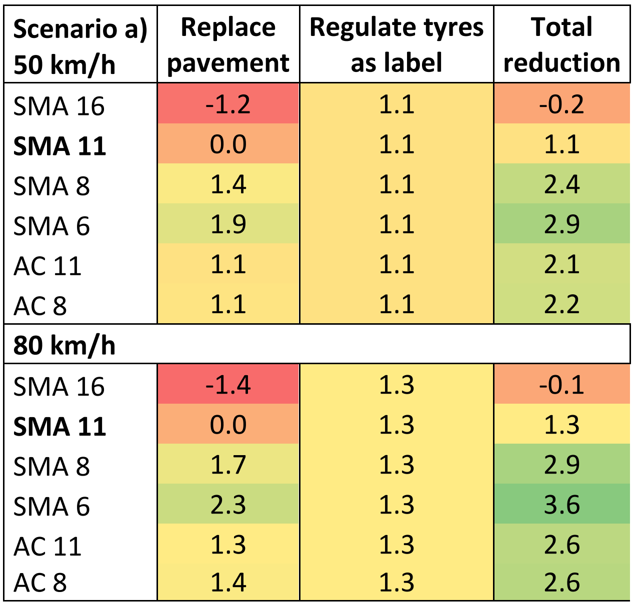
Table 29

Potential passenger car noise reduction, Scenario a); see Section 10.3. Reference = Norwegian SMA 16



Scenario a) 50 km/h	Replace pavement	Regulate tyres as label	Total reduction
SMA 16	0.0	1.2	1.2
SMA 11	1.2	1.2	2.4
SMA 8	2.6	1.2	3.8
SMA 6	3.2	1.2	4.3
AC 11	2.3	1.2	3.5
AC 8	2.4	1.2	3.6
SMA 16	0.0	1.3	1.3
SMA 11	1.4	1.3	2.7
SMA 8	3.1	1.3	4.4
SMA 6	3.7	1.3	5.1
AC 11	2.7	1.3	4.0
AC 8	2.8	1.3	4.1

Reference = Danish SMA 11



Scenario a) 50 km/h	Replace pavement	Regulate tyres as label	Total reduction
SMA 16	-1.2	1.1	-0.2
SMA 11	0.0	1.1	1.1
SMA 8	1.4	1.1	2.4
SMA 6	1.9	1.1	2.9
AC 11	1.1	1.1	2.1
AC 8	1.1	1.1	2.2
80 km/h			
SMA 16	-1.4	1.3	-0.1
SMA 11	0.0	1.3	1.3
SMA 8	1.7	1.3	2.9
SMA 6	2.3	1.3	3.6
AC 11	1.3	1.3	2.6
AC 8	1.4	1.3	2.6

Table 30: Potential passenger car noise reduction, Scenario b) or d); see Section 10.3. Reference = Norwegian SMA 16

Scenario b) or d) 50 km/h	Replace pavement	Regulate tyres as label	Total reduction
SMA 16	0.0	0.7	0.7
SMA 11	0.8	0.7	1.5
SMA 8	1.5	0.7	2.2
SMA 6	1.7	0.7	2.4
AC 11	1.3	0.7	2.1
AC 8	1.4	0.7	2.1
80 km/h			
SMA 16	0.0	1.1	1.1
SMA 11	1.2	1.1	2.2
SMA 8	2.4	1.1	3.5
SMA 6	2.9	1.1	4.0
AC 11	2.1	1.1	3.2
AC 8	2.2	1.1	3.3
110 km/h			
SMA 16	0.0	1.2	1.2
SMA 11	1.3	1.2	2.5
SMA 8	2.7	1.2	3.9
SMA 6	3.3	1.2	4.5
AC 11	2.4	1.2	3.6
AC 8	2.5	1.2	3.7

Reference = Danish SMA 11

Scenario b) or d) 50 km/h	Replace pavement	Regulate tyres as label	Total reduction
SMA 16	-0.4	0.3	-0.1
SMA 11	0.0	0.3	0.3
SMA 8	0.4	0.3	0.7
SMA 6	0.5	0.3	0.8
AC 11	0.3	0.3	0.6
AC 8	0.3	0.3	0.6
80 km/h			
SMA 16	-0.9	0.7	-0.2
SMA 11	0.0	0.7	0.7
SMA 8	0.9	0.7	1.7
SMA 6	1.3	0.7	2.0
AC 11	0.7	0.7	1.5
AC 8	0.8	0.7	1.5
110 km/h			
SMA 16	-1.1	1.0	-0.2
SMA 11	0.0	1.0	1.0
SMA 8	1.2	1.0	2.2
SMA 6	1.7	1.0	2.6
AC 11	1.0	1.0	1.9
AC 8	1.0	1.0	2.0

Table 31: Potential passenger car noise reduction, Scenario c), see Section 10.3. Reference = Norwegian SMA 16

Scenario c) 50 km/h	**Replace pavement**	**Regulate tyres as label**	**Total reduction**
SMA 16	0.0	0.9	0.9
SMA 11	1.0	0.9	1.9
SMA 8	2.0	0.9	2.9
SMA 6	2.4	0.9	3.3
AC 11	1.8	0.9	2.7
AC 8	1.8	0.9	2.8
80 km/h			
SMA 16	0.0	1.2	1.2
SMA 11	1.3	1.2	2.5
SMA 8	2.8	1.2	4.0
SMA 6	3.4	1.2	4.6
AC 11	2.5	1.2	3.7
AC 8	2.5	1.2	3.8
110 km/h			
SMA 16	0.0	1.3	1.3
SMA 11	1.4	1.3	2.7
SMA 8	3.0	1.3	4.3
SMA 6	3.6	1.3	4.9
AC 11	2.6	1.3	3.9
AC 8	2.7	1.3	4.0

Reference = Danish SMA 11

Scenario c) 50 km/h	**Replace pavement**	**Regulate tyres as label**	**Total reduction**
SMA 16	-1.1	1.0	-0.2
SMA 11	0.0	1.0	1.0
SMA 8	1.2	1.0	2.2
SMA 6	1.7	1.0	2.7
AC 11	1.0	1.0	1.9
AC 8	1.0	1.0	2.0
80 km/h			
SMA 16	-1.4	1.2	-0.1
SMA 11	0.0	1.2	1.2
SMA 8	1.6	1.2	2.9
SMA 6	2.2	1.2	3.5
AC 11	1.3	1.2	2.5
AC 8	1.3	1.2	2.6
110 km/h			
SMA 16	-1.4	1.3	-0.1
SMA 11	0.0	1.3	1.3
SMA 8	1.7	1.3	3.0
SMA 6	2.4	1.3	3.7
AC 11	1.3	1.3	2.6
AC 8	1.4	1.3	2.7

APPENDIX 9 – CPX NOISE LEVELS VS. CPB AND CB NOISE LEVELS

A.9.1 FRENCH MEASUREMENTS OF CPX AND CPB NOISE LEVELS

To establish the relation between CPX noise levels and Controlled Pass-By (CPB) noise levels a series of measurements were made by LCPC on a dense and a porous asphalt concrete surface, respectively, [16]. Some of the results are illustrated in Figure 28. A total of eight runs were made with a vehicle fitted with four passenger car tyres (Michelin Energy XH1 195/60/R15) at speeds between 70 km/h and 110 km/h. Both CPX (at one of the four vehicle tyres) and CPB noise levels (at 7.5 m distance) were measured at the standard microphone positions. The CPX noise levels are L_{Aeq} averaged over 20 m while the Controlled Pass-By noise level is L_{AFmax} recorded during the pass-by. The differences between the overall A-weighted noise levels were found to be CPX-CPB = 22.5 dB on the dense road surface and 23.3 dB on the porous road surface. The paper [16] also gives the noise level differences in 1/1 octave-bands.

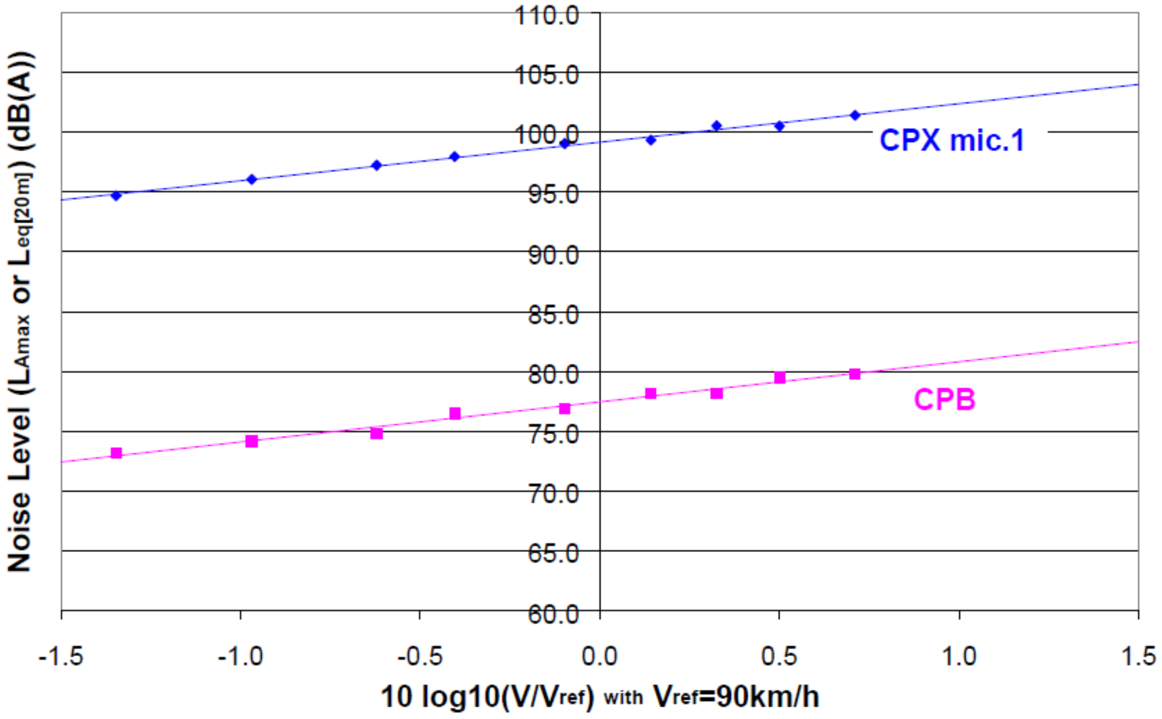


Figure 28

CPX noise levels and CPB noise levels as a function of the (logarithm of the) vehicle speed while cruising at constant speed on dense asphalt, [16]

In 2004-05 LCPC carried out more comprehensive series of similar measurements in a project denoted Predit and in 2006 in a project denoted Deufrako [18]. In Predit the average difference between CPX and CPB noise level was 21.8 dB with 1.4 dB standard deviation on nine non-porous pavements, and 23.5 dB with 0.3 dB standard deviation on three porous asphalts. In Deufrako the average difference was 21.9 dB with 0.2 dB standard deviation on nine pavements including two porous asphalts. The average difference on these two porous asphalts was 22.1 dB.

Thus, for non-porous pavements and for some porous asphalt pavements the typical difference between CPX and CPB noise levels in the French data is 22 dB.

A.9.2 DANISH MEASUREMENTS OF CPX AND SPB NOISE LEVELS

This 22 dB difference in noise levels derived from the French data is in line with the data in Figure 29. The figure shows the relation between more than 90 individual measurements of CPX_{SRTT}, the CPX noise levels measured with Standard Reference Test Tyres (SRTT), and the pass-by (SPB) noise levels from passenger cars cruising at constant speed. These measurements were made by DRD in 2010 - 2011 by on 45 -50 different dense or semi-dense asphalt pavements. The CPX noise levels measured at 80 km/h were on an average 21.5 dB higher than the average pass-by noise levels from cruising cars. This is a slightly smaller average difference than found in the French measurement series. This could be because an average Danish car had more or less worn tyres generating higher noise levels than the French CPX vehicle tyres and/or that SRT tyres used in the Danish measurements generate slightly lower noise levels than an average car tyre.

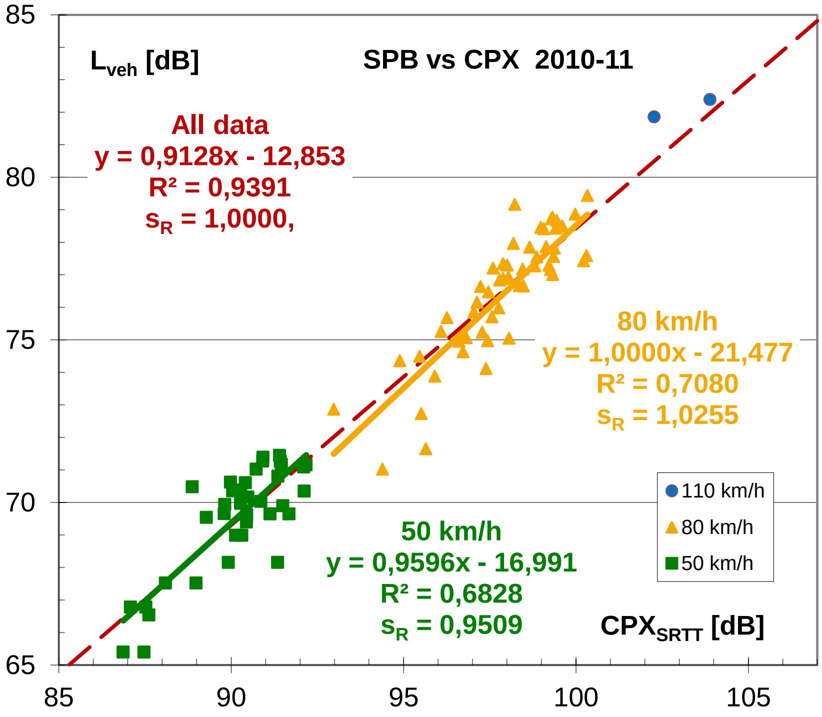


Figure 29

Relation between CPX noise levels measured with standard reference test tyres SRTT and pass-by noise levels measured 2010 - 2011 on Danish road surfaces, dense and semi-porous asphalt pavements

A.9.3 COAST-BY VS CPB NOISE LEVELS

Noise labelling of car tyres is based on Coast-By (CB) noise levels at 80 km/h. The CB noise level should be approximately 0.5 dB lower than the total pass-by noise level (be it the SPB or CPB noise level) from the tyre/road contact plus the propulsion system, see Figure 4.

A.9.4 NOISE LEVEL OFFSET IN TRAILER AND COAST-BY NOISE MEASUREMENT

For the purpose of the present project it was presumed that CPX trailer noise levels can be translated to Coast-By noise levels as used for tyre noise labelling by subtracting 22.5 dB. This was based on the French measurements mentioned in Section A.9.1 and that the CB noise level is 0.5 dB lower than the SPB noise level. These French CPX measurements were made with a self-propelled vehicle also used for the CPB measurement, and therefore the tyre load and the tyre inflation pressure was the same in CPX and CPB measurement.

> Note 1: Late in the project it became clear that a direct relation between CPX noise levels and CB noise levels cannot necessarily be expected when CPX and CB noise measurements are made with different tyre loads and tyre inflation pressure. See Section 14.

> Note 2: LEO results from 2014 [19] indicated that with CPX standard (ISO 11819-2) conditions then the trailer noise levels are on the average 1.0 dB lower than under labelling (R117) conditions. In that case only 21.5 dB should have been subtracted, not 22.5 dB which was actually done; see the following section.

APPENDIX 10 - COMPLIANCE WITH DIRECTIVE NOISE LIMITS

The noise label values declared by manufacturers are compared with the Directive noise limits in Figure 30. Noise limits depend on tyre size (C1A or; C1B-C) and tyre type (S/A or W). Seven tyres had label values exceeding the Directive noise limit. The tyres were procured in May 2012, the Directive entered into force in November 2012, and tyre labels were read from manufacturers' websites in January 2013.

Figure 31 shows NordTyre trailer measurement results from the test track in Hällered. These noise levels were translated into Coast-By noise levels as mentioned in Section A.9.4. These translated results are shown (in blue) in Figure 32. In accordance with the tyre Directive, the measurement results were truncated and 1 dB was subtracted, yielding the results shown in green. Nine of these results exceeded the Directive noise limit, and two of these were among the seven tyres having noise label values exceeding the limits in Figure 30.

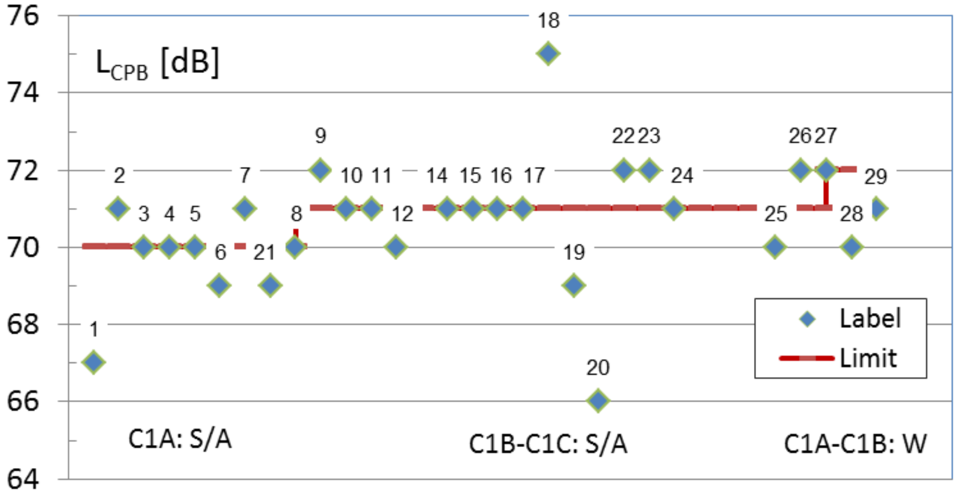


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Figure 30

Manufacturer labels and Directive noise limits for the investigated tyres of various sizes (C1A-C) and types; S = Summer; A = All-year; W= Winter

A.10.1 REQUIREMENTS ON TYRE LOAD AND INFLATION PRESSURE

For labelling of tyres, noise levels shall be measured during coast by of a test vehicle having four wheels on two axles. The average test load Q_t for the tyres shall be 75 % ± 5 % of the tyre reference load Q_r. The tyre reference load Q_r corresponds to the load capacity index of the tyre. These indices are listed in Table 16 for the tyres used in the NordTyre project. They vary between LI = 75 corresponding to a tyre reference load of 388 kg, and LI = 98 corresponding to a tyre reference load of 752 kg. Thus, for labelling measurements, the average tyre load should be between 0.75·388 = 291 ± 19 kg for the smallest tyre and 0.75·752 = 564 ± 38 kg for the widest tyres.

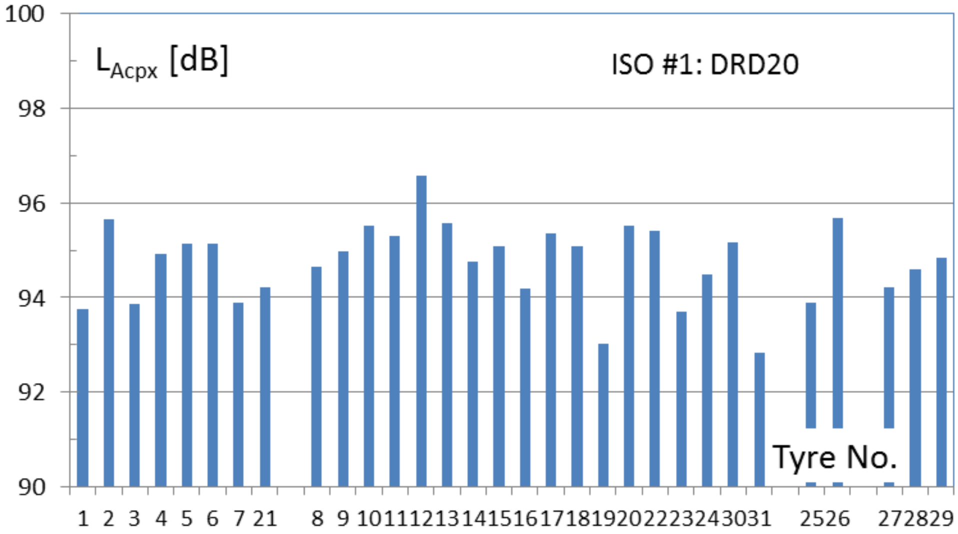

Figure 31

Trailer measurement results from the ISO #1 test track

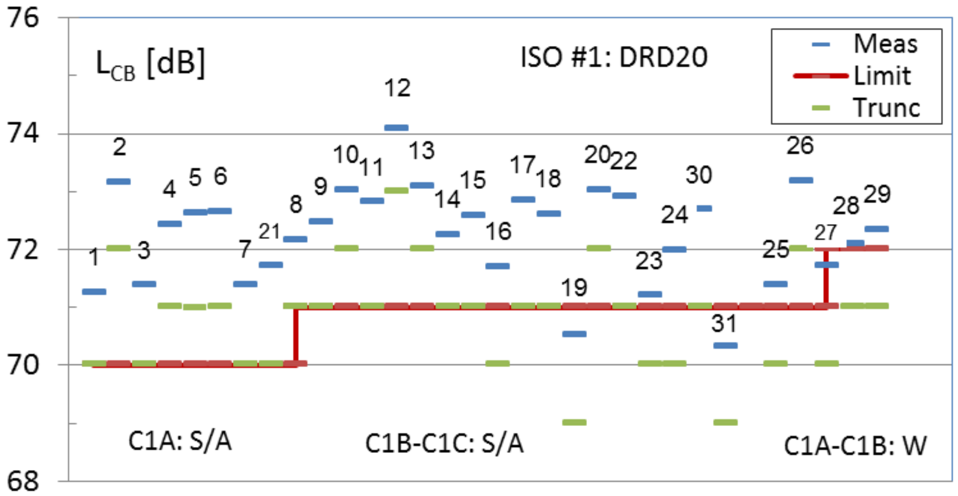

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Figure 32

Trailer results translated into coast-by noise levels, truncated and rounded down, compared with the Directive noise limits

For CPX noise measurements using reference tyres a load of 3200 kN ± 200 kN (326 ± 20 kg) is prescribed in ISO 11819-2 and this load was applied in the NordTyre trailer noise measurements. The tyre inflation pressure was 200 kPa ± 10 kPa as prescribed, in cold condition.

The *tyre load* applied in the NordTyre CPX noise measurements differed from those required for noise labelling CB measurements. These deviations are illustrated in Figure 33. The upper part of the figure shows the relation between the tyre load index and the tyre load capacity. The bottom part shows the average tyre load Q_t required during noise labelling CB noise measurements, i.e. 75% of the load capacity, and the error bars show the allowed load intervals of ± 5 %. The dashed line marks the specified tyre load 3200 kN for CPX noise measurement. The applied tyre load during the CPX noise measurements was too high for noise labelling measurements for the smallest tyre and too low for the remainder of tyres. File: <C:\JK\Tyre_road\Tire_Directive\ Tyre_load_index_feb14.xlsx>

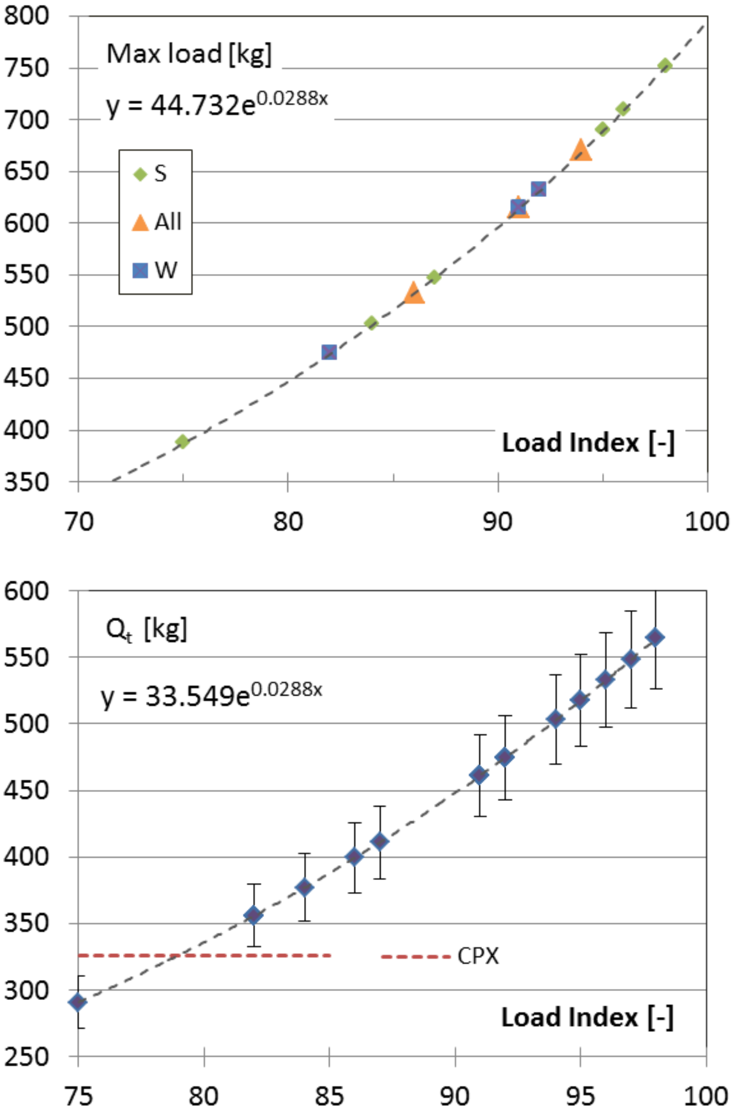


Figure 33

Relation between load Index and load capacity (maximum permissible load) (top) and required average tyre load Q_t (bottom)

The *tyre inflation pressure* applied during the NordTyre CPX noise measurements was 200 kPa. For tyre noise labelling measurements the test pressure P_t shall be in the interval given by Eq. (1)

$$P_r \cdot \left(\frac{Q_t}{Q_r}\right)^{1.25} \leq P_t \leq 1.1\, P_r \cdot \left(\frac{Q_t}{Q_r}\right)^{1.25}$$

Eq. (1)

where the reference pressure P_r is the pressure corresponding to the pressure index on the tyre sidewall. For Class C1 P_r = 250 kPa for "standard" tyres and 290 kPa for “reinforced” tyres. This implies that tyre inflation pressure P_t during noise labelling CB measurement shall be

$160 \leq P_t \leq 208$ kPa for “standard” tyres; $186 \leq P_t \leq 241$ kPa for “reinforced” tyres

For the standard tyres dealt with in NordTyre the inflation pressure required for noise labelling measurements is the around the same or slightly lower than the 200 kPa applied during NordTyre CPX noise measurements.

The authors do not know the origin of the requirement to measure with a load of 75 % of the load index and corresponding inflation pressure. For a medium class car such as a 2015 VW Golf 1.2 TSI the net weight of the car is 1205 kg. With a driver inside its minimum weight is below 1300 kg. Its maximum permissible weight is 1720 kg. This implies an average load of 325 – 430 kg per wheel. The tyres specified for such a vehicle are 195/65 R15 T which could have a load index in the range 91 – 93. LI = 92 means maximum permissible load 630 kg; 75 % of which is 472.5 kg, i.e. the required load for noise labelling measurement of such a tyre is 10 % higher than the maximum permissible load of the car. The load used in NordTyre for CPX measurements corresponds to the minimum average load of such a tyre on such a vehicle.

A.10.2 IMPORTANCE OF DEVIATIONS AND POSSIBILITIES TO CORRECT FOR THEM

The above deviations in tyre load / tyre inflation pressure requirements led to comments, received late in the project, that NordTyre CPX noise levels measured on ISO test tracks could not in fact be expected to correlate with manufacturers’ noise label values. These comments could be summarised in the following statement: “While it may be OK to compare road surfaces by means of CPX measurement, even when applying other tyres than specified in the draft CPX standard, it does not make sense to try to compare the noise emission from different car tyre lines based on the results of CPX measurements. This came as an unpleasant surprise to project participants, in particular because the comments also stated that there is no way of correcting for the influence of such deviations.

Some information on the influence of variations in tyre load and tyre inflation pressure could be identified as mentioned in the following sections. This influence is probably due to differences in the size and shape of the tyre/road footprint, including different interactions between various parts of the tyre tread and the road surface, differences in the amplifying horn effect etc.

Donavan 2009

In [20] it was found for SRTT & Dunlop Winter Sport M3 tyres:

a) + 0.4 – 0.9 dB/100 kg extra load;
b) +0.7 dB/100 kPa extra inflation pressure

For the smallest tyre in NordTyre with LI = 75, the load should have been 291 kg, i.e. the load was 35 kg too high, corresponding to an overestimation of the noise level by 0.1 – 0.3 dB. The tyre inflation pressure was around 16 kPa too high, corresponding to an overestimation of the noise level by 0.1 dB. The overall overestimation thus may be judged to be 0.2 – 0.4 dB.

For the largest tyres in NordTyre with LI = 98, the load should have been 564 kg, i.e. the load was 238 kg too low, corresponding to an underestimation of the noise level by 1.0 – 2.1 dB. The tyre inflation pressure was around 16 kPa too high, corresponding to an overestimation of the noise level by 0.1 dB. The overall underestimation thus may be judged to be 0.9 – 2.0 dB.

Sandberg 2014

In [21] the following average dependencies were found for tyres SRTT, Avon AV4, and BF Goodrich MudTerrain on an ISO replica surface and on a surface dressing with 11 mm chippings:

a) With fixed inflation pressure:	+0.2 – 1.0 dB/100 kg
b) With fixed load:	+0.5 – 1.0 dB/100 kPa

de Graaff 2007

In an investigation [22] of many tyres with a range of load indices 75 – 98 a 0.7 dB average increase in CB noise level was seen, but with a large spread, see Figure 34.

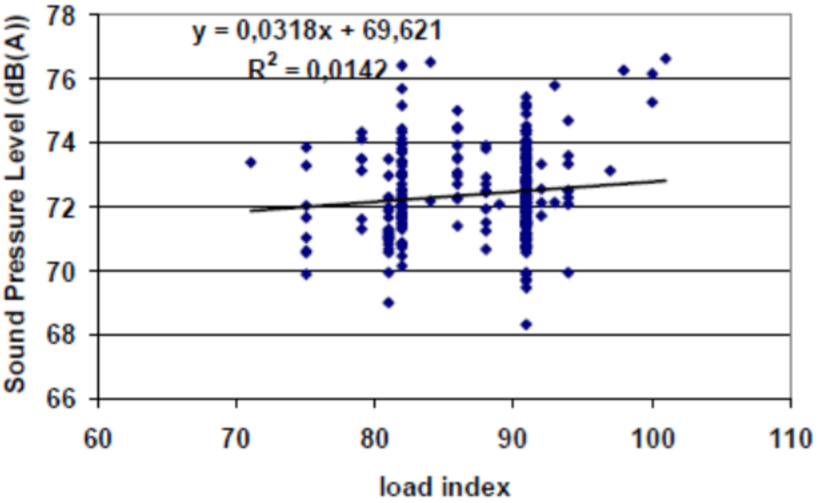


Figure 34

Measured CB noise level as a function of the tyre load index [22]

Summary

The trend in the data in Figure 34 is for a smaller variation between (average) noise levels from different tyres than the variations observed for the two individual tyres in the American investigation [20] and for the three tyres in the TUG measurement series [21]. These variations for individual tyres due to changes in tyre load and inflation pressure are of the same order of magnitude as the measured range in noise levels from the group of tyres measured in NordTyre.

A.10.3 AN ATTEMPT TO CORRECT FOR DEVIATIONS IN TYRE LOAD

Even though an attempt to correct the measured CPX noise levels for the deviations in tyre load and tyre inflation pressure did not seem likely to succeed such an attempt was made. Beginning with Figure 2 on p. 12, where the sum of R^2 from the two graphs in the top part of the figure $\Sigma R^2 = 0.023 + 0.0706 = 0.0936$, the ordinates were all corrected by a factor *x* dB per 100 kg that the actual trailer tyre load deviated from what the load should have been for a tyre labelling CB measurement, i.e. 75 % of the load corresponding to the tyre load index. For each correction value *x*, the sum of the correlation coefficients R^2 was calculated. The results are shown in Figure 35. The figure illustrates that no matter which correction was applied the sum of the correlation coefficients did not reach higher than 0.23, meaning that the variation in label values only explains about 10 % of the variation in the trailer CPX noise levels, no matter whether they are corrected or not for the deviations in tyre load. Figure 36 shows how the results from Figure 2 look after having been corrected by 1.4 dB per 100 kg load deviation. In this case $\Sigma R^2 = 0.0905 + 0.1379 = 0.23$ which for all practical considerations is the same as a lack of correlation.

If the analyses had been limited to the sub-set of tyres for which the trailer tyre load deviated least from the required tyre load, i.e. tyres #1-7; 14; 25-26, the results would look like those in Figure 37. For the smallest tyre the load was 35 kg too high and for the largest tyre it was 51 kg too low, corresponding to 12 % and 14 % of Q_t, respectively. The correlation coefficients for this small subset of data is higher than for the total set of data, but even for this subset only 20 – 25% of the variation in CPX trailer measurements are explained by the variation in noise label values. The data in Figure 37 have not been corrected for the load deviations, and applying corrections like those in Figure 36 - Figure 35 would only reduce, not increase R^2.

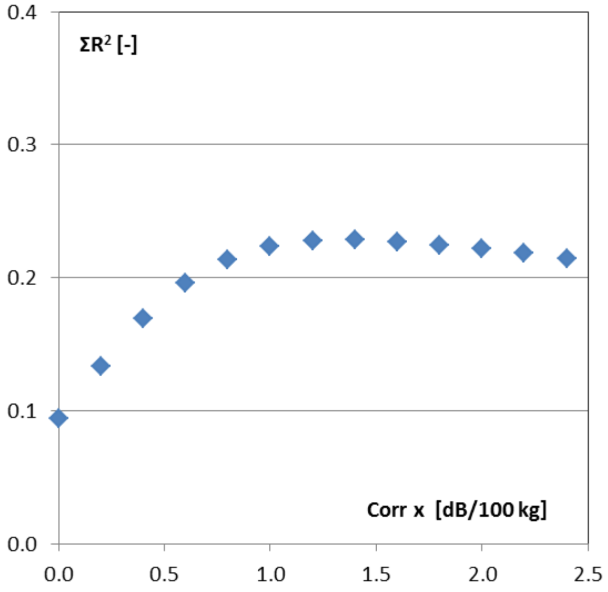


Figure 35

Sum of R^2 as in Figure 2 as a function of the correction value *x* dB per 100 kg of actual tyre load deviation from 75 % of the load corresponding to the tyre load index

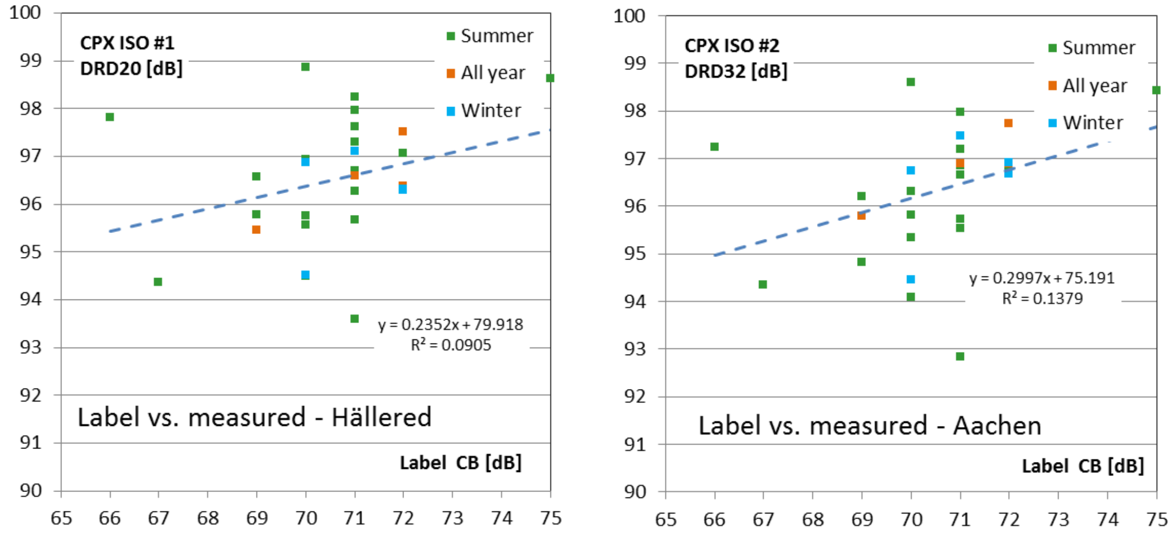


Figure 36

Modified Figure 2: All DRD measurement results have been modified by 1.4 dB per 100 kg of actual tyre load deviation from 75 % of the load corresponding to the tyre load index

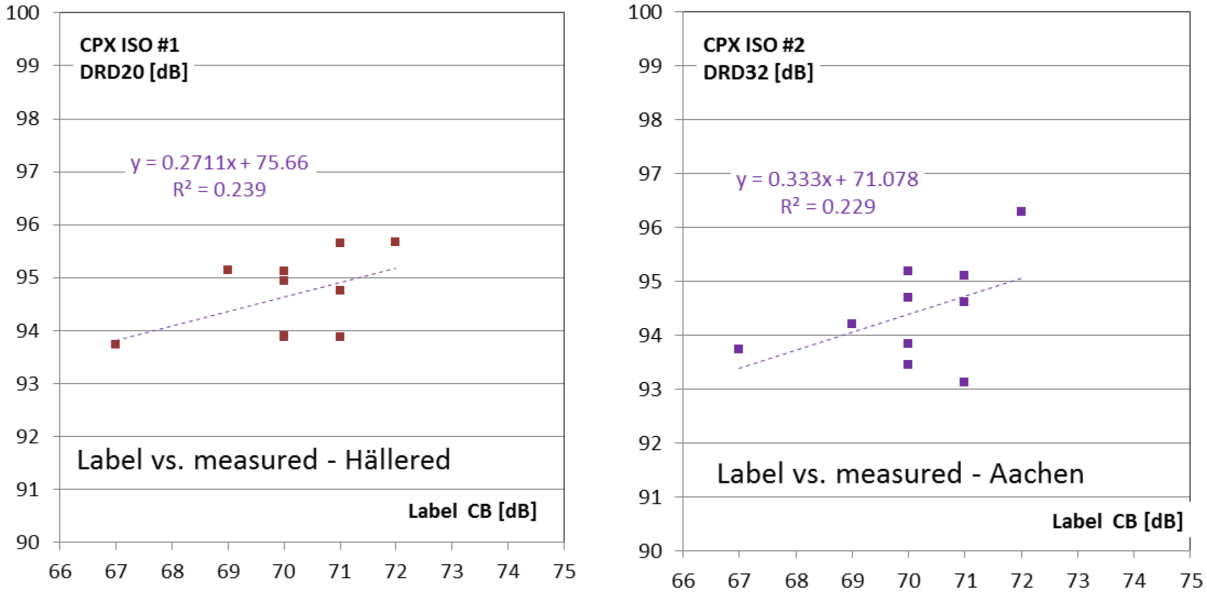


Figure 37

CPX noise levels measured on the two ISO tracks as a function of manufacturers, noise levels for a subset of tyres (tyres #1-7; 14; 25-26) with the smallest deviation between trailer load and required tyre load for labelling

A.10.4 RESULTS FROM POLISH – NORWEGIAN PROJECT “LEO”

In a joint Polish-Norwegian project LEO, “Low Emission Optimised tyres and road surfaces for electric and hybrid vehicles”, an experiment was carried out in which a number of car tyres were driven on various road surfaces while mounted on a CXP trailer with different loads [19]:

- "standard" load, measured as 339 kg per tyre, and "standard" tyre inflation pressure 200 kPa, according to ISO 11819-2
- with extra load and with tyre inflation pressure to satisfy the conditions for tyre labelling measurement according to ECE Reg.117, see Section A.9.4

Some results are shown in Figure 38 from a newly laid dense pavement not unlike an ISO test track. The correlation is excellent. There is a trend for the noise levels measured with extra load and adjusted inflation pressure to be 0.6 dB higher than those measured with standard load and standard inflation pressure. In similar sets of data from older, and therefore probably rougher pavements the correlation was slightly poorer, with $R^2 = 0.72 – 0.87$. This more or less excellent correlation contrasts the statement mentioned in Section 14.1 that no correlation should be expected, but the data in Figure 38 comprise noise levels from tyres having pretty much the same dimensions while the tyres selected for NordTyre included both smaller and larger tyres than the LEO project.

Figure 39 shows the CPX noise levels measured without or with extra load as a function of the tyre manufacturers' label values. Adding extra load on the trailer tyres increases correlation but less than 4% of the variation in trailer noise levels are explained by the tyre labels.

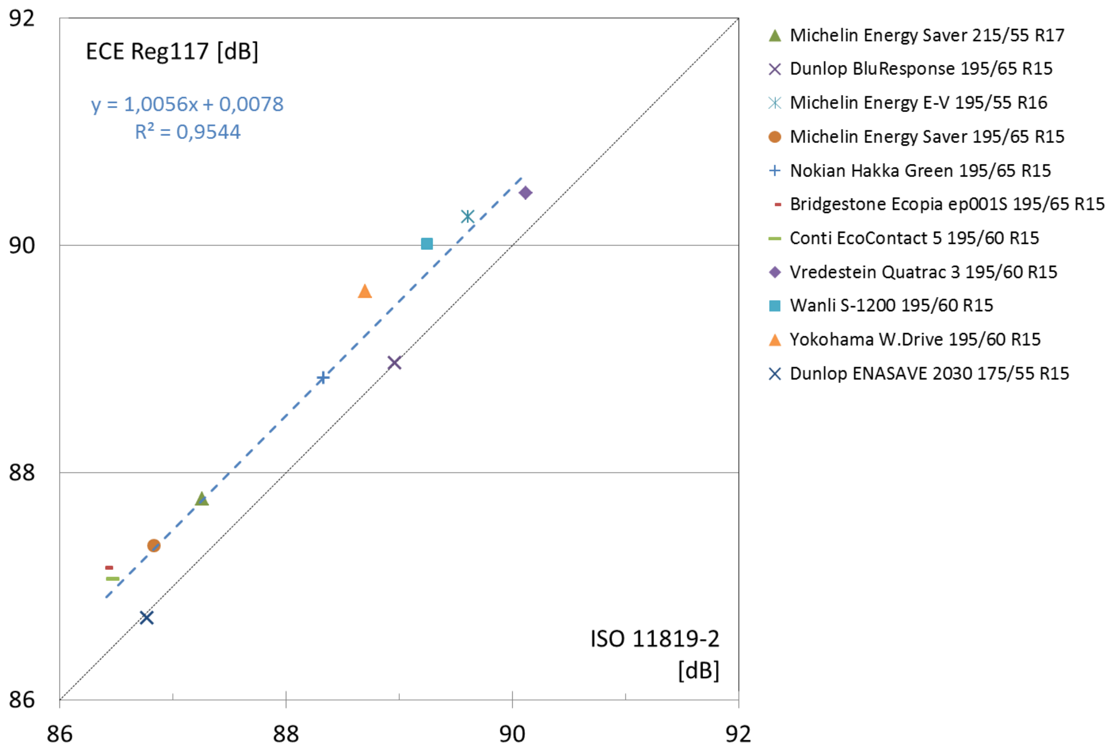


Figure 38

Example of trailer noise levels measured on SMA 8 pavement with an extra load added as a function of the trailer noise level measured with standard load according to ISO 11819-2. Data from [19]

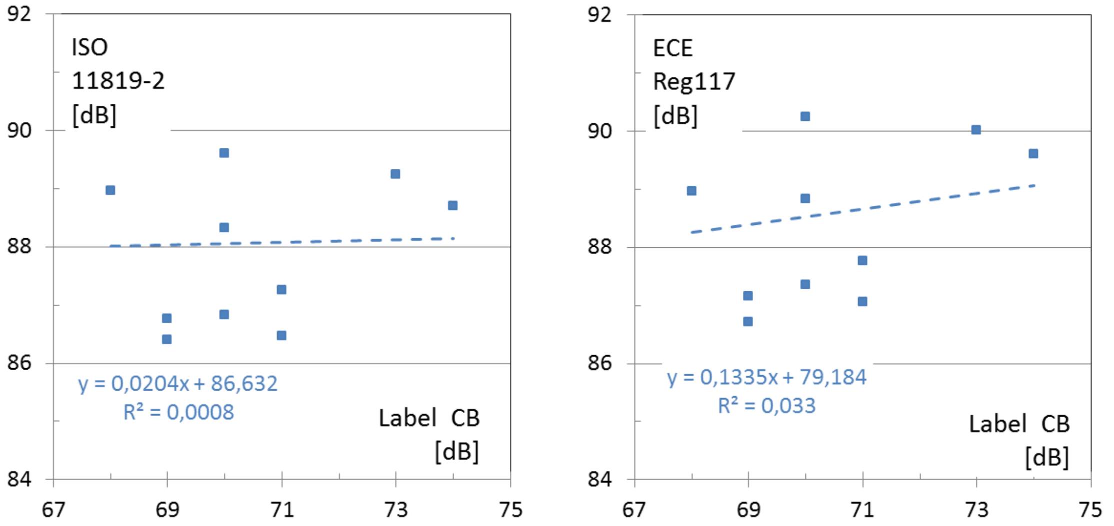


Figure 39

CPX noise levels measured in the LEO project without (left) or with (right) extra load as a function of the tyre label values. Data from [19]

Data in File: < K:\AD\BBM\BEF\Støj\Projekter\Nordtyre\SINTEF_data\LEO\Kragh_Kopiaf LEO_CPX with extra load_TrulsB_revised.xlsx>

APPENDIX 11 – SCATTER PLOTS

This appendix consists of figures with examples of scatterplots selected among the numerous possible choices of figures illustrating the interrelation between noise levels measured on 33 different pavements. Each scatterplot shows the noise level from each tyre line on one pavement as a function of the noise level measured on another surface. Data point signatures discriminate between summer, winter and all-year tyres. The regression line is shown in red colour and the percentage R^2 of explained variance is given in each diagram.

Figure 40Figure 40 shows, for each of the 24 pavements which are best represented by SMA 11 (see Table 25), the noise levels from each of the 31 selected tyres measured on that individual pavement as a function of the noise level measured on SMA 11 at Höör (DRD22).

Figure 41 shows the same type of scatterplots but with the noise levels measured on the ISO test track at Hällered (DRD20) as an independent variable, of the results from six sections best represented by the ISO track (see Table 25), supplemented with the results from SMA 6+8 at Herning-II (DRD 19) which were also included in Table 1. DRD19 was represented almost equally well by DRD20 and DRD22.

At the bottom of Figure 41the drum pavement results (TUG11 and TUG12) are shown, one with DRD20 and the other with DRD22 as an independent variable.

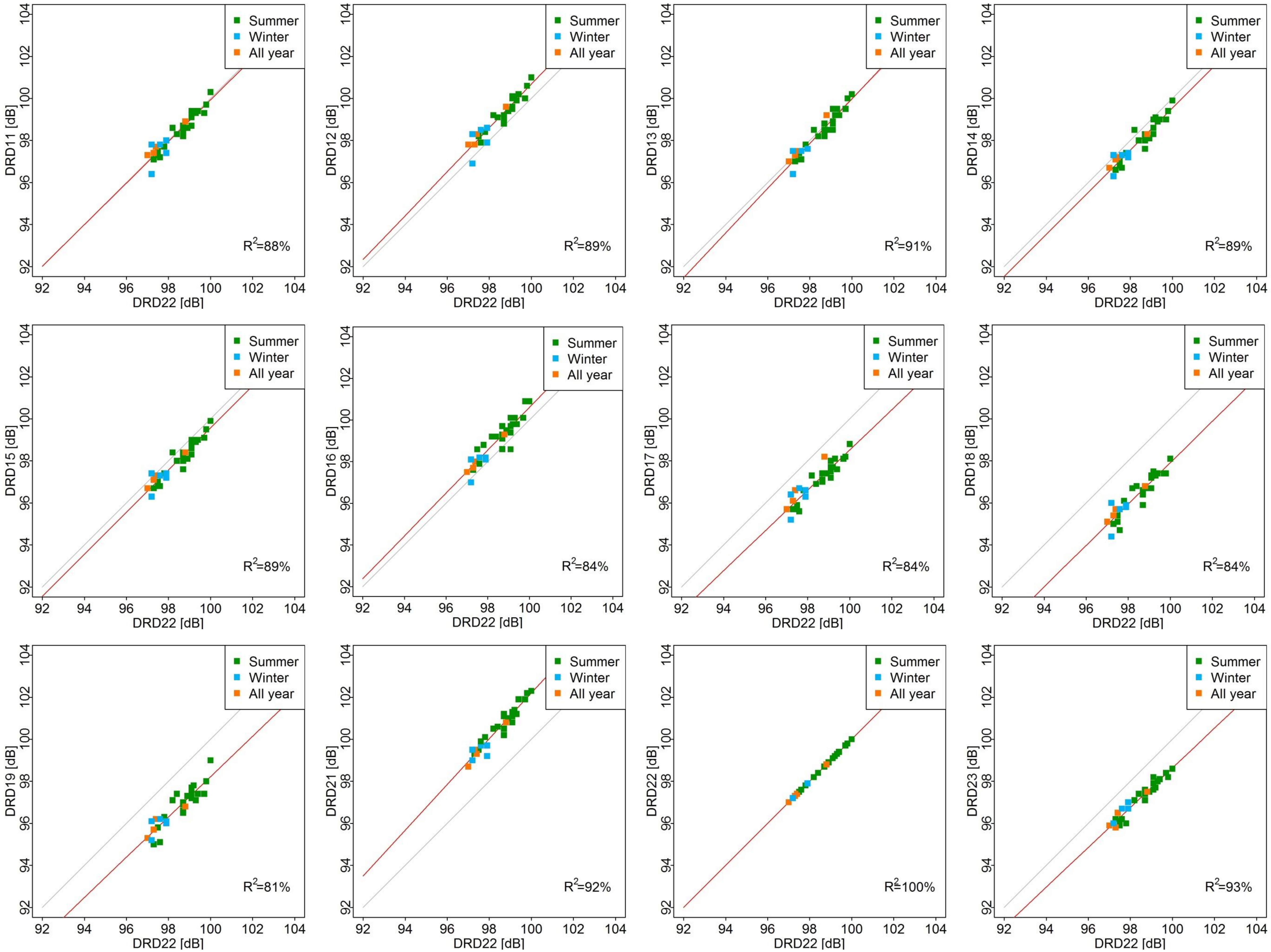
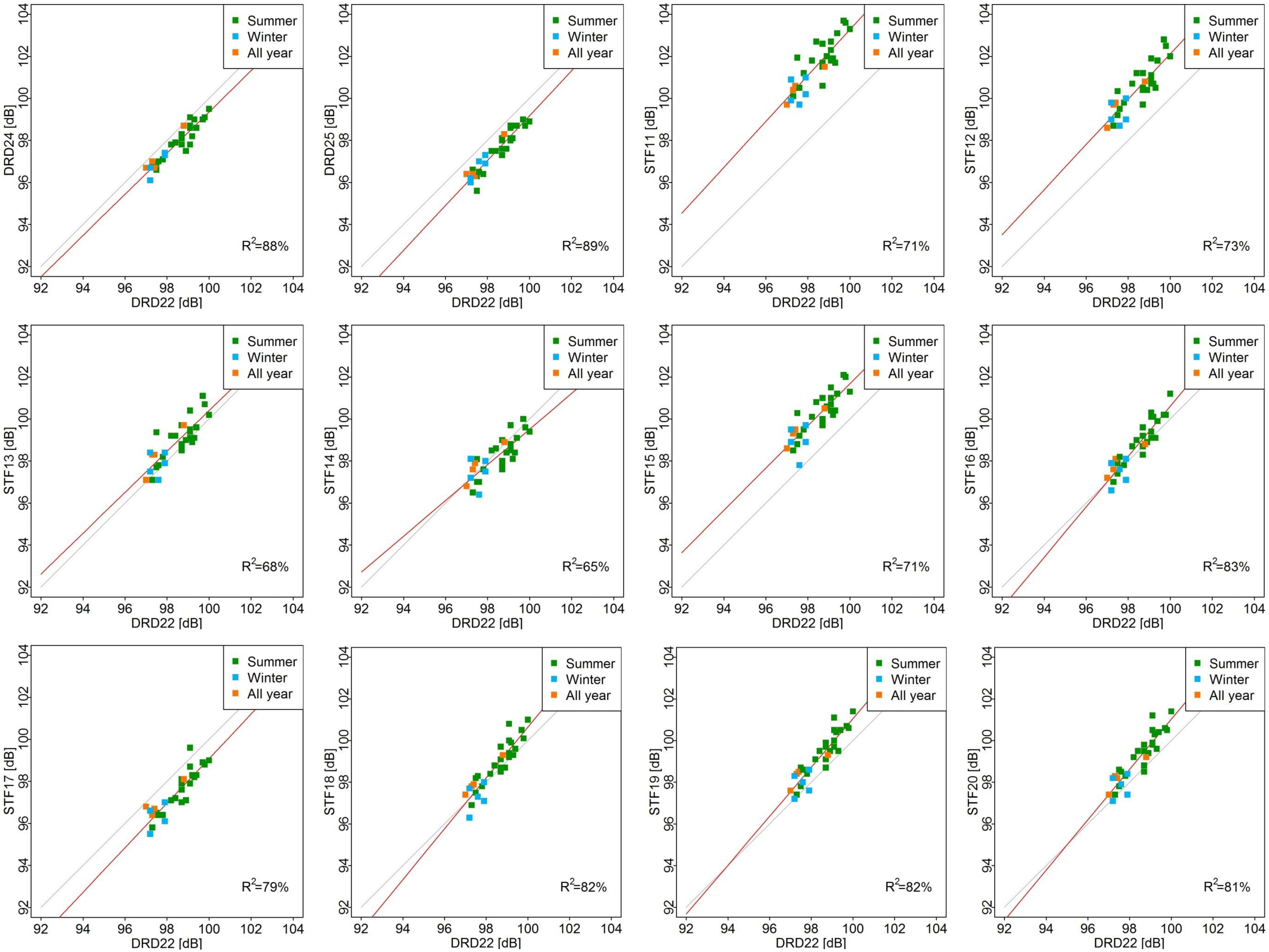


Figure 40

Noise levels from all 31 tyres on pavements in the group well represented by SMA11 a function of the noise level on SMA 11 (DRD22)

Figure 40 Continued



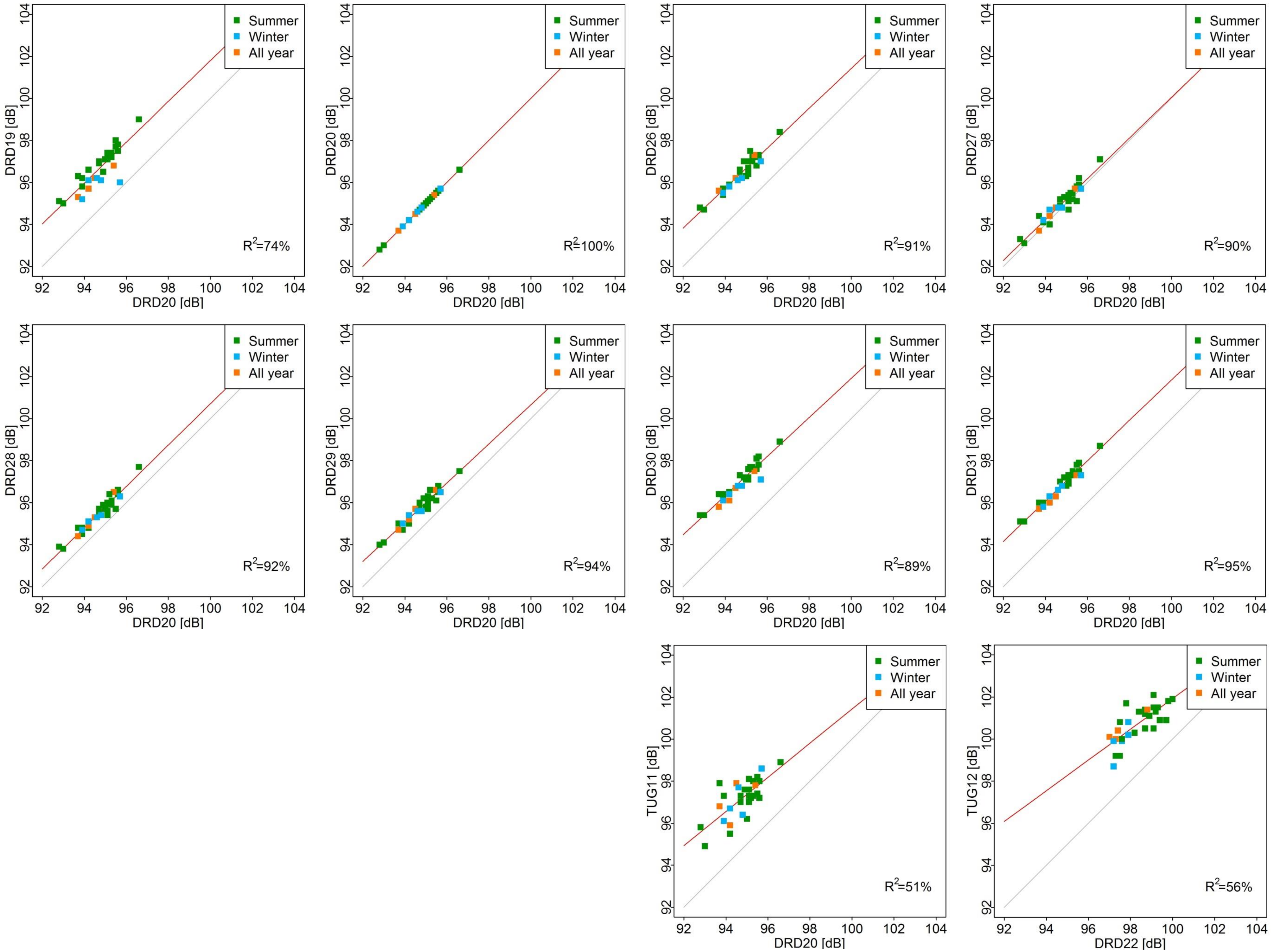


Figure 41

Noise levels from all 31 tyres on pavements in the group well represented by the ISO test track DRD20as a function of the noise level on DRD20

APPENDIX 12 - ANNOYANCE SCENARIOS

This section explains how the values of annoyance indicators given in Section 11 were determined. The basis was results of national noise mappings made in accordance with the European Directive 2002/49/EF. In 2012, noise mapping should be made for agglomerations having more than 100.000 inhabitants and for roads with a traffic intensity exceeding 3 million vehicles per year. Data on dwellings exposed to L_{den} = 55 dB or more should be reported. In Denmark, though, the whole State road network was mapped, no matter the traffic intensity on the road.

A.12.1 NUMBER OF NOISE EXPOSED DWELLINGS

Denmark

The results of the Danish noise mapping were reported in [12] in which results of mappings made by the Danish Road Directorate and by a number of municipalities were merged. The total number of mapped dwellings was 1.5 million, 723,000 of which were exposed to 58 dB or more. Tables are given in [12] specifying the total number of dwellings per 1 dB exposure class from the lowest class $55 \leq L_{\mathrm{den}} < 56$ dB up to the highest class ≥ 75 dB. The noise levels were calculated at a height of 1.5 m above the ground.

The Danish mapping results did not contain information on the speed of the traffic giving rise to the noise exposure of the dwellings. In order to be able to distinguish between different “balances” between tyre/road noise and propulsion system noise on roads with different traffic speed, the exposed dwellings were grouped, as an approximation, into traffic speed classes as follows:

- dwellings exposed to noise from municipal roads were assumed to be exposed to noise from traffic travelling at a speed of 40-60 km/h, represented by 50 km/h
- dwellings exposed to noise from national roads (other than motorways) were assumed to be exposed to noise from traffic travelling at a speed of 70-90 km/h, represented by 80 km/h
- dwellings exposed to noise from motorways were assumed to be exposed to noise from traffic travelling at a speed of 110 km/h

The starting points were the complete table in [12] from the national noise mapping of dwellings in both urban and rural areas, and a corresponding table provided by the Danish Road Directorate on the exposure of dwellings along national roads. The national roads were divided into “roads” and “motorways” by a GIS count of affected dwellings along the motorway network. Actual noise contours in 5 dB steps were used and the number of houses in each noise level interval was counted and subsequently converted to 1 dB increments based on the table in [12]. The results are given in Table 32 [23], although only for noise level classes 58(8) – 73 dB and ≥ 73 dB. Data on municipal roads were also delivered in noise classes up to and including ≥ 75 dB [23]. The large number of dwellings exposed to 73 dB or more has important impact on some aggregate noise indicators, so the information on municipal roads was used to extrapolate data to ≥ 75 dB. The extrapolation was based on the number of dwellings along municipal roads exposed to 73-74 dB, 74-75 dB and ≥75 dB, respectively. The extrapolation result is given in Table 33.

---

(8) The readily available table of noise exposure from the State road network did not contain data on the noise exposure classes 55 - 57 dB because only dwellings exposed to L_{den} = 58.0 dB and higher are taken into account when calculating the Danish noise indicator SBT

Table 32

Number of dwellings exposed to noise levels in 1 dB classes along different types of road

L_{den} [dB]	58-59	59-60	60-61	61-62	62-63	63-64	64-65	65-66
Municipal roads	61,542	63,922	56,795	51,351	52,943	42,705	38,594	36,997
National road, motorway	18,405	14,835	11,997	9,726	8,986	6,870	5,573	4,505
National road, other roads	3,513	2,813	2,453	2,298	2,117	2,145	1,929	1,952
All roads	83,460	81,570	71,246	63,374	64,046	51,720	46,096	43,454

L_{den} [dB]	66-67	67-68	68-69	69-70	70-71	71-72	72-73	≥ 73
Municipal roads	36,980	32,038	27,085	27,096	27,361	19,531	15,198	13,848
National road, motorway	3,289	2,156	1,637	1,117	796	554	583	1,394
National road, other roads	1,596	1,231	1,184	867	830	646	458	954
All roads	41,865	35,426	29,905	29,080	28,988	20,731	16,239	16,196

Table 33

Number of dwellings exposed to noise level classes 73-74 dB, 74-75 dB and ≥ 75 dB, respectively, along different types of road, without and with extrapolation of the ≥ 73 dB interval

Without extrapolation		Extrapolated		
L_{den} [dB]	≥ 73	73-74	74-75	≥ 75
Municipal roads	13,848	6,738	3,817	3,293
National road, highways	1,394	678	384	332
National road, other road	954	464	263	227
All roads	16,196	7,880	4,464	3,851

Norway

The Norwegian data were delivered by Statens Vegvesen, originating from the Norwegian database “Støybygg”. The parameter applied is “*UteHøyL$_{den}$*“, i.e. the highest L_{den} at height of 4 m at any dwelling façade. The noise levels were given with one decimal point, the lowest being 53.0 dB. The Norwegian method of assessing road traffic noise, like European strategic noise maps, only requires dwellings exposed to more than 55 dB to be included, and therefore data below 55 dB were omitted. Data exceeding 55.0 dB were sorted into 1 dB wide classes. When calculating impacts of noise reduction on the noise indicators, the few data exceeding 75 dB were assumed to be equal to 76 dB. Data were sorted into groups according to the speed limits on the roads giving rise to the noise exposure: 30 – 50 km/h roads were represented by 50 km/h; 60 - 80 km/h roads were represented by 80 km/h; and 90 - 100 km/h roads by 110 km/h, respectively.

The data cover five regions of Norway and they are complete for four of these five regions, see Table 34. The received data contains information on 223,824 dwellings, out of which both speed limit and noise level information was supplied for 146,728. After limiting data to ≥ 55 dB, the total number of dwellings had been reduced to 126,505. The distribution on 1 dB intervals, at roads with different speed limits, is given in Table 35.

Sweden

The information obtained on the Swedish results of noise mapping was supplied by Lars Dahlbom, Swedish Transport Authority (Trafikverket) [13].

Table 34

Overview of received data for Norwegian regions

Region	**Comment**
Eastern	Complete
Southern	Complete
Northern	Complete.
Middle	Complete
Western	Only data from Bergen and from one of three counties

Table 35

Number of exposed dwellings in 1 dB noise level classes, distributed along roads with different speed limits

L_{den} [dB]	55-56	56-57	57-58	58-59	59-60	60-61	61-62	62-63	63-64	64-65
30-50 km/h	9,622	8,905	7,853	6,982	6,212	5,466	4,749	4,154	3,763	3,490
60-80km/h	4,971	4,594	4,186	3,835	3,351	3,091	2,699	2,327	2,075	1,948
90-100 km/h	1,008	1,011	842	816	724	613	502	429	343	279
Total	15,601	14,510	12,881	11,633	10,287	9,170	7,950	6,910	6,181	5,717

L_{den} [dB]	65-66	66-67	67-68	68-69	69-70	70-71	71-72	72-73	73-74	74-75
30-50 km/h	3,072	2,565	2,202	2,041	1,695	1,422	1,090	830	533	369
60-80km/h	1,750	1,458	1,244	1,086	821	666	493	330	255	168
90-100 km/h	235	195	154	107	89	62	39	34	35	38
Total	5,057	4,218	3,600	3,234	2,605	2,150	1,622	1,194	823	575

L_{den} [dB]	75-76	76-77	77-78	78-79	79-80	80-81	81-82	82-83	>83
30-50 km/h	140	56	13	5	1	0	0	0	0
60-80km/h	121	77	31	38	40	12	7	6	2
90-100 km/h	11	13	8	4	1	1	0	0	0
Total	272	146	52	47	42	13	7	6	2

The Swedish Environmental Protection Agency (Naturvårdsverket, NV) has collected data from State roads and from 13 municipalities having more than 100,000 inhabitants, and reported data to the European Commission (COM). The data can be found on the website of COM. In view of the lack of information on traffic speed and the rough classification into 5 dB wide noise level classes, it was decided not perform further analysis of the Swedish data.

Swedish noise mapping is based on 1) equivalent noise levels $L_{Aeq,24h}$ and 2) the maximum noise level L_{Amax} exceeded a) five times per hour during the day or b) five times during the night period. Noise levels are calculated using the Nordic prediction method for road traffic noise, version 1996, i.e. for light downwind propagation.

For State roads the reporting was kept to the minimum requested by COM which means the number of inhabitants exposed to noise levels in each 5 dB L_{den} interval above 55 dB. The results for the State roads were: 500,000 persons were exposed to $L_{den} \geq 55$ dB along 4,000 km heavily trafficked roads. 10,000 km of road trafficked by 500 – 8,000 veh/24h have also been mapped with L_{eq24h}. Lars Dahlbom offered to extract these at a later stage, if wanted. It was announced, that variations may exist between mapping methods applied in different regions (län).

For data on the noise exposure from municipal roads, reference was given to Marta Misterewicz at Naturvårdsverket. As mentioned earlier, the analysis of Swedish data was discontinued.

A.12.2 EFFECTS OF REGULATION ON THE VALUE OF OVERALL NOISE INDICATORS

This section gives the values of the noise indicators calculated for the situations “Before” and “After” regulating tyre/road noise. Assuming the distributions of dwellings on classes of different noise exposure given in the preceding sections, each noise indicator was calculated by accumulating the contributions from all noise level classes. For each class the noise indicator contribution was calculated according to the definitions given in Table 10, by multiplying the number of dwellings or persons by the appropriate annoyance factor or fraction of annoyed persons, represented by the class midpoint noise level.

The results are illustrated in Figure 42 for the Danish data and in Figure 43 for the Norwegian noise exposure data. In each figure the contributions from the noise level classes to the overall accumulated noise indicator is shown as a function of the noise level. Each figure shows the contributions to the noise indicators: Støjbelastningstal (SBT), Støyplageindeks (SPI) and Number of Highly Annoyed (NHA) persons, from dwellings located at low speed (50 km/h), medium speed (80 km/h) and high speed (110 km/h) roads, respectively.

In Figure 44 and Figure 45 the contributions from each noise level class have been summarized for all three groups of traffic speed. For the “Before” situation these total contributions per noise level class are shown as a function of the noise level calculated in the noise mapping process. In the “After” situation, the noise level reductions are different for different traffic speeds and it has been chosen to show the contributions in the “After” situation as a function of a “weighted” noise level L_{After} calculated according to Equation 2.

$$L_{\text{After}} = L_{\text{Before}} - \Delta L_{\text{Weighted}} \qquad \text{(Eq. 2)}$$

where

L_{Before} = noise level before regulation, [dB]

$\Delta L_{\text{Weighted}}$ = weighted noise reduction calculated according to Equation 3, [dB]

$$\Delta L_{\text{Weighted}} = \sum_1^3 \Delta L_i \cdot \frac{N_i}{N_{tot}} \qquad \text{(Eq. 3)}$$

where

ΔL_i = noise reduction at i = 1: low; i = 2: medium; and i = 3: high speed roads, [dB]

N_i = number of dwellings or persons at road in group No. i, [-]

N_{tot} = total number of dwellings at all groups of road, [-]

Danish data

The results are illustrated in Figure 42 for the Danish data for each noise indicator for each group of traffic speed. “After” calculations were made for scenario c)[9] assuming that standard SMA 11 pavement is replaced by SMA 8 and all but the tyres labelled 69 dB have been removed. Figure 44

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[9] the conditions used for noise mapping i Denmark

shows the sum of contributions to each of the three noise indicators for the results of the Danish 2012 EU noise mapping.

In the Danish noise indicator only dwellings exposed to $L_{den} \geq 58.0$ are included in the calculation of SBT. If instead, as is the case with the Norwegian SPI, dwellings exposed to levels higher than 58.0 dB “Before” but lower than 58.0 dB “After” are included, then the results would have been as in the right part of Table 36. The total change in SBT as a consequence of the regulation would then have been 28 % rather than 35 %.

Table 36

SBT calculated with and without excluding dwellings at $L_{den} \geq 58.0$ dB “Before” and < 58.0 dB “After”

Speed	Only dwellings ≥ 58.0 dB					Incl. dwellings < 58.0 dB “After”			
	SBT 10^{-3}		ΔSBT 10^{-3}			SBT 10^{-3}		ΔSBT 10^{-3}	
[km/h]	Before	After	[-]	[%]		Before	After	[-]	[%]
50	135.4	90.5	-44.8	-33		135.4	98.5	-36.9	-27
80	5.8	3.3	-2.5	-43		5.8	3.9	-2.0	-34
110	14.4	6.7	-7.8	-54		14.4	9.3	-5.1	-35
Total	155.6	100.5	-55.1	-35		155.6	112.2	-44.0	-28

Norwegian data

Figure 43 illustrates the results for Norwegian data. Contributions to each noise indicator are shown for each group of traffic speed. The calculations for the “After” situation were made for scenario d)[10] assuming that standard SMA 16 pavement is replaced by SMA 8 and that all but the tyres labelled 69 dB have been removed. Contributions from dwellings exposed to noise levels 55.0 dB or higher in the “Before” situation are included in the resulting overall value of SPI even if they are exposed to less than 55.0 dB after the tyre/road noise has been regulated.

In Figure 45 the sum is shown of contributions to each of the three noise indicators for the results of the Norwegian 2012 EU noise mapping.

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[10] the conditions used for noise mapping in Norway

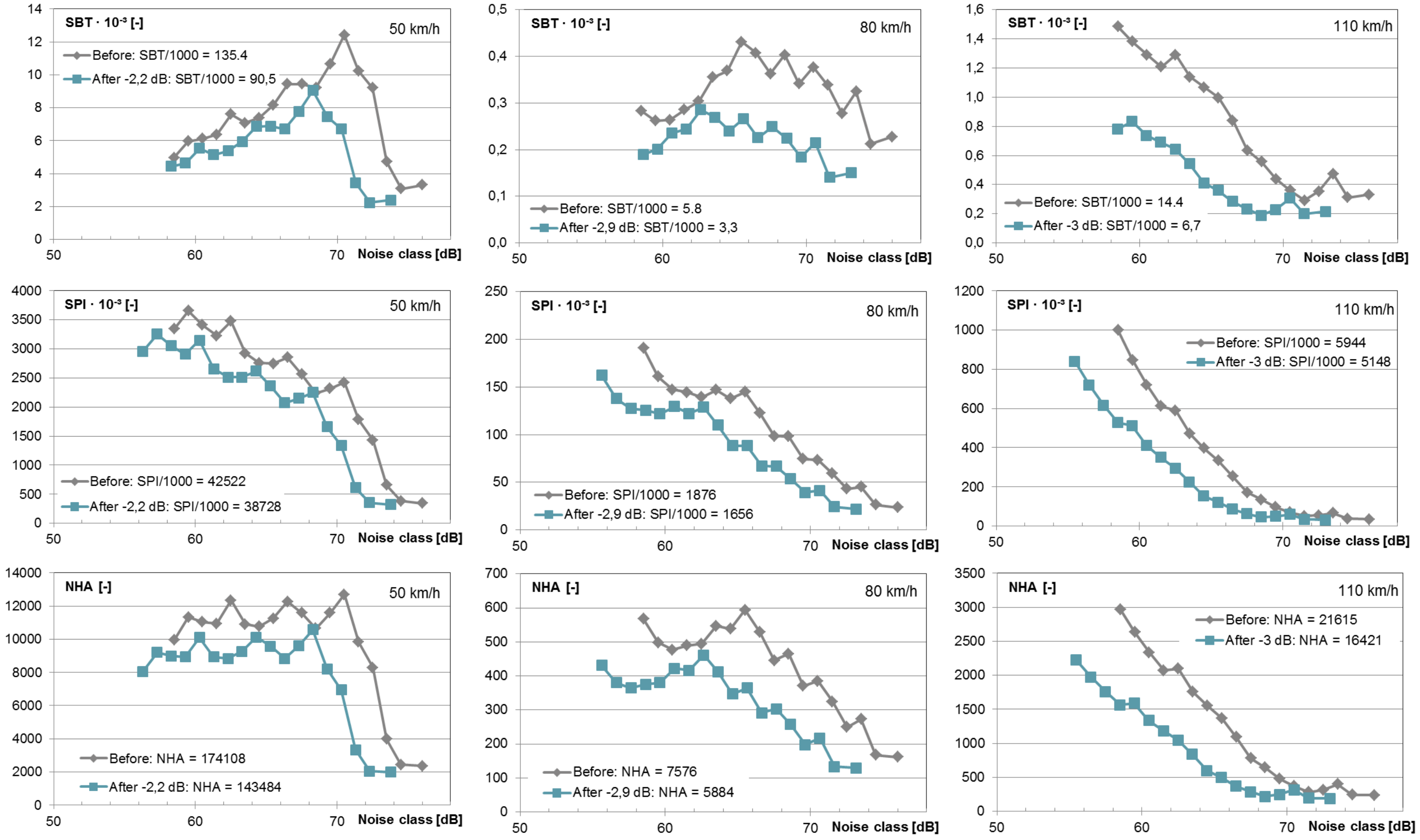

Figure 42

Danish data - Illustration of impacts on Støjbelastningstal (SBT), Støyplageindeks (SPI) and Number of highly annoyed (NHA), in different speed classes for scenario c), of replacing SMA 11 by SMA 8 and reducing the tyres to the ones labelled 69 dB

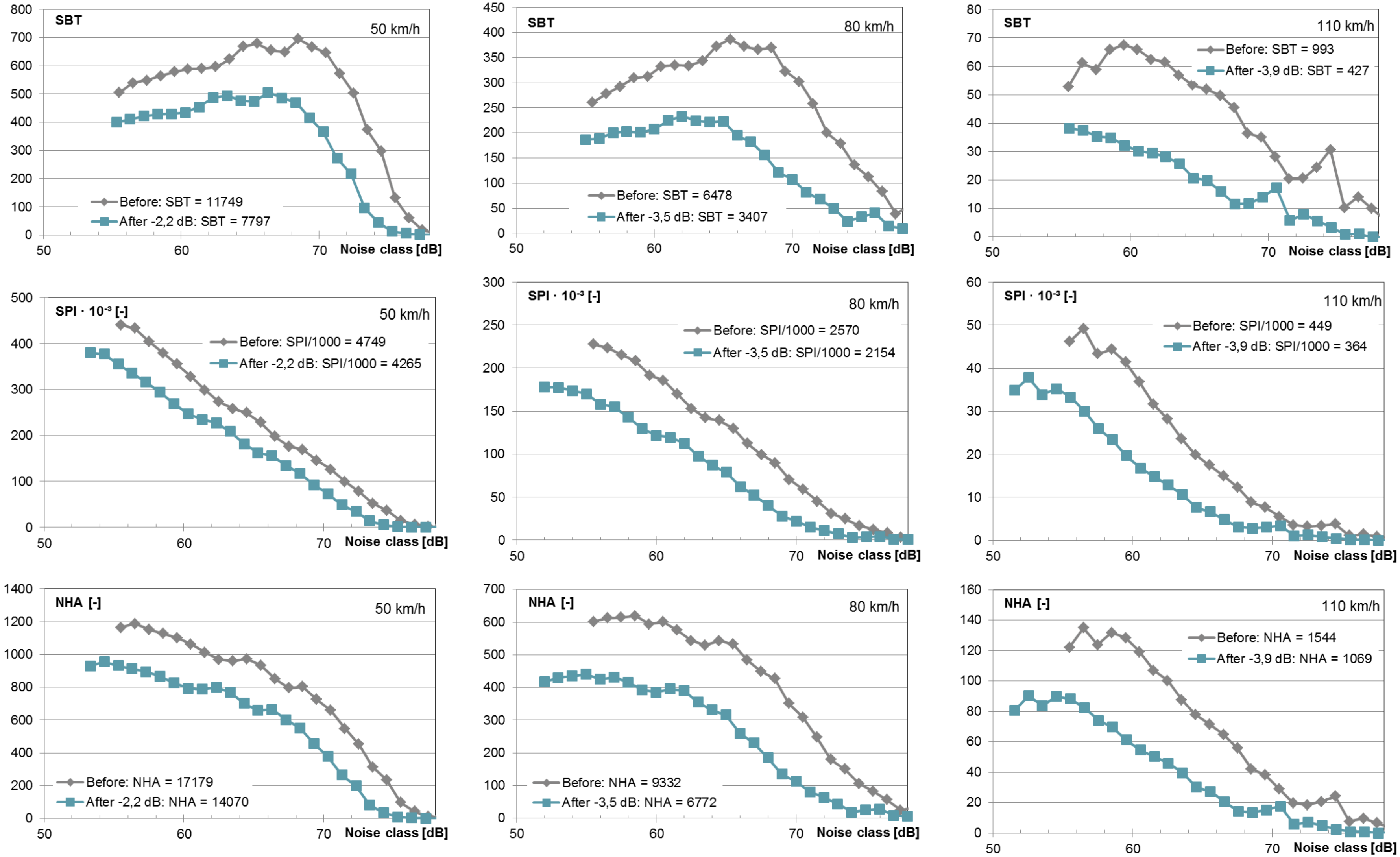

Figure 43

Norwegian data - Illustration of impacts on Støjbelastningstal (SBT), Støyplageindeks SPI) and Number of highly annoyed (NHA), in different speed classes for scenario d), of replacing SMA 16 by SMA 8 and reducing the tyres to the ones labelled 69 dB

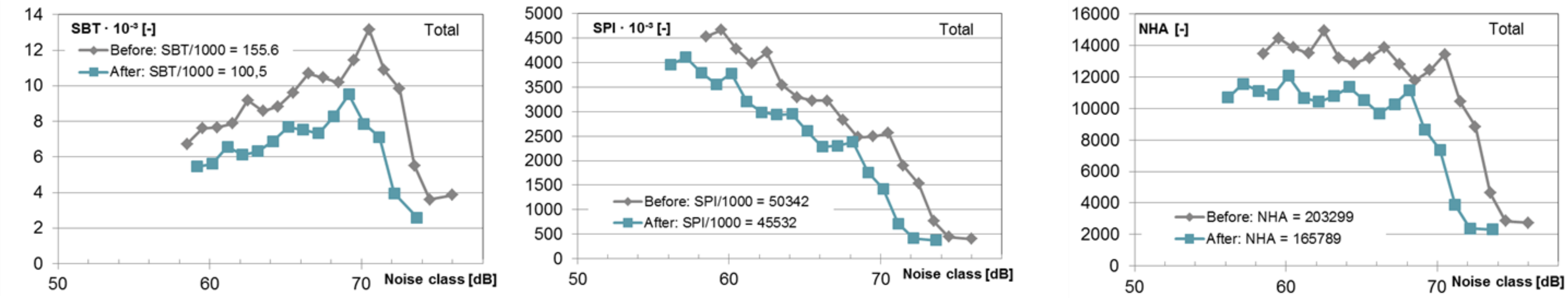

Figure 44

Danish data - Illustration of impact on Støjbelastningstal (SBT), Støyplageindeks (SPI) and Number of highly annoyed (NHA), for scenario c), of replacing SMA 11 by SMA 8 and reducing the tyres to the ones labelled 69 dB

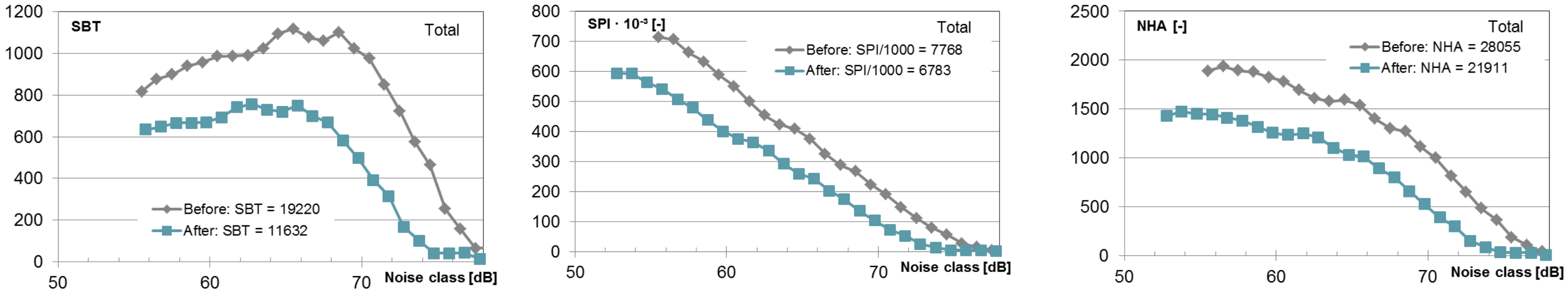

Figure 45

Norwegian data - Illustration of impact on Støjbelastningstal (SBT), Støyplageindeks (SPI) and Number of highly annoyed (NHA), for scenario d), of replacing SMA 11 by SMA 8 and reducing the tyres to the ones labelled 69 dB