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ELANORE Improvement of the EU tyre labelling system for noise and rolling resistance

Deliverable D2.3

Proposed calibration procedure for ISO test tracks

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CONTENTS

1 INTRODUCTION

Several investigations have shown that the noise variation between ISO test tracks is too large, in the range of 4-5 dB, depending on tyre type [1,2]. Such a large variation is the main contribution to the overall measurement uncertainty when measurements are made according to the present test method for type approval and labelling of noise from tyres; UN ECE Regulation No.117 [3].

In this deliverable, the variation between ISO test tracks is investigated, both with regards to previous investigations and to results conducted within the ELANORE project.

To reduce this uncertainty, which is directly linked to the noise labelling of the tyres, different options for a "calibration" procedure are presented and discussed in this deliverable. From this investigation, a calibration procedure is proposed, based on the CPB method and the SRTT tyre. However, the method needs further development and validation.

2 ISO TEST TRACK VARIATIONS

2.1 ROUND ROBIN TESTS

Over the last 20 years, several investigations have been made to study the variation between ISO test tracks. The most important are:

1. **RRT by M+P in 2005**: This test was conducted by M+P on ISO tracks in the Be-Ne-Lux countries and Germany in 2005. In this investigation, coast-by and acceleration measurement of tyre/road noise on 7 ISO tracks and 2 SMA surfaces [2] were performed. All ISO tracks were built according to the first edition of ISO 10844, published in 1994.

   Four car tyre sets were used in the tests, of which one was a slick tyre (thus not a legal tyre), one was a summer tyre, one was a winter tyre and the fourth was an off-road tyre.

   Figure 1 shows the coast-by levels at 80 km/h, including the error bars showing 95% confidence intervals.

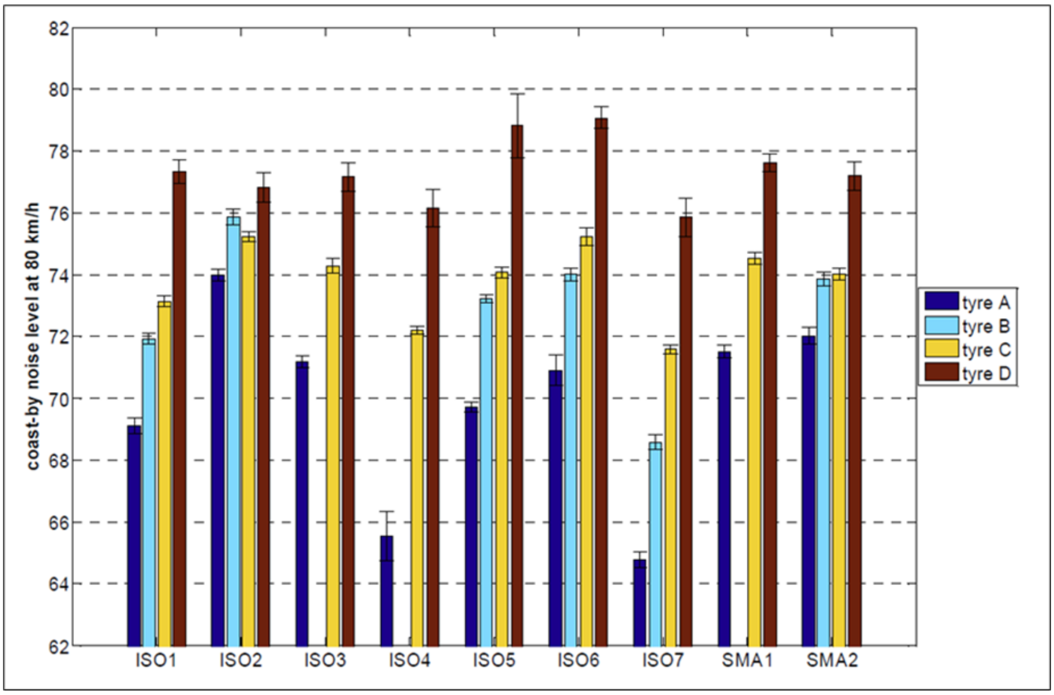


Figure 1. *Coast-by levels at 80 km/h, for all tyres tested on ISO tracks and SMA surfaces, including error bars showing 95% confidence intervals [2]*

Two of the test tracks were found to have an absorption value above the limit given in the ISO standard (ISO4 and ISO7) and thus these surfaces were discarded for the analysis of the spread.

Excluding the two SMA surfaces and two test track surfaces which appeared to have higher sound absorption than accepted, the maximum difference between the remaining five test tracks in noise levels for the four tyre sets were:

- Tyre A (slick tread): 4.9 dB
- Tyre B (summer tyre): 4.0 dB (NB, not measured on ISO3 and ISO4)
- Tyre C (winter tyre): 2.0 dB
- Tyre D (off-road tyre): 1.9 dB

The most relevant result for the ELANORE project is the variation of 4 dB for the summer tyre and 2 dB for the winter tyre.

2. **RRT by JSAE (Japan) in 2006**: Eight ISO test tracks were tested in 2006 by Japan Society of Automotive Engineers [4]. Tyres B and C from the M+P study were used (noted as Tyre 1 and Tyre 2 in Japan), and supplemented with two Japanese summer tyres. The test vehicle was a Japanese car, used on all test tracks. Noise measurements according to the Reg.117 test procedure were made at the speeds of 50 and 80 km/h (except missing one test track at 80 km/h).

The spread of the noise results is shown in figure 2. The spread in tyre/road noise levels were 1.7 to 3.3 dB at 50 km/h and 2.0 to 3.6 dB at 80 km/h, which is lower than in the M+P test in Europe.

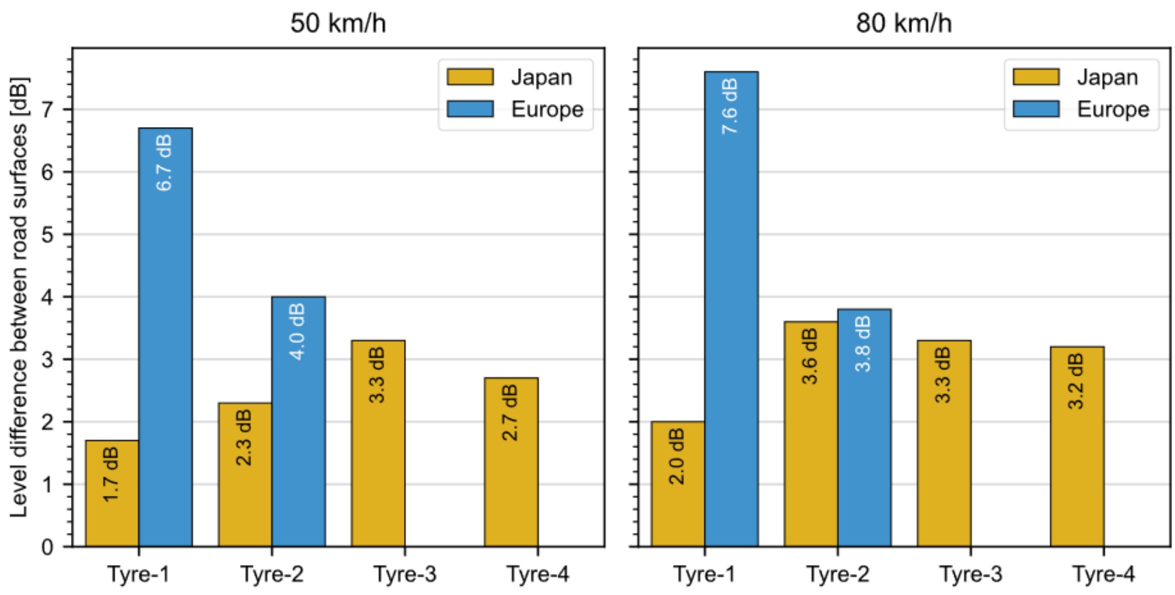


Figure 2. *Spread of coast-by tyre/road noise levels at 50 km/h (left) and at 80 km/h (right) between test tracks for the four tyres in Japan in yellow and the European tyres B and C in blue. Graphics by STEER [5]*

The blue columns for Tyre 1 show a difference of 7.2 dB for the European data, while only 2.0 dB for the Japanese test tracks. However, the 7.2 dB includes two ISO tracks with too high absorption values. If they are discarded, the difference is 4.0 dB, but still higher than the Japanese track variation. The reason for the lower values in Japan is not known but may be caused by a higher building accuracy during the construction of the tracks.

3. **RRT made by VDA in 2016:** In this investigation, made by the German Association of the Automotive Industry (VDA), pass-by measurements (coast-by, cruise-by and acceleration) were made on 13 different ISO tracks in Europe in 2016 [1]. All test surfaces were constructed according to ISO 10844:2014 probably around or just after 2014. Thus, they were relatively new at the time of the RRT.

   An electric vehicle (VW e-Golf) was used for testing. The following tyre sets were used:

   - Four different typical summer tyre sets by different tyre manufacturers, size 205/55R16
   - One typical summer tyre set, size 245/40 R18
   - One slick tyre set (without negative profile), size 205/55 R16
   - One SRTT tyre set, size 225/60 R16

   Driving conditions included a number of cruise-by at speeds in the range 10-80 km/h and pass-by at 2 m/s^2 acceleration, and 50 km/h. All were made with the engine switched on.

   No final report from this investigation has been made available, but a summary of the main findings was presented to GRBP Informal Working Group on Measurement Uncertainties in 2019 [1]. Figure 3 shows the results from cruising at 50 km/h for the 13 ISO tracks. The red dots in the figure (R06) are values for the SRTT tyre, and the green dots for the slick tyre (R02). The grey line is the average levels (excluding the slick tyre) on each test track.

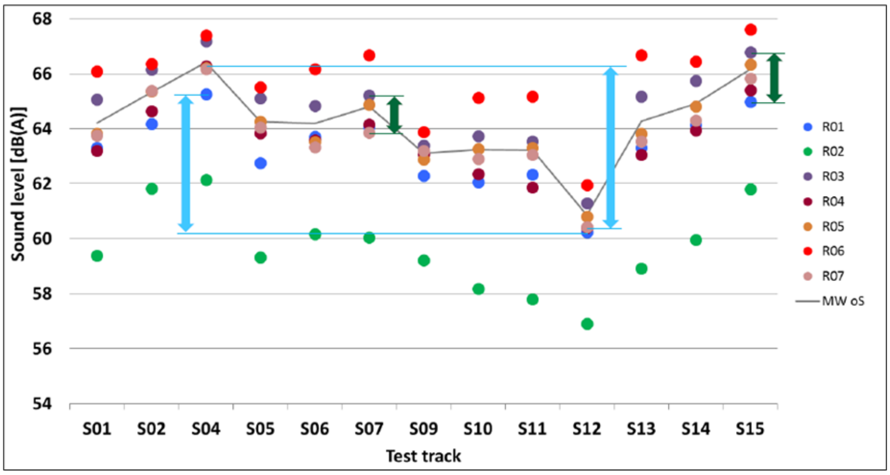


Figure 3. *Cruise-by levels at 50 km/h for 7 tyres on 13 ISO tracks [1]*

The main conclusions from this figure (excluding tyres R02 and R06 from the analysis) were:

- The sound level **spread** among the test tracks for **tyres** with tread pattern is approx. **5.0-5.9 dB** depending on the tyre.
- Without the SRTT tyre, the spread among test tracks remains nearly unchanged with a range from **5.0-5.7 dB** depending on the tyre.
- If test tracks S09 and S12 are not counted, due to their measured sound absorption (although they were originally certified), the spread is reduced to approx. **2.6-3.2 dB**, depending on the tyre.

Note that an analysis of the absorption data revealed that S09 and S12 appeared not to meet the requirements of ISO 10844:2014, although they were produced to do so. To compare these results with the findings from Japan and Europe (M+P), it is most relevant to exclude S09 and S12 test tracks and also the SRTT tyre, which was not part of the previous studies. A spread of 2,6 to 3.2 dB is then in line with previous findings, taken into account the changes made in the 2014 version of ISO 10844 to reduce track variability. This is further discussed in chapter 2.2.

4. **RRT made for ISO/TC 31/WG 11 by ETRTO in 2018:** The main results of this RRT were presented by ETRTO in 2019 [3].

This RRT involved five different tyres (both summer and winter, 16" and 18") and four different ISO test tracks. In this case, all measurements were conducted at the speed of 80 km/h, to meet the requirements of Reg.117. Figure 4 shows the results.

Their main conclusions were that these results, with a spread of 1.3 to 2.4 dB depending on tyre, were in line with the findings in the VDA RRT. Then it shall be noted that this study included only four test tracks while the VDA study included 13 test tracks. It is natural that differences increase when more test tracks are added to the sample, or vice versa.

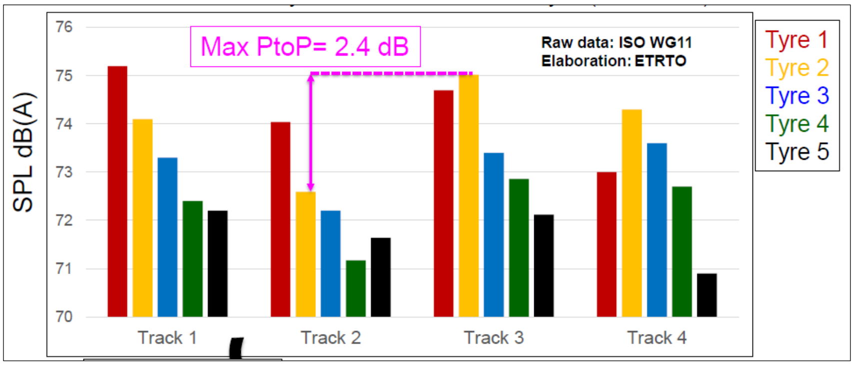


Figure 4. *Results of the study within ISO TC31/WG11, elaborated by ETRTO. The results show track-to-track variations at 80 km/h [3]*

They are more relevant to the ELANORE project than the results presented in the VDA study as these measurements were made according to Reg.117. The slick tyre is excluded from the comparison.

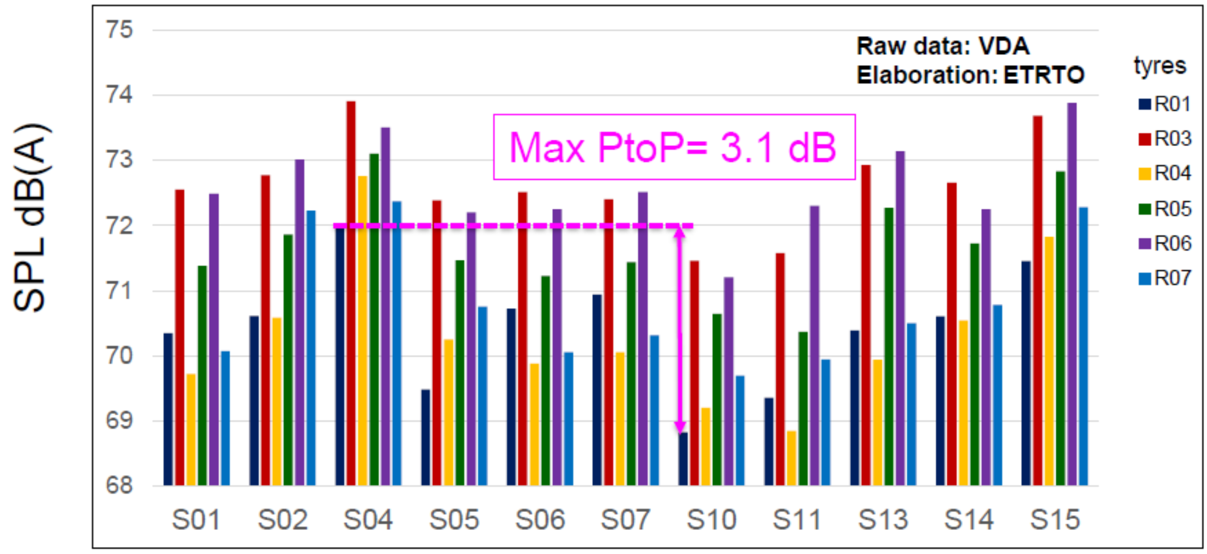


Figure 5. *The VDA RTT results elaborated by ETRTO showing track-to-track variations at 80 km/h [3]*

The spread in tyre/road noise levels between the tracks seems to be 2.3 to 3.9 dB, depending on the tyre set.

5. **RRT made within ELANORE 2021/2022:** In this part of the ELANORE project, a total of 5 tyres were measured on 4 ISO test tracks in Northern Europe. 3 of the test tracks were measured in 2021, and one track in 2022. The Deliverable D2.2 [6] gives a full presentation of all results from the test tracks. In this deliverable, only the part dealing with track-to-track variations is presented.

A total of 5 sets were measured using the coast-by test (Reg.117) with speeds in the range of 40 to 90 km/h. Based on the linear regression analysis, the noise level at the reference speed of 80 km/h was calculated. The following sets of tyres were used:

- Tyre 1: Yokohama Advan Fleva V701, 215/55 R17, summer
- Tyre 2: Michelin CrossClimate+, 215/55 R17, all-season
- Tyre 3: Bridgestone Blizzak LM005, 215/55 R17, winter
- Tyre 4: Evergreen EH23, 215/55 R17, summer
- Tyre 5: Uniroyal Tiger Paw, P225/60 R16, SRTT

All tests were performed using the same car, Skoda Superb 2.0 TDI with 7 speed DGS gear box. The tests were performed using the same test driver and measurement equipment on all 4 ISO tracks (ISO1 to ISO4).

All ISO tracks had been constructed according to the ISO 10844:2014 edition. However, ISO4 was at the end of its lifetime, as it did not any longer met the requirements of the ISO standard for MPD values. The maximum allowed value is 0.70, while measurements conducted during the RRT showed a value of 0.95. This causes additional uncertainty for the results from this test track.

Due to weather constraints (rain/humidity) on ISO3, only measurements with Tyres 1 and 2 were completed in this test track.

Figure 6 shows the track-to-track variation for the 4 ISO tracks at 80 km/h.

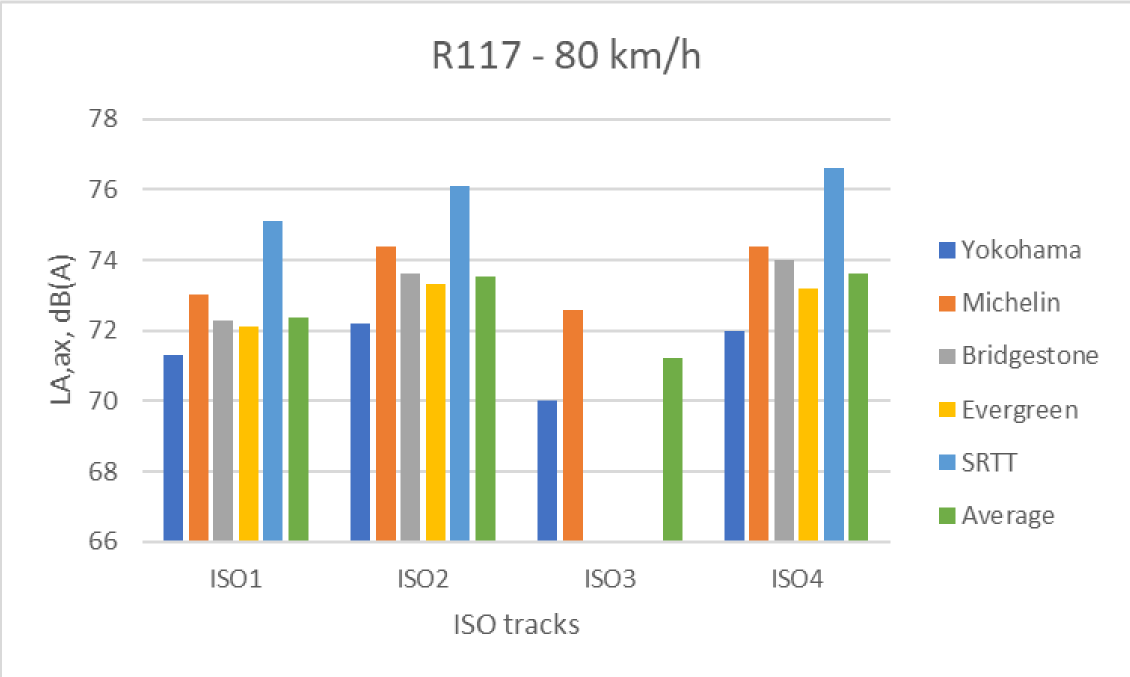


Figure 6. *ELANORE RRT test on 4 ISO tracks. Track-to-track variations at 80 km/h*

The figure shows that even if the MPD values of ISO4 is above the limit of 0.70, it does not seem to influence the noise levels, as the average level is quite identical to the levels on ISO2, who has an MPD level of 0.46. This may be caused that the absorption level is higher on ISO4 than the others (not measured). This can probably compensate for the expected increase in noise level due to age and higher MPD values.

In general, the track-to-track variation is in the range of 1.2 to 2.0 dB. The largest spread is for the Yokohama tyre (2.0 dB) which was measured on all 4 ISO tracks. If only ISO1, ISO2 and ISO4 are included in the comparison, the average variation is 1.2 dB. If ISO3 is included, the variation is 2.7 dB, which is in line with the ETRTO RRT, but one should then be aware that only two tyres were measured on ISO3.

Figure 7 shows a comparison between the EU noise label values and the measured noise levels on the 4 ISO tracks. The ranking of the tyres based on the labelled values does not correspond to the measured levels on the ISO tracks. Especially, the largest difference is for the Michelin (winter tyre. The labelled value is 69 dB, while it is measured to 74 dB on two of the ISO tracks.

This deviation from the labelled value, cannot be just the track-to-track variations, or environmental conditions, but may be related to the fact that only one sample of a tyre family is normally chosen for the labelling process and to be representative for all variants in this tyre family.

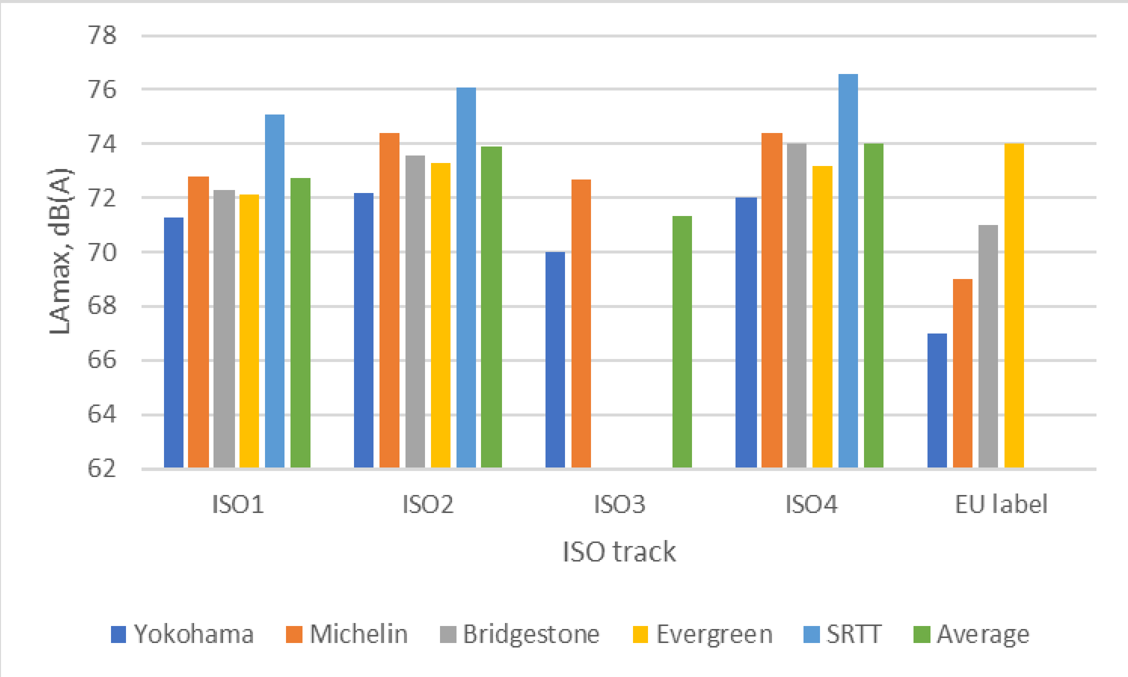


Figure 7. *ELANORE RRT test on 4 ISO tracks, compared to the EU Label values*

2.2 IMPROVEMENTS OF THE ISO TRACK

Different updates of the ISO standard, ISO 10844, which the tracks have been constructed to, have aimed to reduce this variability as shown above. A majority of the existing ISO tracks have been constructed according to the edition from 2014. The main improvements of this standard, compared to the previous edition from 2011 are shown in the table below:

In 2021, a revised version of the standard was published [7]. In the future, all ISO standards (like ISO 362-1/2 and ISO 16254) and ECE regulations (like Reg.117 and Reg.51.03) will be updated to refer to this latest edition. In the 77th meeting of GRBP, several documents were presented by

ISO to update the ECE regulations using ISO 10844 as a basis for measurements [8, 9] The improvements from the 2014 edition are shown in Table 2.

Table 1. *Improvements of the ISO 10844:2014 edition compared to the first publication in 1994*

First edition of ISO 10844:1994	**Improvements for the 2014 edition**	**Effect of improvements**
Straight bitumen	Polymer modified bitumen allowed	Improved stability of acoustic properties over time due to reduced surface wear, Bitumen can be chosen to match climatic conditions of the track
Flatness and smoothness required but not defined	Flatness and smoothness defined with test method	Quality control of track in megatexture to unevenness ranges improved. Unevenness limited by specification
Texture specification by sand patch mean texture depth (MTD)	Measurement of texture by machine fulfilling ISO 13473-3	Reduced variations in measurements due to differences in hand process. Elimination of the possibility to manipulate results
Texture (MTD) specification one-sided	Bounded texture specification	Eliminates the possibility of the texture becoming large. Acoustically, this reduces the variation in loud direction
Sieving curve informative	Sieving curve normative as MPD chosen as texture descriptor	Reduction in variation
Absorption implied by void content or directly measured by core samples with limit of 10 % average over band	Absorption measured *in-situ* device with specification of 8 % in each 1/3 octave band	*1) In-situ* testing vs destructive testing eliminates the cracking and repair concerns *2)* Performance requirements on absorption eliminates the possibility that a track can meet void content, but not meet the expected absorption *3)* Change in absorption provides control of the track and provides reduced variation between different test sites i.e. that some tracks are less noisier than others

Table 2. *Improvements of the ISO 10844:2021 edition compared to the publication in 2014*

Third edition of ISO 10844:2014	**Improvements for the 2021 edition**	**Effect of improvements**
Measurement irregularity	Permit more modern and accurate methods of measurements (i.e. laser methods) in addition to straightedge	Improved practicality and accuracy of irregularity measurements
Periodic check criteria for irregularity of tracks exclusively for testing heavy vehicles	Irregularity requirement changed to 10 mm in consideration of permanent deformation caused by heavy vehicles, and through acoustical analysis of potential shielding found negligible impact	Improved durability of tracks used exclusively for heavy vehicles without impacting acoustical measurements
Step requirement	Implement a step requirement that includes allowance for a step-up of maximum 5 mm to harmonize with irregularity requirements	Improved constructability while maintaining same surface geometric tolerances
Sieving curve	Replace sieving curve figure with equivalent tabulation of sieve values defining aggregate grading envelope	Reduced track-to-track variability caused by subjective interpretation of sieving curve figure
ENDt method	Replace optional calculation of ENDt with optional calculation of texture skewness, shape factor (g-factor) and texture spectrum	Skewness, shape factor (g-factor) and texture spectrum reported to correlate with measured pass-by noise and are proposed for track correlation methods.

Sampling for aggregate grading	Sampling of loose asphalt mixture as alternative to coring for evaluating aggregate grading	Sampling of loose asphalt mixture is more practical, and representative compared to the small sample extracted from four cores
Example of track construction	Examples have been removed	Avoided conflicts and confusion in interpretation of the technical requirements in the standard

Comparing these two tables, it is obvious that the main improvements to track-to-track variability came in the 2014 edition. The changes in the absorption criteria and going from MTD to MPD limitations in this version can directly influence the pass-by noise levels.

However, as for example the VDA RRT shows, the variability is still too high, in the range of 3-4 dB (depending on tyre).

The main change in the 2021 version to reduce track-to-track variability is related to the replacement of the figure showing the sieve curve with tabulated numbers to be met. However, it is difficult to estimate any direct effect of this change for pass-by levels.

When the 2021 edition of ISO 10844 has been implemented in regulations, and existing (and new) ISO test tracks have been built according to this edition, it is recommended to check again track-to-track variability by round-robin-tests.

3 UNCERTAINTY ANALYSIS

To evaluate the impact and importance of track-to-track variation and other measurement quantities on the labelling process, a measurement uncertainty analysis is necessary. Both within the STEER project [5] and the GRBP Informal Working Group on Measurement Uncertainties (IWG MU) such an analysis for Reg.117 has been performed [3].

In the STEER project, a total of 41 quantities were investigated for the overall uncertainties. They are related to:

- Measurement equipment (sound level meters, calibrator, speed measuring device, etc.)
- Environmental conditions (temperature, wind, humidity, altitude, background noise, etc.)
- Test track influence, tyre influence (tyre fleet variation, tyre temperature/hardness), test vehicle (influence of vehicle design)

Based on this, a total of 8 categories were defined:

1. Equipment
2. Experimental set-up
3. Measurement conditions
4. Measurements
5. Test vehicle
6. Test track
7. Test tyres
8. Calculations

The contribution to the overall uncertainty was calculated, based on the ISO GUM procedure. The combined uncertainty u_c is calculated according to equation (10) in [10]. The combined uncertainties per uncertainty group were calculated as well. The parameter u_c is the uncertainty - expressed as a standard deviation - of the measurand and according to the Central Limit Theorem, the measurand is normally distributed (at least in a good approximation if not all of the constituents are normally distributed). To determine the confidence interval, the right coverage factor must be selected, see Table G.1 in [10]. The 95 % confidence interval can be obtained by multiplying u_c with the factor k_p = 1.95.

Figure 8 shows the results of the uncertainty for C1 and C2 tyres, as the STEER project evaluated the current uncertainty for the noise labelling process, based on measurements according to Reg.117. Note that the uncertainty of the test method itself, for type approval, would differ from these calculations. In the labelling process one has to take into account that only one set of a tyre family is normally tested for labelling. Normally, this is believed to be the tyre assumed to have the highest noise level of the tyre family. This is discussed further in the final report from the STEER project [5].

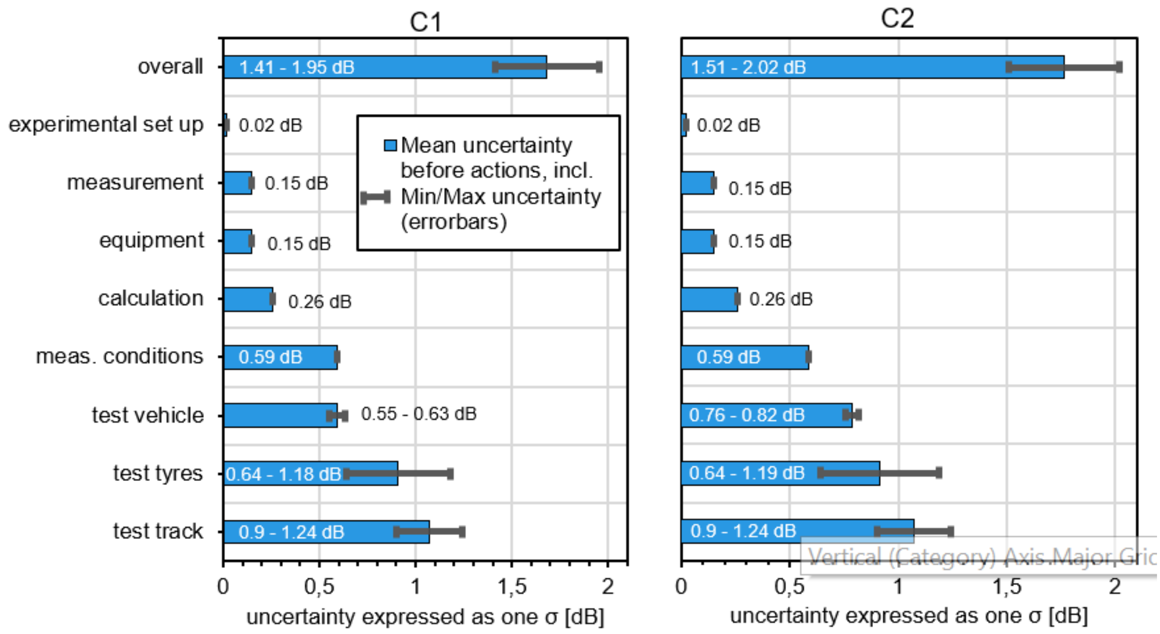


Figure 8. *Uncertainty contributions per uncertainty group for C1 tyres (left) and C2 tyres (right) [5]*

From this analysis, it is clear that the track-to-track variation is the main contributor to the overall measurement uncertainty.

The STEER consortium evaluated different options to reduce the different contributors to the uncertainty and the main actions were:

- **Test track:** an acoustic calibration of the ISO test tracks by means of coast-by measurements with SRTT reference tyres. The calibration measurements would yield an overall value for the noisiness of the test track, which can be compared to the one of a virtual ISO track (average of a large number of ISO test tracks) from which the correction term can be deducted to be added to each measurement obtained on the considered ISO test track. This procedure would considerably reduce the uncertainty contribution of the test track. The tyre-to-tyre variance for the SRTT tyre is only 0.15 dB, as specified in [11]. The uncertainty contribution from the test track before introduction of the calibration procedure was estimated to be between 0.92 and 1.24 dB. After calibration and taking into account the actions below, the uncertainty contribution from the test track would reduce to 0.55 dB, both for C1 tyres and the C2 tyres. This test track calibration procedure is further presented and discussed in chapter 5.
- **Temperature influence:** C1 tyres and C2 tyres improved temperature correction procedure: a better temperature correction might cut the uncertainty on the measurement conditions from 0.58 dB to 0.31 dB.

- **Test vehicle #1:** reducing the range of the wheelbase and a more restrictive description of the rim could only yield a marginal reduction for the C1 tyres, but a significant one for the C2 tyres: stricter limitations of the wheelbase range of the test vehicle could reduce the uncertainty to 0.21 dB.
- **Test vehicle #2:** a better description of the car underbody – ground clearance would be worthwhile and might reduce the total vehicle contribution from 0.63 to 0.45 dB.
- **Testing all variants in a tyre line:** reduction/annihilation of the "tyre line effect" by doing simplified tyre/road noise measurements on a drum facility for every member of the tyre family (line) could reduce this important uncertainty contribution (from 0.59 up to 1.2 dB) to a much lower value. An uncertainty of 0.25 dB (standard deviation between tyres due to tolerances in the production) can be assumed if one tyre is tested on a drum. If four tyres are tested the uncertainty on the average is reduced to $0.25/\sqrt{4} = 0.13$ dB.

Table 3. *Uncertainties for C1 tyres and possible actions to reduce these [5]*

Uncertainty group	Uncertainty contribution	Options for reduction of the uncertainty	Est. improvement uncertainty	Practical implications
Text track	0.92 up to 1.30 dB	• Narrowing down specifications in ISO 10844 • Acoustic calibration procedure of test track • Second rough ISO 10844 test track	☆☆ ☆☆☆☆ ☆	Difficulties meeting requirements, increases costs of construction (- -) Repeated calibration measurements necessary (-) Doubles costs for construction and tyre testing (- - -)
Measurement Conditions	0.59 dB	• Stricter requirements wind speed (correction not possible) • Improved temperature correction procedure • Update temperature corrections	☆☆ ☆ ☆	Only limited number of measurement days for open test tracks (- - -) Possible changes to temperature measurement (-) Possible changes to temperature measurement (-)
Test vehicle	0.55 up to 0.63 dB	• Narrowing specifications of test vehicle	☆☆	
Calculation	0.26 dB	• Small contribution, no further reduction needed		
Test tyres	0.26 up to 0.46 dB	• Narrowing the definition of “tyre family”	☆☆☆	Increase number of required tests and hence cost (- -)
Measurement	0.15 dB	• Small contribution, no further reduction needed		
Equipment	0.15 dB	• Small contribution, no further reduction needed		
Experimental setup	0.02 dB	• Small contribution, no further reduction needed		

As seen in the table, one proposed action is to introduce a calibration procedure for the test track. This is further discussed in chapter 5.

Figure 9 shows the expected reduction in the overall uncertainty for C1 and C2 tyres, based on these actions.

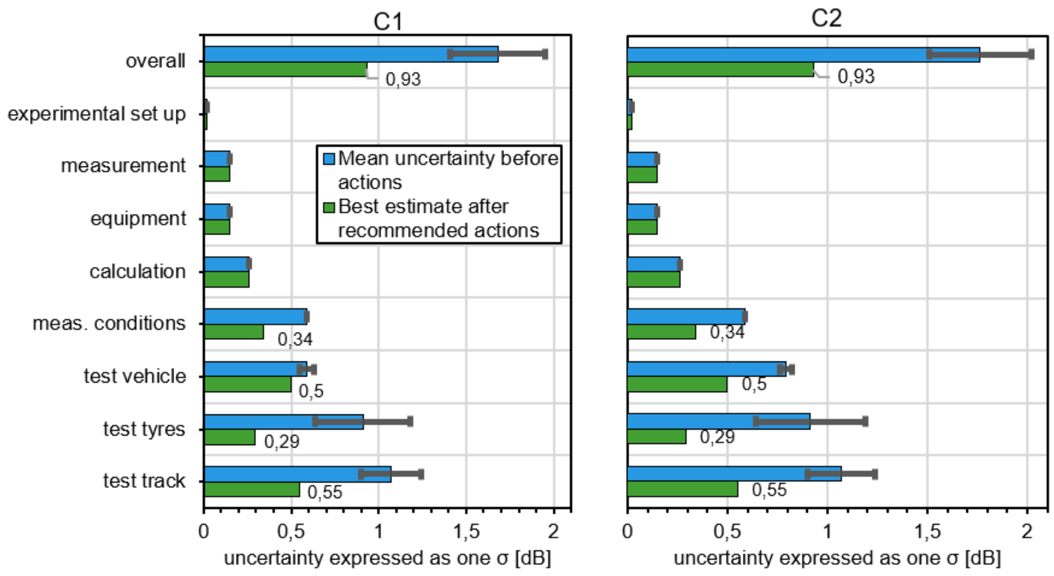


Figure 9. *Uncertainty contributions per uncertainty group for the current tyre noise label procedure (min and max estimations) after actions proposed by STEER, C1 tyres (left) and C2 tyres (right) [5]*

As the figure shows, the overall uncertainty is approximately reduced from a range of 1.41 - 1.95 dB down to 0.93 dB. As listed above, the introduction of a test track calibration was estimated to reduce the uncertainty contribution from a range of 0.92 – 1.4 down to 0.55 dB.

4 REPRESENTATIVITY OF THE ISO TEST TRACK

4.1 MPD EVALUATION

The ISO 10844 test surface is basically a dense asphalt surface with a maximum chipping size of 8 mm. In addition to the specification of the chipping sizes (a table for the sieving curve is given, as shown in chapter 2.2), the maximum allowed absorption in defined 1/3 frequency octave bands shall be less than 8 % and the allowed MPD value range is 0.30-0.70. Thus, this is a smooth textured surface, and it was originally designed as a test surface for measuring the noise of an accelerating vehicle (ISO 362). During the acceleration phase, the ambition was to measure the power-train noise, with as little as possible contribution from the tyre/road noise source. Since it was the only standardized test surface for external noise measurements, it was also selected for the standards and regulations for measuring the noise from tyres, like ISO 13325 [12] and 2001/43/EC [13].

Since the 10844-test surface is a smooth and specially designed road surface, never to be found on normal trafficked road, it is important to evaluate the representativity of the test surface, when compared to typical road surfaces used.

The MPD value is one important characteristic of the road surface texture and is also influencing the pass-by noise of tyres.

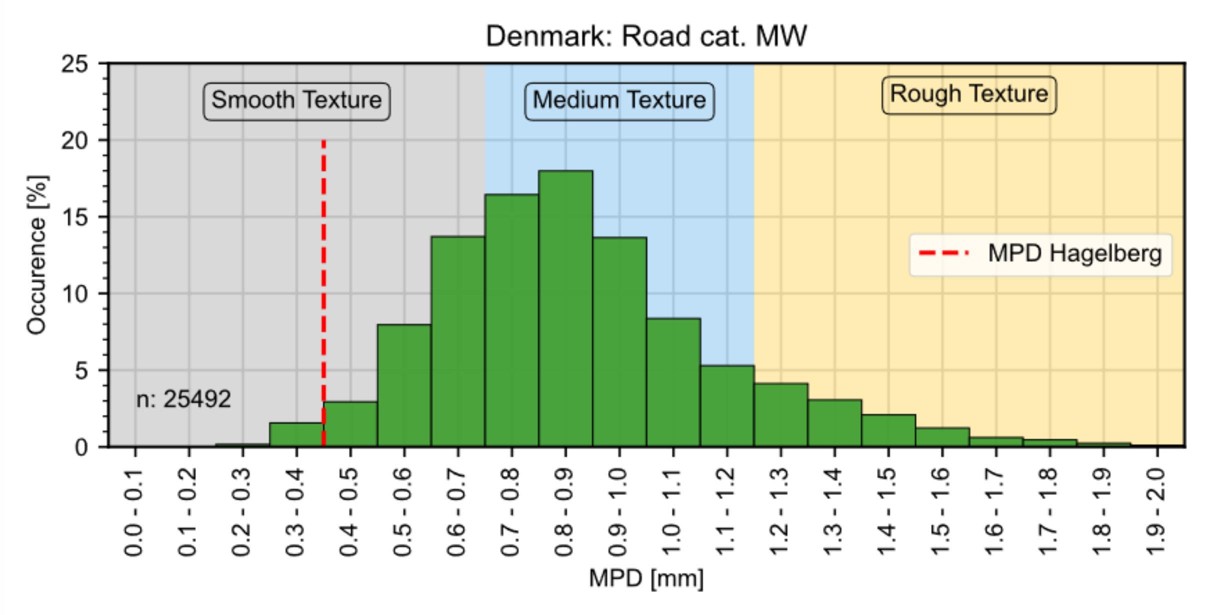
In the STEER project, a survey was conducted to investigate the distribution of MPD values on normal, trafficked roads in some selected European countries. In this survey, a distinction between a smooth, a medium and a rough textured road surface was made, based on the MPD values:

Smooth: Below 0.7 mm (in practice this covers a range of 0.2-0.7 mm, hence with a width of 0.5 mm)

Medium: 0.7 – 1.2 mm (width = 0.5 mm)

Rough: Above 1.2 mm (in practice this covers a range from 1.2 – 1.7 mm, width = 0.5 mm, excluding very rough roads with surface dressing)

The distribution of MPD values, compared to the MPD value for a defined ISO test track in Sweden, is shown for some selected countries. Figure 10 shows the distribution in Denmark for motorways (MW) and rural roads (RU) and in figure 11, the same kind of roads in Sweden. Compared to Denmark, Sweden is normally using SMA16 types of surfaces on roads with high traffic volume like motorways. In combination with the use of studded tyres in the winter season, this gives high MPD values. The situation in Norway should be comparable to Sweden, however most of the SMA16 surfaces has been replaced by SMA11 type of surfaces on many roads with high traffic volume.



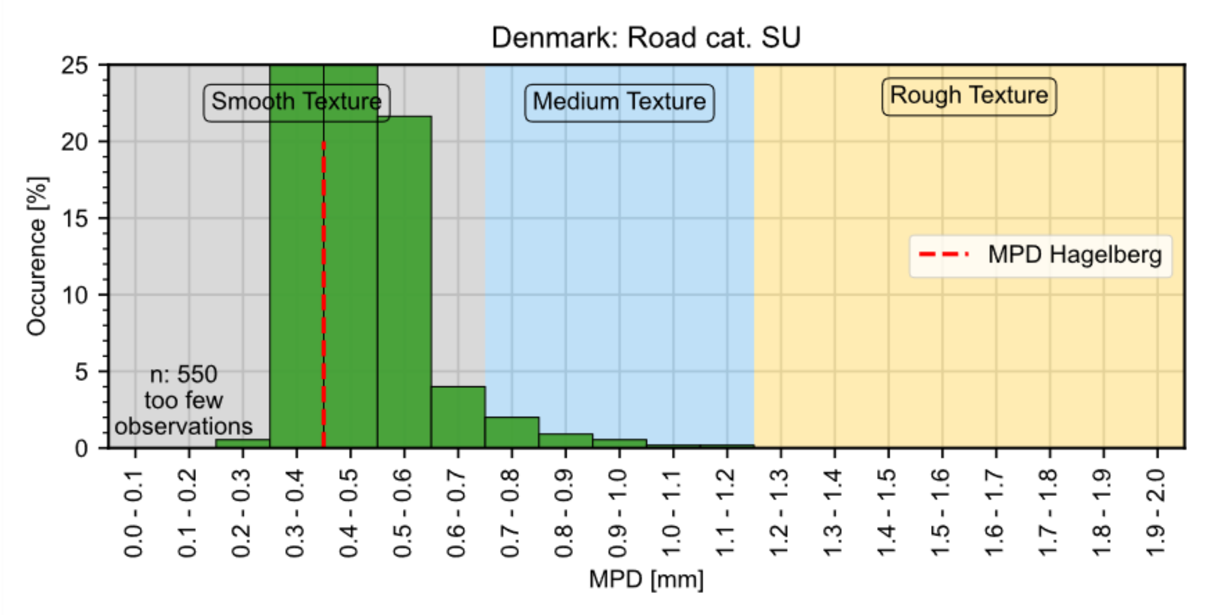


Figure 10. *Distribution of MPD values in Denmark on highways (top) and on local roads (bottom). Red line is the MPD value of the ISO test track*

In Figure 12, the distribution of MPD values on trunk roads in Ireland is shown (data from 2020).

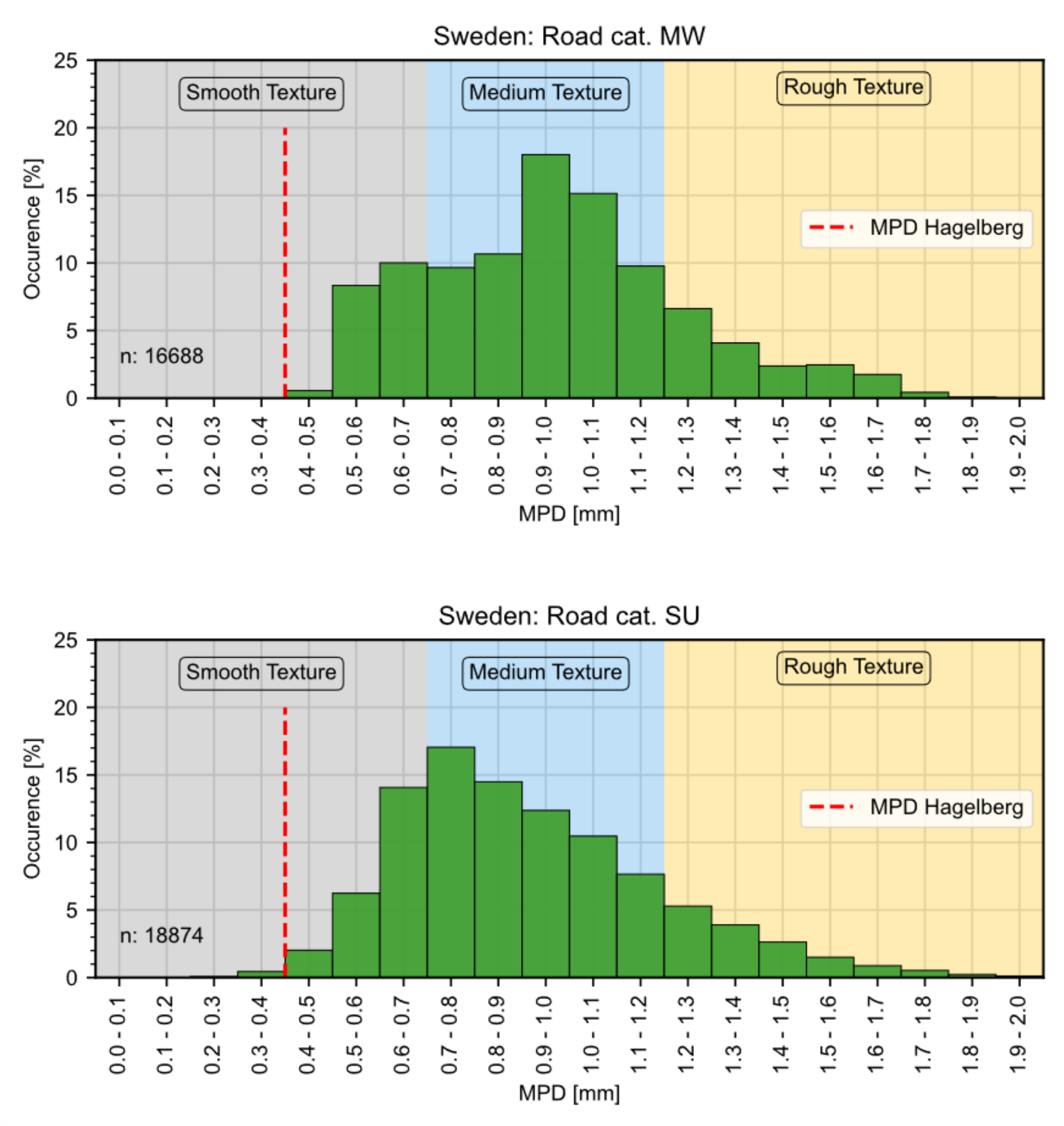


Figure 11. *Distribution of MPD values in Sweden on highways (top) and on local roads (bottom). Red line is the MPD value of the ISO test track*

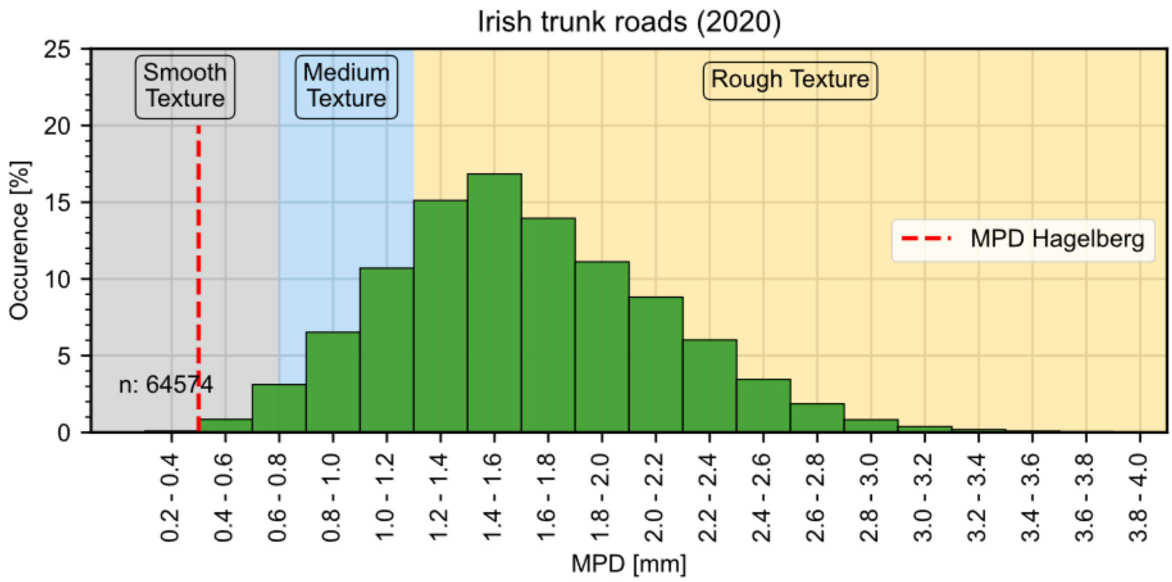


Figure 12. *Distribution of MPD values in Ireland on trunk roads. Red line is the MPD value of the ISO test track*

Similar distribution was also found for other European countries, like Netherlands, Belgium, Finland and Great Britain. The STEER conclusion on MPD values compared to the ISO test surface was [5]:

"The conclusion is that the pavement specified in ISO 10844 is far from having a common pavement macrotexture which one can find on the roads of the funding and other European countries. The ISO surfaces having MPD values at or below 0.4 mm can be considered as very uncommon for real roads, while the range of 0.50 to 0.70 mm exists to a significant degree when considering rather narrow low speed urban or suburban roads. Such roads do not generally carry such a high load of traffic that noise emission becomes a significant nuisance."

4.2 COAST-BY METHODS

Even if the conclusions were that the ISO test track does not represent most of the road surfaces found on European roads, the important issue for the ELANORE project concerning the efficiency of the noise labelling procedure is this:

Is the ranking of noise levels on the ISO test surface comparable to the noise ranking on normal trafficked roads, even if the MPD values are higher?

To investigate this, one can compare the ranking of tyres based on either the label values given by the tyre manufacturer and the measured values in the ELANORE project, or alternatively compared the ranking with *measured* values on the ISO test tracks from the RRT in this project compared with the ranking on trafficked roads.

Comparison with labelled values:

In Figure 13, the ranking based on the labelled values are compared with the ranking on the two Norwegian road surfaces, Ma11 and SMA16 and the three Polish surfaces: SMA8, SMA11 and EACC.

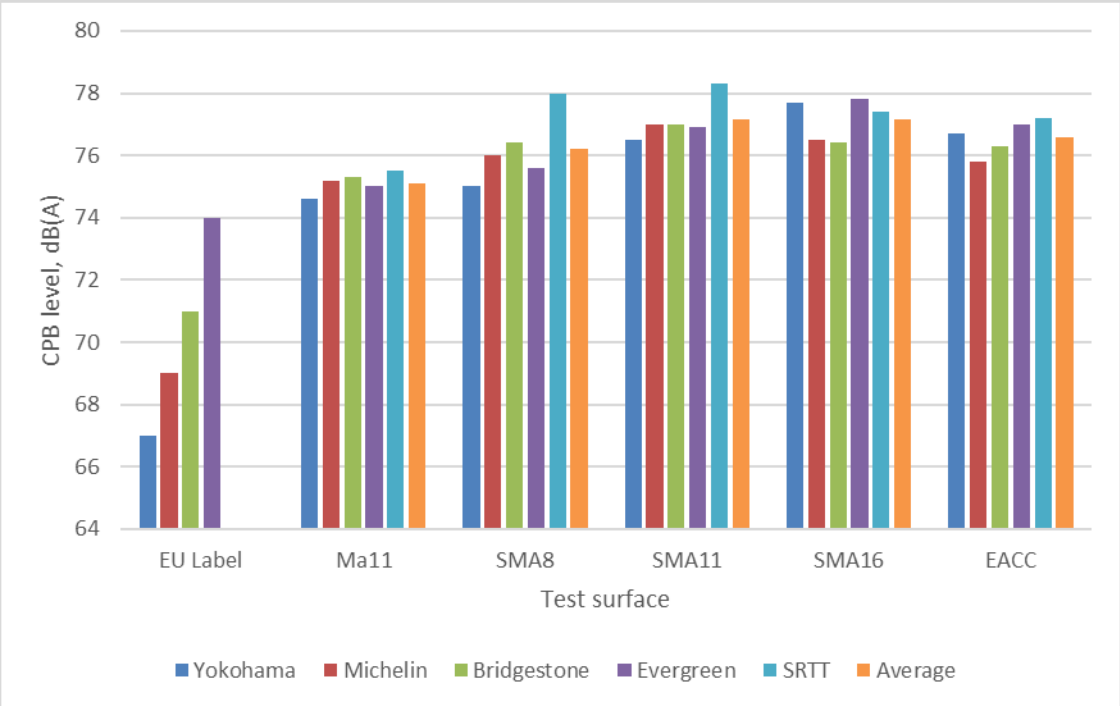


Figure 13. *Comparison of the ranking of the tyres based on the EU label values and measured values on five conventional road surfaces*

This figure shows no significant relationship between the EU label values and the noise ranking on these five road surfaces. Even on the smooth textured road surface (MPD values in the range of 0.5-0.7) like the Ma11, the difference in noise levels of the five tyres are very small, less than 1 dB, while the range of label values is 7 dB (note that the SRTT tyre does not have a label value).

If one considers the results on the smooth Ma11 surface, it was a surprise that this surface did not discriminate the noise levels between the tyres, in the same way as the ISO surface does (Figure 7). Since CPX measurements have been made on the same pavements, it is possible to compare the CPX results, as shown in chapter 4.3 and in Figure 17. As these results show, there is higher differences between tyres (2.4 dB), than during CPB (only 0.7 dB). The lack of correlation with the rougher SMA16 and EACC pavements is what could be expected and is in line with previous studies [14].

Comparison with measured values on ISO track:

As Figure 6 shows, there is no difference in the ranking of the tyres on the different ISO tracks in this investigation. In Figure 14, the measured values on ISO4 are compared with the measured values on the five conventional pavements.

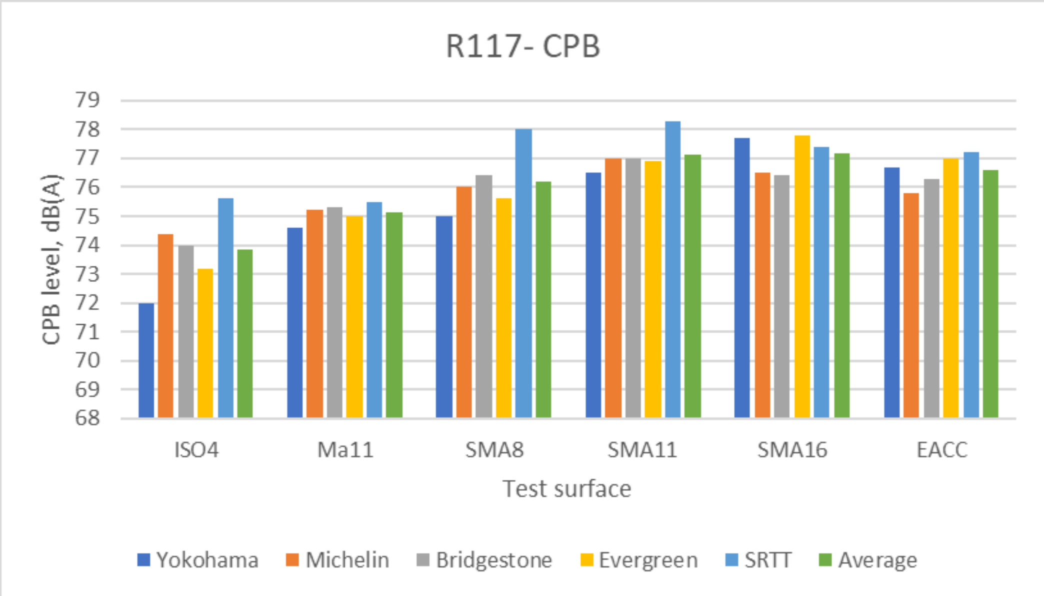


Figure 14. *Comparison of the ranking of the tyres based on measured levels on ISO4 and measured values on the five conventional pavements*

As for the label values, there is no significant correlation between the noise levels on ISO4 and the measured values on the five pavements. However, the Yokohama tyre is the quietest tyre, on the ISO test track, as well as the smoother surfaces, like Ma11 and SM8/11, However, on the rougher surfaces (SMA16 and EACC), this tyre is no longer the quietest. Interesting to see, is also that the SRTT tyre no longer is the noisiest tyre on the rough surfaces. In RRTs like the VDA and ELANORE, the SRTT tyre is clearly noisier than the average C1 tyre, as shown in figures 3 and 6. Therefore, it is regarded not to be representative of the current fleet of C1 tyres, when regarding the noise performance. However, as Figure 12 shows, the SRTT tyre on the SMA16 is no longer the noisiest.

In Figure 15, a linear regression analysis has been made for the correlation between measured levels on ISO2/ISO4 and Ma11, and in Figure 16, the linear regression analysis between ISO4 and SMA8 and SMA11 is shown.

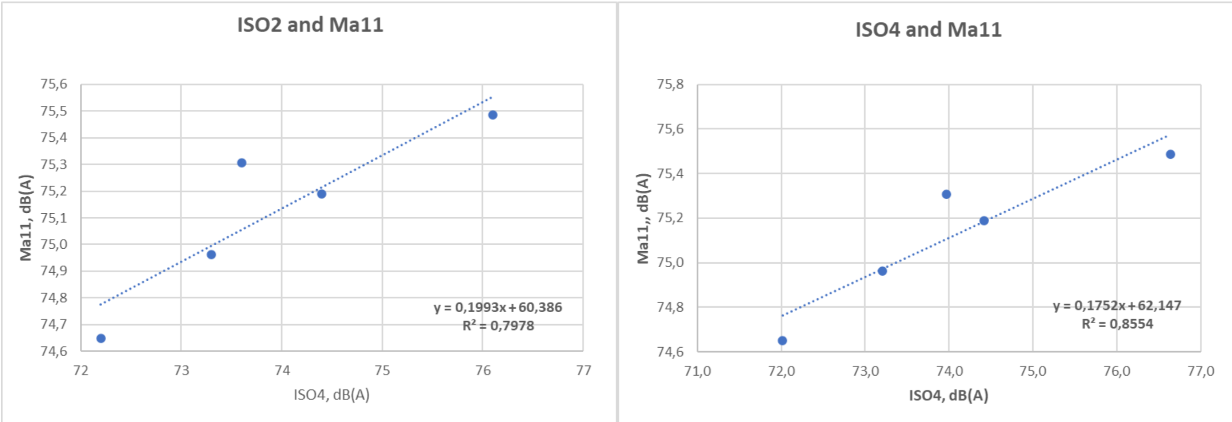


Figure 15. *Linear regression analysis between measured levels on ISO2 (left) and ISO4 (right) and measured levels on Ma11*

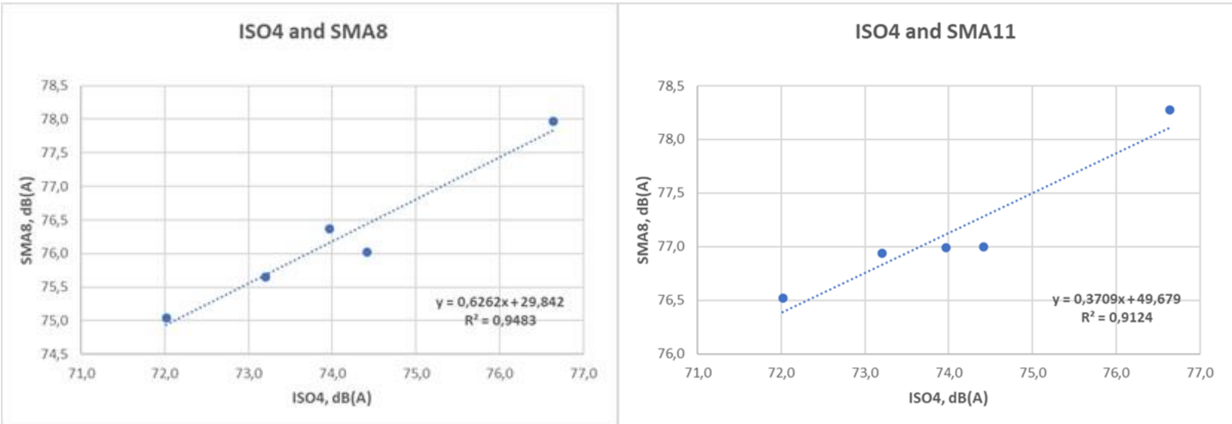


Figure 16. *Linear regression analysis between measured levels on ISO4 and SMA8 (left) and ISO4 and SMA11 (right)*

For the SMA8 and SMA11 pavements, there is a high correlation between the measured levels on ISO4 and these pavements, with R^2 = 0.94 and 0.91. The slope for the regression analysis for SMA8 (0.62) indicates a potential reduction of 0.6 dB if the level on the ISO track is reduced by 1 dB.

Even if the difference in measured levels between the five tyres are rather small, there is a reasonably good correlation between the ISO levels and Ma11 levels, with R^2 around 0.80-0.85. This indicates that a noise reduction on the ISO track will give a certain reduction on the Ma11 smooth surface. However, the slope of the regression is low (around 0.2), indicating a small benefit on the Ma11 due to a noise reduction on the ISO tracks.

4.3 CPX MEASUREMENTS

All the 5 tyres which were included in the CPB measurements have been measured using the GUT CPX trailer on all ISO tracks and on the five conventional pavements. Table 4 and Figure 17 present the measured levels at 80 km/h (same speed as for the CPB measurements). The ISO levels are the average of 4 ISO tracks. The numbering of the tyre corresponds to the numbering used by GUT for test tyres.

Table 4. *Measured CPX levels on ISO tracks and on five conventional pavements*

Tyre	Number	Average ISO level dB(A)	Ma11 dB(A)	SMA8 dB(A)	SMA11 dB(A)	SMA16 dB(A)	EACC dB(A)
Yokohama	T1254	91.4	91.3	94.5	97.6	102.2	97.2
Michelin	T1259	92.4	92.7	94.7	97.3	100.7	96.5
Bridgestone	T1264	92.5	93.1	95.5	97.8	100.6	96.8
Evergreen	T1269	92.6	92.5	95.3	98.1	102.6	97.6
SRTT	T1273	94.4	93.7	96.0	98.6	102.4	97.9
Average	-	***92.7***	***92.8***	***95.2***	***97.9***	***101.7***	***97.2***

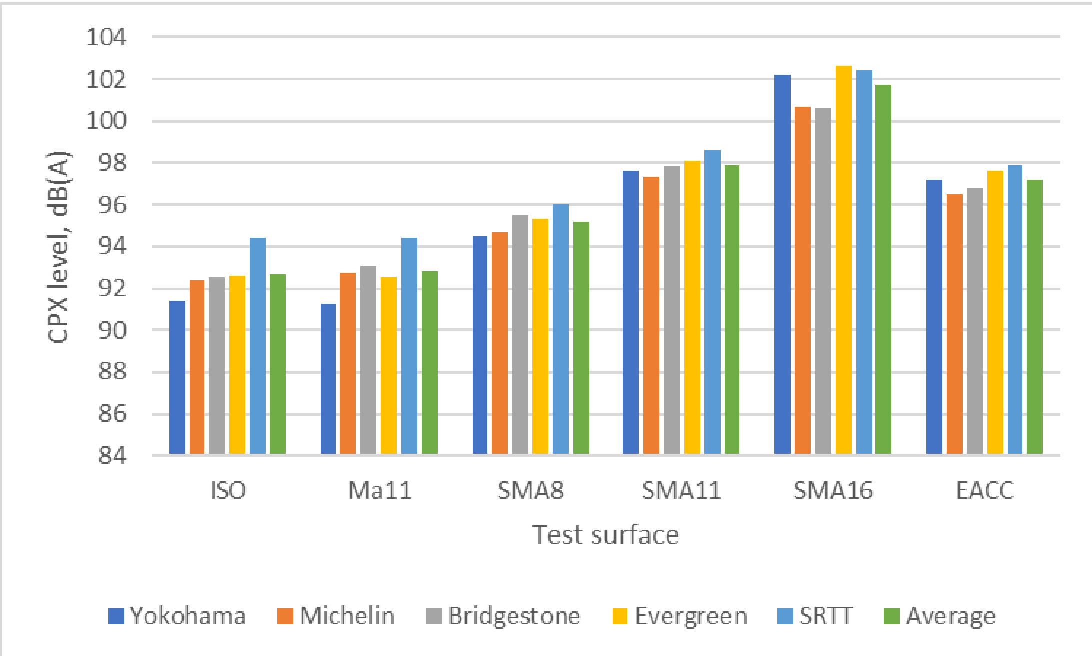


Figure 17. *CPX levels at 80 km/h on average of four ISO tracks and on five conventional pavements*

Using the CPX method, there is clearly a better correlation between the ISO levels and the levels on the Ma11 pavement, as illustrated by the linear regression analysis (Figure 18). However, it should be stressed that only 5 tyres are included in this analysis, and the regression is clearly defined by the quietest and the noisiest tyre.

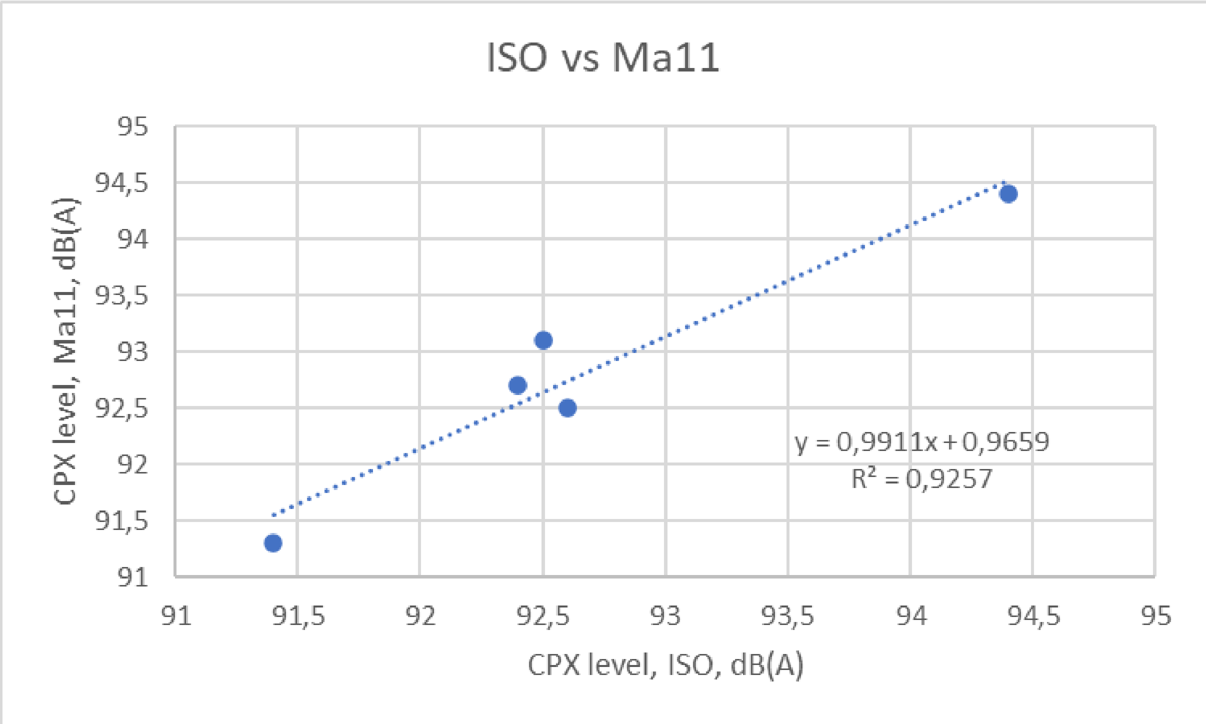


Figure 18. *Linear regression analysis between average of ISO tracks and levels on Ma11*

5 CALIBRATION OPTIONS

5.1 GENERAL CONSIDERATIONS

First some clarification of the use of the term "calibration" in this project. Normally, this term is used to calibrate measurement equipment according to standards like IEC for sound level meters and calibrators), to reduce the uncertainty during measurements.

In this project, the term is used to reduce track-to-track variations, in order to reduce the overall uncertainty. By using such calibration procedure, the target is to improve the trustiness of the noise label value given by the tyre manufacturer.

As shown in Chapter 3, such a calibration procedure has the potential to reduce the uncertainty caused by track-to-track variability by half, from an estimated range of 0.92-1.24 dB down to 0.55 dB (see Figures 8 and 9).

The known variation in the acoustic performance of ISO 10844 surfaces have been analyzed, by using the main physical properties, macrotexture, air voids and sound absorption, to try to explain the measured sound differences.

The STEER project listed the following options for consideration:

1. **Calibration by using reference tyres:** By selecting reference tyres with very stable tyre/road noise properties and measuring noise emission from them at regular time intervals on every ISO test track, the method can provide a relatively accurate measure of the test track noise properties. These can then be used to normalize the surface to a defined reference.
2. **Modelling of test track noise properties:** Very tight requirements on road surface texture, including MPD (Mean Profile Depth) according to ISO 13473-1, skewness according to ISO 13473-2 and texture spectrum according to ISO/TS 13473-4, also the German-derived g-factor or skewness.
3. **Round Robin Tests (RRT):** RRT:s may be performed at regular time intervals to determine how the track noise properties differ between each other or to a defined reference. Thereafter a correction may be made to normalize all tracks to a similar and defined reference. Very limited RRT:s have been conducted in the past. It would be impractical and too expensive to perform on most (hundreds of) ISO test tracks worldwide.
4. **3D-printed reference surface**: A durable and accurately copied hard surface from a defined ISO test surface can be applied in the wheel tracks of the test track using 3D-printing. It can be used to produce replicas of a reference surface (the same for all users worldwide) applicable and virtually identical on all test tracks. Most of the deviations in noise properties can be eliminated if this method is used. Although 3D-printing is already possible, in principle, it is not yet tried to lay such pavement replicas on an actual test track, but it is technically possible.

In addition to these options, it may also be possible to establish a "virtual reference ISO track". This may be evaluated based on a sufficient number of measurements on different ISO tracks and in different regions of the world.

Options 1 and 2 were considered as the most promising alternatives for calibrating ISO test tracks with respect to their noise properties while still being reasonably practical to implement.

For option 1, there are (at least?) 4 different possibilities:

1. Using the SRTT tyre and CPB measurements
2. Using "average tyre" and CPB measurements
3. Using the SRTT tyre and CPX measurements
4. Using "average tyre" and CPX measurements

5.2 CALIBRATION USING REFERENCE TYRES AND CPB MEASUREMENTS

The option to reduce the track-to-track variation by using a reference tyre would include the following steps:

1. using a set of reference tyres of the SRTT 16” type, specified in ISO/TS 11819-3 [11],
2. mounting on a relatively well-defined vehicle,
3. conducting tyre/road noise measurements according to the method in R117,
4. normalizing the resulting noise level to a reference temperature,
5. and then normalizing the final result to some defined ISO 10844 reference level.

Then the tested ISO test track will be normalized to a common reference level, reducing the spread between results on different test tracks to a significantly lower level.

As only 4 ISO tracks were included in this project and a complete set of measurements for all tyres were only possible to be finalized on 3 ISO tracks, this is not a sufficient number to evaluate a calibration procedure based on the tyres and test tracks used in this project.

However, the VDA RRT was made on 13 ISO tracks, where also the SRTT tyre was part of the tyres used for testing. As mentioned in chapter 2.1, two of the test tracks were assumed to have too high absorption, and thus will not be included in this analysis of the calibration process. Then, a total of 11 ISO tracks from the VDA study and 3 ISO tracks from the ELANORE project have been included in this study.

The analysis has been made for measurements at the speed of 80 km/h. The calibration process using the SRTT has been done the following way (references in parentheses to Table 5):

1) List the measured noise levels for the SRTT tyre on each test track (column 2)
2) Calculate the average noise levels for SRTT tyre for all 14 test tracks (end of column 2)

3) For each of the test track, subtract the average level of the SRTT (end of column 2) from the measured noise level of the SRTT level on each test track (column 2, results in column 4 listed as" correction factor""), This correction factor can be negative or positive.
4) For each average noise levels (all tyres) add the correction factor (column 4)and the corrected noise level for each track is then given in column 5.,

This approach has been applied to both the ELANORE RRT and to the VDA RRT, but separately as these two RRTs differ quite much in test conditions:

- Different test vehicle (VDA: VW e-Golf, ELANORE: Skoda Superb)
- Different testing conditions concerning tyre load and tyre inflation pressure (VDA: Cruise-by in UN ECE Regulation 51.03 conditions, ELANORE: UN ECE Regulation 117)
- Different sets of test tyres, including SRTT

Figure 19 shows the measured average noise levels at 80 km/h for the VDA test tracks (excluding slick tyre and test tracks S09 and S12) and the average levels from the ELANORE test tracks. In addition, the measured noise levels for the SRTT tyre are shown. The figure illustrates that the variation in the SRTT levels follows the variation in the levels of the other tyres. This indicates that it is feasible to use the SRTT tyre as a "calibration tyre".

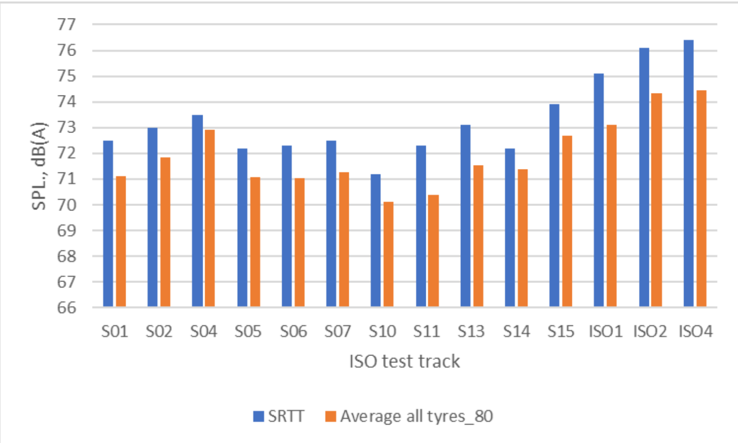


Figure 19. *Comparison of measured sound levels at 80 km/h for each test track (average of all tyres, excl. slick tyre at VDA) (red columns) and the corresponding sound level for the SRTT tyre on each test track (blue column)*

Table 5 presents the results from this procedure, including max-min values for the 3 ISO test tracks in the ELANORE project. Results from ISO3 could not be used, as no measurements with the SRTT were made on this test track, due to rainfall.

Table 1. Using the SRTT tyre values to reduce track-to-track variability

Test track	SRTT noise level	Average tyre noise level	"Correction" factor	Corrected average noise level
ISO1	75.1	73.13	0.77	73.89
ISO2	76.1	74.35	0.23	74.12
ISO3	76.4	74.43	0.53	73.90
Average	75.87	73.97		73.97
Max-min	1.3	1.3		0.23

This approach shows that the track-to-track variation is reduced from 1.3 dB down to 0.23 dB, a reduction of 18 %.

Using the same approach on the VDA RRT results (including S09 and S12) gave a reduction of track-to-track variation from 5.6 dB down to 1.2 dB. The effect of this calibration approach is shown in figure 20 (from STEER [5]).

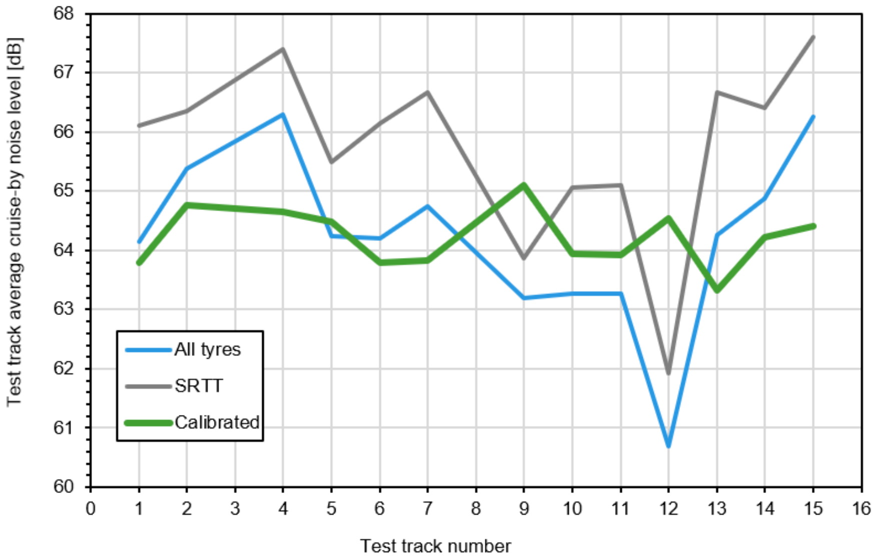


Figure 20. Comparison of measured cruise-by sound levels at 50 km/h for each of the test tracks (average of all tyres excl. slick tyre, blue curve) and the corresponding sound levels after implementing the calibration procedure (green curve). The SRTT sound levels are shown in the back (brown curve). (Graph from STEER [5]).

In the present estimation of the overall uncertainty for UN Regulation 117, the track-to-track variation is set to 5.4 dB, giving a standard uncertainty of 1.56 dB. The overall combined expanded uncertainty (95 % confidence) is calculated to 3.44 dB[20]. If this variation is reduced to 2 dB (considered global variations of ISO tracks), the standard uncertainty is reduced to 0.58 dB and the combined expanded uncertainty to 1.85 dB.

Such an improvement of the uncertainty will be an important contributor to the improvement of the tyre noise labelling procedure. However, it is recommended that the measurements with an SRTT tyre on the various test tracks are done with the same loading, even if the test vehicles are different.

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5.3 CALIBRATION USING AVERAGE TYRES AND ROAD SURFACE

The SRTT tyre is regarded not to be representative of the current fleet of C1 tyres. Therefore, it is interesting also to look for alternatives.

One option could be to establish the "average" ISO test surface, based on an average level from a batch of tyres, as for example data from the VDA RRT.

According to the VDA RRT, the average level from all tyres on all ISO test tracks (excluding slick and tracks S09 and S12) is 64,3 dB at 50 km/h and approximately 71.3 dB at 80 km/h (value taken from ETRTO figure [3]). It is then possible to use this value instead of the average for the SRTT tyres (73.3 dB) or one could choose the tyre having a pass-by level as close as possible to this value and this was found to be R05 on S14. The average level on S14 is 71.4, so very close to the average of all VDA test tracks. And on S14, the tyre R05 was measured to 71.9 dB. From the VDA report [1] the average MPD values are in the range of 0.4 – 0.5, which indicates a typical value for ISO tracks. The tyre R05 is not specified in the report, but it can either be a summer tyre of dimensions 205/55 R16 or a summer tyre with dimensions 245/40 R16.

In practice, choosing either the average value of 71.4 dB for test track, or the "average" tyre (R05 on S14) does not make a significant difference for the "calibrated" results. By using the average test track value, the track-to-track variation is reduced from 2.82 dB down to 1.35 dB. Figure 20 shows the effect of this method for calibration.

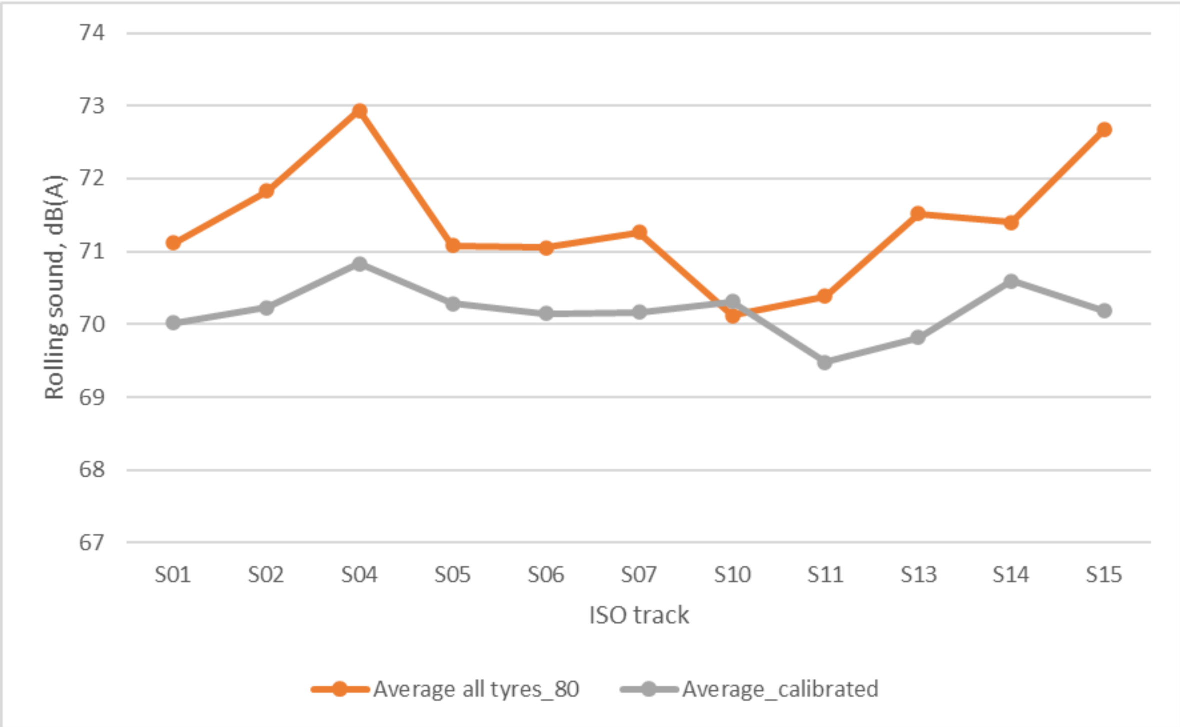

Figure 20. *Calibration of track-to-track variation (VDA RRT) by using the average level of all test tracks as correction factor.*

Using either the "average" ISO track level from a batch of tyres or the "average" tyre on these surfaces reduces the track-to-track variability. However, it does not seem to be as effective as using the SRTT tyre.

Another "uncertainty" for this method is that the pass-by level of "the average tyre" may change over time. Also, to use only the VDA results to establish an "average" ISO test track pass-by noise level is also not very reliable. More data from round-robin test should be included.

If average measured pass-by levels of a wide range of tyres (C1, C2 and C3) can be established from ISO tracks around the world, it should be feasible to establish a so-called average ISO track, or a "virtual" test track.

5.4 CPX CALIBRATION

On all 4 ISO tracks, CPX measurements were conducted with 11 tyres and loading according to Reg.117. Due to the weather conditions, only 7 tyres were measured on ISO3. The SRTT tyre were among the tyres which were included in all 4 ISO tracks. Table 6 shows the measured levels of the SRTT tyre, as well as the average level of all tyres measured on the tracks, using the GUT CPX trailer at a speed of 80 km/h. For this case, and with only 4 ISO tracks measured, any calibration procedure based on the SRTT tyre will not work. The main reason being that the variation of the SRTT tyres is larger than the variation of the average levels of the tested tyres. The track-to-track variation using the CPX method is only 1.2 dB. Using the calibration approach as described in the previous chapter will *increase* the spread to 2.5 dB, rather than reduce it. If the approach of using an "average" tyre (in this case a tyre with the average level on all 4 ISO tracks of 93.4 dB), does not give an improvement of the track-to-track variation.

Table 6. *Measured CPX levels at 80 km/h for the SRTT tyre and the average levels of all tyres measured on the 4 ISO tracks*

Track	SRTT (T1273), dB(A)	Average of all tyres, dB(A)
ISO1	92.2	92.5
ISO2	95.9	93.7
ISO3	94.7	92.6
ISO4	94.7	93.7
Average	94.1	93.1
Max-min	3.7	1.2

5.5 OTHER OPTIONS

There are two additional options for establishing an "average" pass-by level of a tyre on ISO tracks:

- using a replica of an "average" ISO test surface mounted on a drum
- using a theoretical calculation of the expected pass-by level by road surface input data such as MPD-value, g-factor and absorption values (VDA approach)

5.5.1 LABORATORY DRUM METHOD AND ISO SURFACE REPLICA

In a future method, a 3D printed pavement replica, representing an "average" ISO track may be used. There are ongoing discussions in different working groups on this topic. Such a standard replica may then be implemented in laboratories with drum measurement facilities.

As part of the ELANORE project, all tyres have been measured on a replica of the ISO surface at the drum facilities of GUT [15]. However, it should be noted that this was a replica of a defined ISO test track in Sweden.

Since these measurements have been made with microphone positions close to the drum (CPX positions), it is not feasible to use these data on the CPB measurements in the VDA project.

The SRTT tyre (T1273) was measured both on the drum replica of an ISO surface ("CPX positions") and on the 4 ISO tracks. As Table 6 shows, the average level was 94.1 dB. The drum measurements have been reported in TR05-2-ELANORE-GUT-05-(2022) [15] and according to these measurements, this SRTT tyre was measured to 99.5 dB at a speed of 80 km/h. Thus, it is not consistent with what was measured on the ISO tracks. To use any "drum" measurements for a calibration procedure then seems not feasible.

5.5.2 THEORETICAL CORRECTION BASED ON SURFACE CHARACTERISTICS

In connection with the VDA project, Müller BBM proposed a method to calculate the pass-by level based on the following road surface texture data:

- The MPD value
- The g-factor
- The absorption value in the wheel tracks

The MPD value and g-factor are measured using a defined unit developed by Müller BBM, named Surface Texture Drone. This drone was hired for the ELANORE project to measure these values on all 4 ISO tracks. Figure 21 shows a picture from these measurements on one of the ISO tracks.

Figure 21. *Surface texture drone (left) and conduction measurements (right)*

Based on the measured surface parameters VDA developed an equation for estimation of a pass-by level at 50 km/h as shown below:

$$L_{crs} = 60.3 + 27.7 * MPD^{1.5} - 143 \cdot \left(\frac{g \cdot MPD}{(100 \cdot 0.97)}\right)^{4.3} - 36 * \alpha^{0.9}\ [dB] \qquad (1)$$

where:

MPD = Mean profile depth in mm
g = g-factor, a factor between 0 and 1.
α = sound absorption factor, between 0 and 1

Figure 22 shows the calculated pass-by levels at the VDA test tracks, compared to the measured levels (assuming these are the average of all 7 tyres).

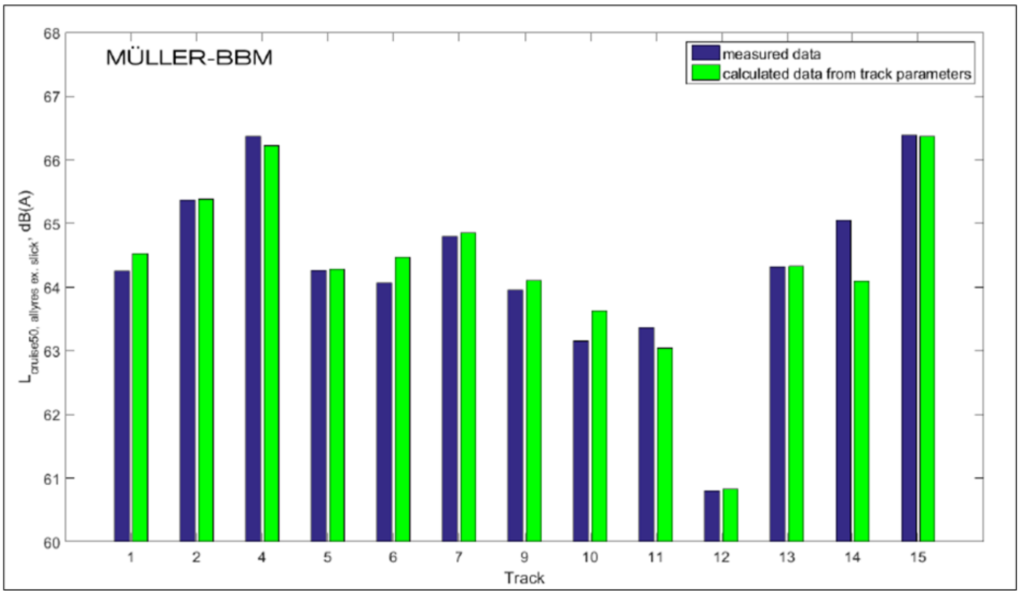

Figure 22. *Comparison of measured levels at 50 km/h (blue) and calculated levels (green) according to equation (1)*

The differences between the measured and calculated data suggest an uncertainty (95 % coverage) of only (±) 0.5 dB. Such an uncertainty, if achieved generally for coast-by at 80 km/h and not just in the VDA study for cruise-by at 50 km/h, would potentially be useful to normalize the ISO test tracks to within an expanded uncertainty of less than 1.0 dB, which would be a great progress.

However, the development of equation (1) is based on the measured data from the VDA RRT. Table 6 shows the results for MPD values, absorption values and estimated pass-by levels on the 4 ISO tracks in the ELANORE RRT, using the surface drone. The absorption values were acquired from the test track owners. These were from recent certification measurements, which are required for the test track to be used for type approval measurements. For ISO4, there are no estimated pass-by level, as the MPD value is outside the allowed range (0.3-0.7).

Table 6. *Test track surface data for the 4 ISO tracks and estimated pass-by level at 50 km/h*

Test track	Year of construction	MPD [mm]	Absorption α	Estimated pass-by level, dB
ISO1	2015	0.59	0.05	62.4
ISO2	2015	0.46	0.03	63.9
ISO3	2016	0.47	0.04	63.7
ISO4	2014	0.95	-	-

In figure 23, the average measured pass-by levels at 50 km/h from the 5 tyres are compared with the estimated level based on equation (1). Note that on ISO3, only 2 tyres were measured, so the comparison with the estimated levels is quite uncertain.

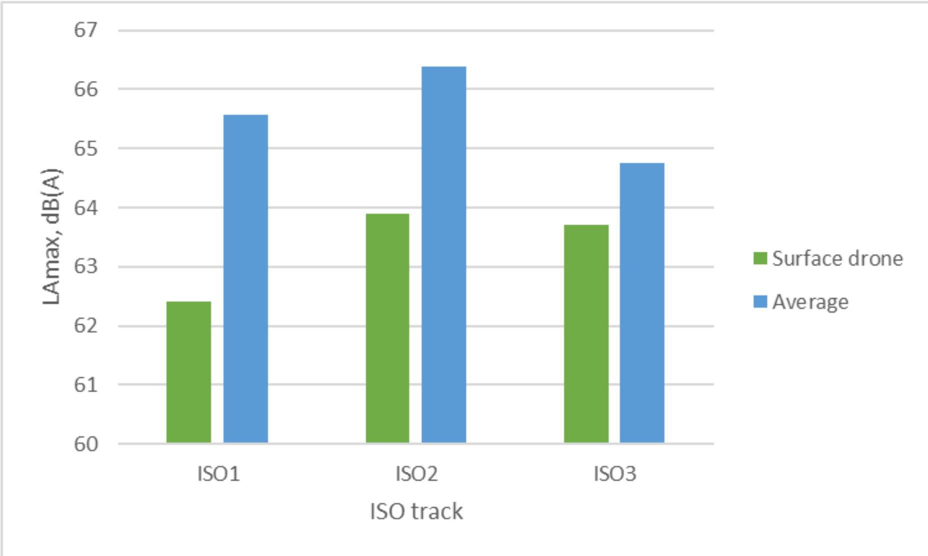

Figure 23. *Comparison of average measured pass-by levels and estimated by the surface drone for the speed of 50 km/h on 3 ISO test tracks*

As the figure shows, there is a quite high difference between measured and calculated levels. The highest difference is for ISO1: 3.2 dB, which is significantly higher than any differences found in the VDA project (Figure 22).

Since only 2 tyres were measured on ISO3, a comparison has been made between the actual measured levels for these two tyres on all the 3 ISO tracks and the estimated pass-by levels. This is shown in figure 24 and in figure 25, the comparison is made for all measured tyres, including average levels, on the ISO tracks compared with the estimated pass-by noise levels.

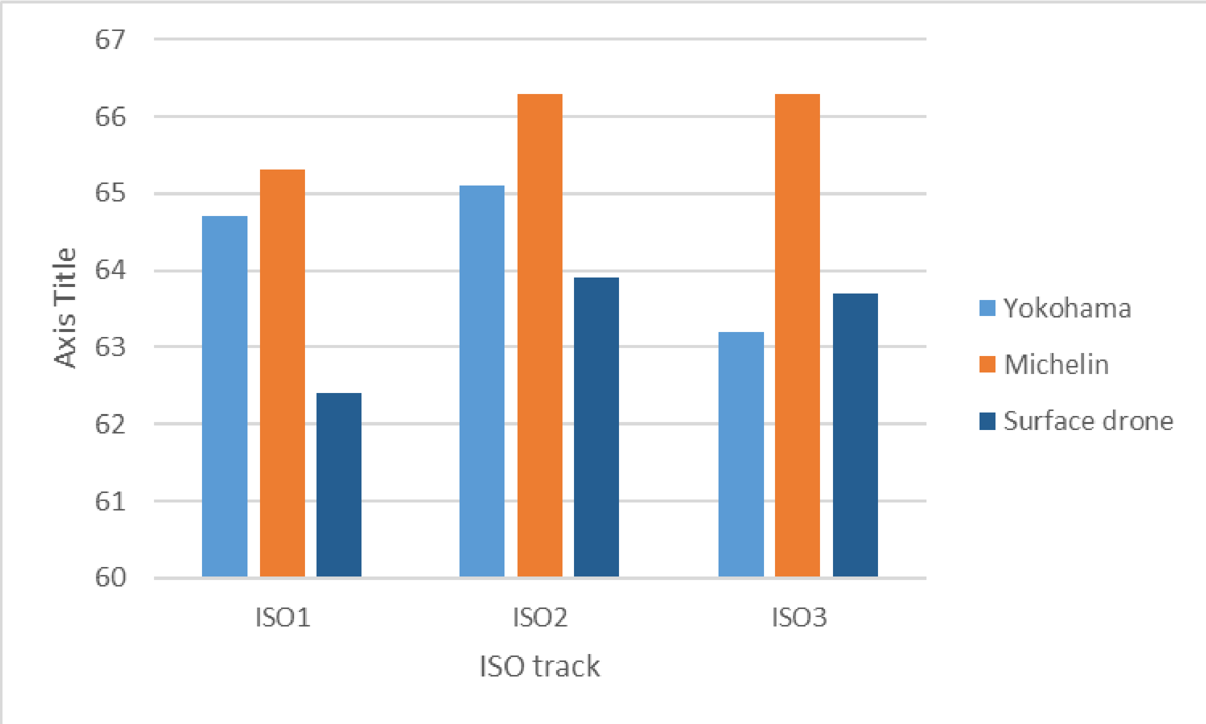

Figure 24. *Comparison of average measured pass-by levels for two tyres and the estimated by the surface drone for the speed of 50 km/h*

The estimated levels seem to be better fitted with the Yokohama summer tyre, than with the Michelin winter tyre, when considering ranking of the surfaces. On ISO3, there is also quite good agreement of the estimated and measured levels for the Yokohama summer tyre.

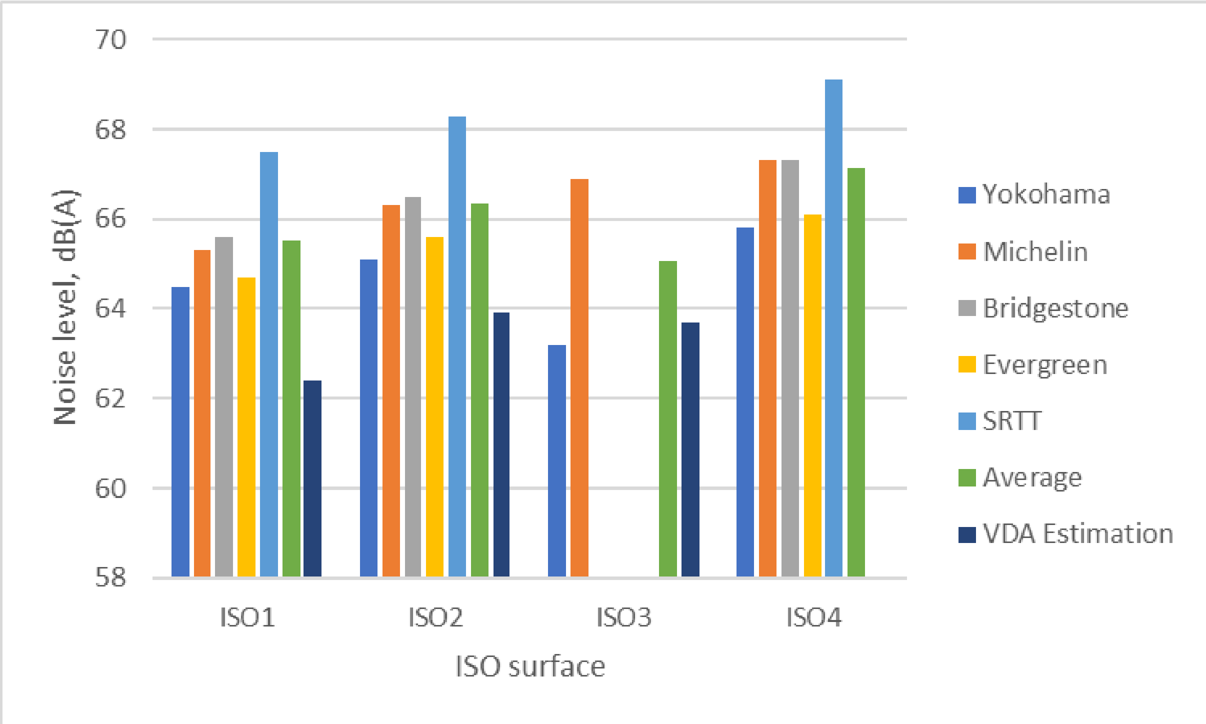

Figure 25. *Comparison of average measured pass-by levels for all tyres and the estimated by the surface drone for the speed of 50 km/h*

The main conclusion from this experiment, is that the use of the VDA equation for prediction of pass-by levels on ISO test tracks that were not part of the development of this procedure, was not successful. Thus, it seems not mature to be used for reducing track-to-track variability between ISO tracks, as the present version is today. Further investigations are needed.

6 CONCLUSIONS AND RECOMMENDATIONS

Some alternative approaches for a calibration procedure to reduce track-to-track variation have been investigated. Based on the findings, the procedure using the SRTT tyre and based on CPB measurements seems the most promising approach. However, one should be aware that this conclusion is based on the data from two independent data sets. Even if the SRTT tyre has been used for both projects, there is a degree of uncertainty of this analysis.

There is some doubt also regarding the use of the SRTT tyre in such a calibration procedure. The main criticism is that the tyre does not any more represent the modern C1 tyres. The measurements on the ISO tracks and also on typical road surfaces like SMA8 or SMA11 this tyre has on average, a higher noise level than modern C1 tyres (see Figure 14). However, on rougher surfaces like SMA16 or EACC, this tyre has an average noise level compared to the present C1 tyres. In any case, as the SRTT tyre is rather old and not certified to be used on vehicles for normal driving purposes, one should look for a replacement tyre to be used in a calibration procedure.

The use of a "theoretical model" for calculation of expected pass-by levels, like the VDA model, is an interesting approach, but needs further development. When using this model on ISO tracks not being part of the RRT from VDA, the accuracy of the calculation is not satisfactory (see Figure 23 and 24). The model needs further development and validation.

The use of a CPX trailer and a reference tyre or using a drum facility could be a simple and economic approach to check the track-to-track variation and the ranking of tyres. This approach is further discussed and developed in the project and will be presented in a technical report from WP4.

As shown in figure 26, the ranking of the tyres changes considerably depending on ISO track, on road surface or on the drum. Note that not all tyres were measured on the ISO3 test track.

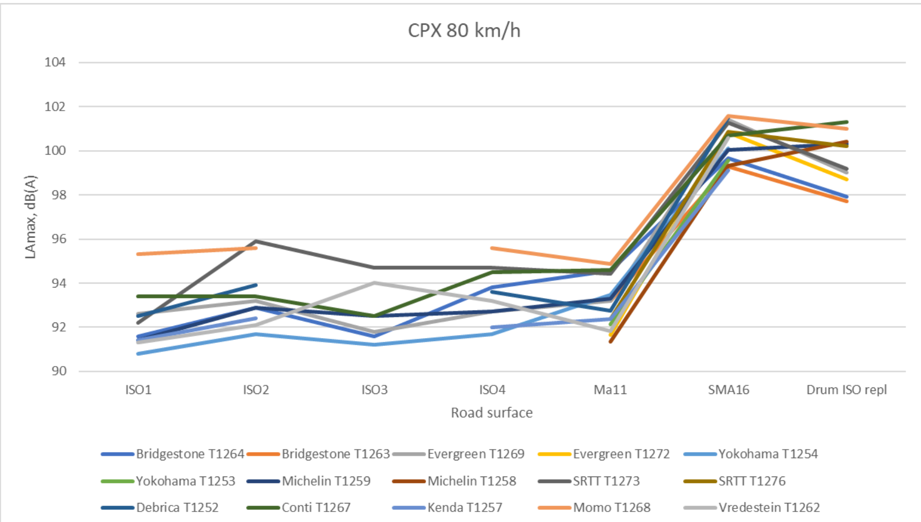

Figure 26. *CPX measurements of 11 tyres on 4 ISO tracks, two trafficked roads and on the drum ISO replica*

It is necessary to reduce track-to-track variations in order to reduce the uncertainty for the tyre test procedure (Reg.117), but also the tyre labelling process for noise. As shown in the STEER project, a calibration procedure can effectively reduce the uncertainty by half.

Based on current knowledge of track-to-track variations, it should be feasible to establish a sort of reference noise level based on the SRTT tyre, which could be used for a calibration procedure. If this procedure should be based on CPB measurements, like in Reg.117, or based on a new procedure based on CPX and a trailer method, needs to be further developed and investigated.

The current data is based on European test track. Data from other regions, like USA or Asia, based on SRTT measurements should be made, to establish a worldwide "reference" ISO track, to be a foundation for a calibration procedure.

The present version of the ISO track standard (ISO 10844) from 2021 is not expected to give any significant improvement of track-to-track variation. However, further development of this standard is a continuous process and may in the future also reduce track-to-track variation

In the future, virtual testing may replace physical testing of the noise performance of tyres, maybe in cooperation with drum testing, and this may be a solution to reduce the influence of track-to-track variations.

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