CEDR Transnational Road Research Programme
Call 2018: Noise and Nuisance

Funded by Belgium, Denmark, Ireland, Netherlands, Norway, Sweden, United Kingdom

Temperature effects on tyre/road noise measurements

Work package: WP3/Task 3.1

Type of document: Project report R3.1

The report is also documentation for Milestone 3.1

Date: 06.07.2021

Main institutions for deliverable:

VTI

Partners:

G+P

BRRC

SINTEF

Nokian Tyres plc

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CEDR Call 2018: Noise and Nuisance

STEER: Strengthening the Effect of quieter tyres on European Roads

Temperature effects on tyre/road noise measurements

Due date of deliverable:	2020-11-15
Actual submission date:	2020-11-30
Draft submission:	2020-11-16
Final submission:	2021-06-29

Start date of project: 2019-12-01 End date of project: 2021-12-31

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SUMMARY

This report reviews the influence of temperature on tyre/road noise emission and the existing ways to correct noise measurements for this influence to a reference condition of 20 ^{o}C. Temperatures considered are mainly air and road (test track) temperatures but also tyre temperatures are discussed.

The aim is to suggest the most relevant, accurate and up-to-date temperature corrections for tyre/road noise measured on ISO 10844 test tracks. Focus is on test conditions existing when tyre noise labelling measurements are conducted, i.e., coast-by measurements on ISO 10844 surfaces within the allowed temperature range of ECE R117.

After the existing temperature corrections in relevant standards and regulations are reviewed, the latest information about the noise-temperature relations is explored and commented. A special aim is to find a way to convert the temperature corrections from being based on air to being based on test surface temperature, and vice versa. It is recognized that, ideally, one would prefer to use tyre temperatures, but since such temperatures vary substantially in both location on and inside the tyre and with time, it is premature to use tyre temperatures for the corrections. The new research reviewed in the report suggest that tyre temperatures are more influenced by air than by surface temperatures measured as dB per degree C, even when compensating for the fact that surface temperatures generally vary more than air temperatures.

Temperature corrections based on air temperature shall be based on ISO/DTS 13471-2 as no reason to revise that correction has been found. Using the relations measured between air and test surface (road) temperature, a corresponding correction based on surface temperature is suggested. This is compared to the presently used correction in the regulation for testing noise emission of tyres, namely ECE R117. It is found that the later is too conservative and shall be revised to a greater correction.

The report deals essentially with C1 and C2 tyres but should ideally be updated with a review for C3 tyres, although such tyres are not primarily dealt with in the STEER project. Unfortunately, no new C3 data were available at the time of writing.

Finally, a set of recommendations with the aim to reduce measurement uncertainties caused by temperature being too far away from the reference temperature (20 ^{o}C) are suggested. In brief, they include the following measures:

- Preferably change from basing the correction on surface temperature to air temperature
- If this is not politically possible, one can retain the old procedure but using a more progressive correction than today, which is part-linear; i.e., it includes two linear relations under and above a certain “knee” temperature
- Conduct research to try to find a suitable and more relevant correction based on tyre temperature for the future. In the meantime, it is envisioned that the use of an average of air and surface temperatures (maybe weighted) would improve the correction, but this must be tested further
- The allowed temperature range is limited to a maximum temperature of 40 ^{o}C for both air and surface temperatures
- To facilitate the above, measures are proposed to colour the usually “black” asphalt ISO surfaces in a light greyish colour and/or to use a temperature-regulating pipe system built into the pavement to heat and/or cool the pavement by means of conventional heating or cooling systems.

By implementing these recommendations, it is expected that the uncertainty contribution of temperature deviating from the reference condition is reduced significantly.

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1. Introduction and scope

In Work Package 3, Task 1, the temperature effects on noise emissions are evaluated, with focus on tyre/road noise labelling measurements. However, according to the original plans, this does not include specific new measurements of temperature influence.

The temperature correction in Regulation ECE R117, i.e., what is presently applied in labelling measurements, is compared to the proposal in this project. For this purpose, the results from ISO/TC 43/SC 1/WG 27 are considered, as well as supplements by existing data from e.g. Switzerland, Poland and Japan were intended to enlarge the data base. However, it appeared that no new data were available from Switzerland and Poland; on the other hand, it was possible to analyze some old data from an international project plus considering some new data presented by the tyre and vehicle industries. The report should ideally be updated with data for C3 tyres, although such tyres are not primarily dealt with in this project. No new C3 data were available at the time of writing.

The aim is to suggest the most relevant, accurate and up-to-date temperature corrections for tyre/road noise measured on ISO 10844 test tracks. Focus shall be on test conditions existing when tyre noise labelling measurements are conducted, i.e., coast-by measurements on ISO 10844 surfaces within the allowed temperature range of ECE R117.

2. Standard procedures for correction of the effects of temperature on noise

2.1. UNECE and EU regulations

The UNECE (United Nations Economic Commission for Europe) Regulation 117, here referred to as ECE R117 [ECE R117, 2011], specifies the approval of tyres regarding the characteristics of “rolling sound emissions”, adhesion on wet surfaces, and rolling resistance. The regulation first entered into force in January 2011 and is currently available in its third revision, which entered into force in February 2014. The document has been further amended four times; the latest amendment is from January 2016 and includes two corrigenda. Even though a fourth revision is available, it has not entered into force yet, therefore, this text focuses on the third revision with the respective amendments and corrigenda.

The origins of the temperature correction date back to when the first regulation on tyre/road noise was published in the EU, in directive 2001/43/EC, in 2001. It was not a recommendation from the responsible ISO Working Group (ISO/TC 43/SC 1/WG 27) but was a proposal by tyre manufacturers. When EU regulations were published in 2009, namely EC 661/2009 [EC 661, 2009] and EC 1222/2009 [EC 1222, 2009], they relied on the specifications found in ECE R117, thereof incorporating the same temperature correction procedure. Note that directive 2001/43/EC is no longer in force and was replaced by EC 661/2009, however, after five amendments and two corrigenda, the temperature correction procedure still refers to that of ECE R117.

According to ECE R117, the “rolling sound emissions” (what ISO and most researchers refer to as tyre/road noise) are measured by coast-by tests, in which the maximum sound pressure level of a vehicle is recorded by microphones located beside the test track. The test is to be carried out on a standard road surface and the test vehicle’s speed shall be within the range of 70–90 km/h for tyres of classes C1 and C2, and within the range 60–80 km/h for tyres of class C3. The reference vehicle speed for classes C1 and C2 is 80 km/h while for class C3 it is 70 km/h. C1 tyres can generally be said to be tyres for passenger cars (including most SUV:s), C2 tyres for light commercial vehicles (such as vans and mini-busses) and C3 tyres for heavy trucks and busses; for exact definitions refer to ECE R117. The test procedure requires at least four measurements on each side of the test vehicle for speeds below the reference speed, and at least four measurements when the speed is above the reference speed. The test speeds are also required to be equally spaced within the speed range for each tyre class. Note that ECE R117 does not provide a temperature correction for tyres belonging to class C3.

It is mandatory to measure both air and surface temperature with an accuracy of ± 1 °C. According to the meteorological conditions required for this test, the air temperature shall be within 5–40 °C or the surface temperature shall be within 5–50 °C. The regulation ECE.R117 also requires the tyres to be warmed-up by running under the test conditions; however, it does not describe in detail how the warm-up process should be.

Regarding the temperature correction proposed by ECE R117, a procedure for normalizing the results to a reference temperature of 20 °C is provided for tyres belonging to classes C1 and C2 only. The temperature correction is carried out by applying the following eq. 1.

$$L_R(\vartheta_{ref}) = L_R(\vartheta) + K(\vartheta_{ref} - \vartheta) \qquad \text{eq. 1}$$

where ϑ is the measured test surface temperature, and ϑ_{ref} is the reference temperature of 20 °C. The coefficient K is defined according to the tyre class and the difference between measured surface temperature and the reference temperature, as shown in Table 1. The speed ranges and reference speeds for each tyre class are also shown in the same table. The procedure is illustrated in Figure 1.

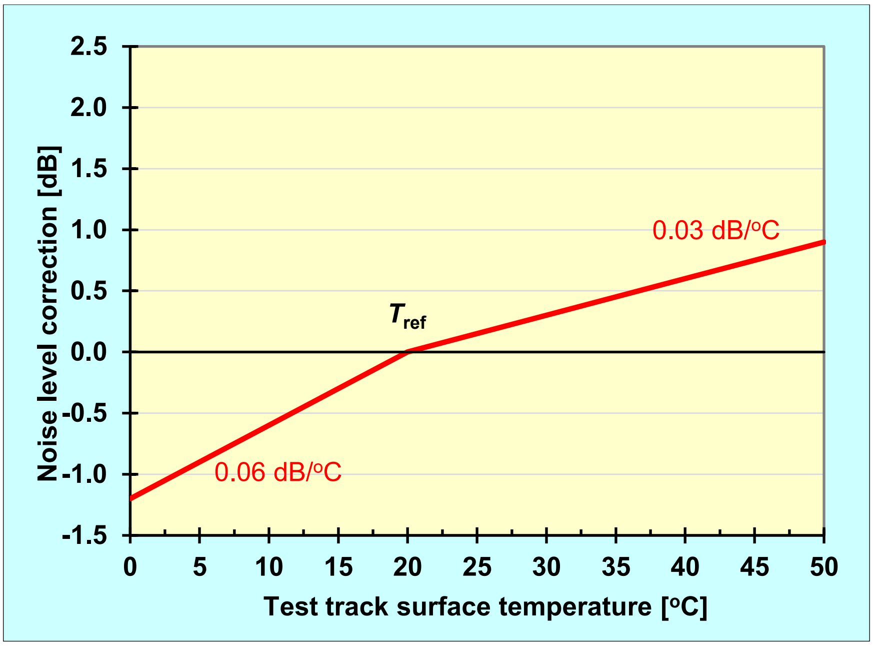

Figure 1: The noise-temperature relation that is used for car (C1) tyres in a number of EU and ECE regulations (see the text).

Table 1: Temperature correction coefficient according to ECE R117 and some test requirements. Note that the Regulation still uses the unit dB(A), which is not allowed according to ISO terminology standards. The unit shall be dB and not dB(A).

Tyre class	Speed range	Reference speed	Road temperature ϑ	Correction coefficient K
C1	70–90 km/h	80 km/h	$> \vartheta_{ref}$	-0.03 dB(A)/°C
			$< \vartheta_{ref}$	-0.06 dB(A)/°C
C2			-	-0.02 dB(A)/°C
C3	60–80 km/h	70 km/h	-	-

If the temperature during measurement does not change more than 5 °C, the mean of the measured temperatures may be used to apply the temperature corrections. Otherwise, the temperature correction shall be applied to each individual measurement using the corresponding measured temperature. After applying the temperature correction, according to ECE R117, the results shall be reduced by 1 dB(A) in order "to account for instrument inaccuracies" and finally rounded down to the nearest lower integer dB value.

2.2. CPX method: ISO/TS 13471-1:2017

The CPX (Close Proximity) method evaluates the tyre/road noise resulting from the tyre/road interaction by analysing the noise near the source, i.e., near the contact between the tyre and the road surface. To do so, at least two microphones are positioned in standardized positions near the tyre/road contact. The measurement method itself is standardized by ISO 11819-2 [ISO 11819-2, 2017]. Two reference tyres for the CPX method are specified in ISO/TS 11819-3 [ISO 11819-3, 2017] and include a tyre for light vehicles, the so-called P1 tyre, and another tyre which is a proxy for heavy vehicles, so-called H1 tyre. Additionally, the temperature correction procedure for the CPX method with its two reference tyres is standardized in ISO/TS 13471-1 [ISO/TS 13471-1, 2017]. All the aforementioned standards are in their first edition and were subject to a review in 2020, in which case all of them were confirmed for another three-year period. However, the ISO/TS 11819-3 has recently been amended regarding the tyre rubber correction coefficient. Note that even though the main focus of ISO/TS 13471-1 is the CPX method, it may also be applied to similar methods, such as the OBSI (On-Board Sound Intensity Method) which is essentially used in North America [AASHTO, 2013].

According to ISO/TS 13471-1:2017 it is mandatory to measure air temperature and optional to measure road and tyre temperature. The air temperature measurement shall have a duration of at least 15 s and the resulting reading shall be rounded to the first decimal, in °C. The correction procedure is a semi-generic one, as it is a function of the road surface category. Three different road surface categories are described in the standard: (i) dense asphaltic surface, (ii) cement concrete, (iii) porous asphalt surface. The correction adopts the reference temperature of 20 °C and uses a linear correction to normalize the measured noise levels to this reference temperature following eq. 2.

$$C_{T,t} = -\gamma_t(T - T_{ref}) \qquad \text{eq. 2}$$

where $C_{T,t}$ is the CPX level correction for a measurement temperature (*T*) and tyre (*t*), γ_t is the temperature coefficient for tyre *t* (either P1 or H1), in dB/°C, *T* is the air temperature during measurement, in °C, and T_{ref} is the reference temperature of 20 °C. Moreover, the temperature correction is speed dependent, which is expressed by the coefficient γ_t and the dependency on speed as shown in Table 2.

Table 2: Temperature coefficients for each road surface category according to ISO/TS 13471-1:2017.

Road Surface Category	Temperature coefficients
Dense asphaltic surfaces	$\gamma_{P1} = \gamma_{H1} = -0.14 + 0.0006v$
Cement concrete surfaces	$\gamma_{P1} = \gamma_{H1} = -0.10 + 0.0004v$
Porous asphalt surfaces	$\gamma_{P1} = \gamma_{H1} = -0.08 + 0.0004v$

In case the surface does not fit any of the surface categories shown in Table 2, a specific coefficient should be determined by experiments or, alternatively, a coefficient for a surface category which is judged to be the most similar shall be used. The fact that the actual surface may have coefficients that differ from those in Table 2 is a source of uncertainty and a consequence of a semi-generic method that is based on a limited number of surface categories. It is underscored that the correction procedure proposed by ISO/TS 13471-1 does not take into account the effect of air density, which may be an issue for OBSI measurement, but is not an issue for the CPX method.

Even though the standard points out that the temperature correction shall ideally be made in the frequency domain, the data available when the standard was published was not sufficiently consistent to propose a temperature correction in the frequency domain. It is, however, pointed out in the standard that the available data suggest that the temperature influence is relatively low at the middle frequencies, between 800 Hz and 1250 Hz, while the influence is higher at the higher and lower frequencies.

Typical uncertainties sourced from the temperature coefficients are normally distributed and are estimated to contribute to the measurement uncertainty with 0.15 dB for tyre P1 and 0.25 dB for tyre H1.

2.3. Pass-by methods: ISO/DTS 13471-2:2021

ISO/DTS 13471-2:2021 is a draft technical specification [ISO/DTS 13471-2, 2021], which will be published later as a final TS. This will probably happen at the end of 2021.

Pass-by methods to evaluate tyre/road noise are methods that measure the resulting noise levels from a vehicle that is either (i) coasting-by, (ii) cruising-by, or (iii) driving-by a roadside section where microphones are installed. In the case of a coasting-by, the vehicle has its engine switched-off and transmission in neutral, which implies that the tyres are in free-rolling. In a cruise-by condition, the vehicle's engine is operating, and the transmission is engaged in a way that allows it to maintain a constant speed. Finally, the drive-by condition means that the vehicle passes by with the engine operating, transmission engaged, and accelerator pedal pressed down to obtain a substantial acceleration. An example of a pass-by method is the SPB (Statistical Pass-by) method, which is standardized in ISO 11819-1 [ISO 11819-1, 1997]. Another common application of pass-by methods where temperature has a relevant role is for type approval of tyres, when measurements are carried out on reference test tracks according to ISO 10844 [ISO 10844, 2014].

The temperature correction procedure in ISO/DTS 13471-2:2021 is a semi-generic one that, similar to ISO/TS 13471-1:2017 adopts the reference temperature of 20 °C. The correction was empirically determined based on the relationship between tyre/road noise and ambient air temperature from a compilation of several published investigations.

According to the standard, it is mandatory to measure air temperature and optional to measure road and tyre temperature. The air temperature measurement shall have a duration of at least 15 s and the resulting reading shall be rounded to the first decimal, in °C. The applicable air temperature range for the correction procedure is 5–35 °C. The temperature correction term is given by eq. 3.

$$C_{T,t} = -\gamma_t(T - T_{ref}) \qquad \text{eq. 3}$$

where $C_{T,t}$ is the noise level L_{Amax} correction for a measurement temperature (*T*) and a tyre or vehicle class (*t*), γ_t is the temperature coefficient for tyre or vehicle class *t* (either C1, C2 or C3 for tyre class, or either P1 or H for vehicle class in SPB measurement), in dB/°C, *T* is the air temperature during measurement, in °C, and T_{ref} is the reference temperature of 20 °C. The temperature coefficient for each tyre class is shown in Table 3.

Table 3: Temperature coefficient for each tyre class and road surface category in the draft for ISO/DTS 13471-2. Note that corrections will have the opposite sign.

	C1	C2	C3
Dense asphaltic surfaces	-0.10	-0.10	-0.06
Cement concrete surfaces	-0.07	-0.07	-0.06
Porous asphalt surfaces	-0.05	-0.05	-0.04

Road or test track surfaces of the type complying with ISO 10844 are included in the first category ("dense asphaltic surfaces"). In case the road surface does not fit any of the categories in Table 3, the specific coefficient should be determined by experiments. As an alternative. the coefficient from the surface in Table 3 that is judged to be most similar can be used. The actual surface may differ from the ones in Table 3 and, as concerns also ISO/TS 13471-1, this is a source of uncertainty.

Typical uncertainties sourced from the temperature coefficients are normally distributed and are estimated to contribute to the measurement uncertainty with 0.15 dB for tyres of classes C1 and C2, and 0.20 dB for tyres of class C3. Uncertainties sourced from the temperature measurement are also normally distributed and typically their contribution to the noise measurement is of 0.1 dB irrespective of tyre class.

2.4. OBSI method and AASHTO TP76-13

The OBSI (On-Board Sound Intensity) method is performed by measuring the sound intensity resulting from the tyre/road interaction by means of two probes placed near the contact between the tyre and the road surface. The method is currently standardized in AASHTO T 360:2016 [AASHTO, 2016] which replaced the previous AASHTO TP 76:2013 [AASHTO, 2013]. The measurement is carried out with the standard SRTT tyre (P1 in ISO/TS 11819-3) and the resulting sound intensity is reported as one-third octave bands. The probes are typically attached to the rear wheel of a vehicle but can also be attached to a trailer. The standard specifies tyre inflation pressure and load, tyre rubber hardness and age, speed and air temperature.

The temperature correction procedure normalizes the measured sound intensity level (*IL*) using a linear correction and reference temperature of 20 °C following eq. 4.

$$IL_{Normalized} = IL_{Measured} + 0{,}072(T - T_{ref}) \qquad \text{eq. 4}$$

where $IL_{Measured}$ is the measured sound intensity, in dB(A), T is the measured air temperature, in °C, and T_{ref} is the reference temperature of 20 °C. The result is the normalized sound intensity, $IL_{Normalized}$ to the reference temperature. An equivalent correction is also available for temperatures in Fahrenheit. This procedure shall be applied both to the overall sound intensity and to the one-third octave band intensity levels. The same correction is valid for all road surfaces and speeds within the range of 40–96 km/h, yet only for the SRTT tyre, which is the only reference tyre for the OBSI method. The testing temperature is restricted to the range 4–38 °C and even though the temperature correction is a function of air temperature, it is also recommended to measure road temperature.

Correcting the sound intensity values leads to a reduction in the standard deviations and average ranges as shown by [Lodico, 2015]. Even though a road surface specific temperature correction was able to reduce the ranges even further, the contribution to a pavement specific correction was only marginal when compared to the more substantial reduction obtained by the general correction.

2.5. SAE J57

The standard J57 of the Society of Automotive Engineers (SAE) (2014) provides a procedure for measuring sound generated by test tyres. The tyres to be tested are mounted on a trailer connected to the towing vehicle. The trailer performs a coast-by (engine switched off) and the resulting sound levels are measured by remote microphones on the roadside. At least five measurements for each speed are to be taken and the maximum level during each pass is recorded. The measurements are repeated until five levels are recorded which are within ±0.5 dB(A) of their arithmetic average and this average value is to be used in the temperature correction procedure.

The standard takes temperature effects into account by adopting the reference temperature of 20 °C and requiring that measurements shall be made with at least one set of measurements at surface temperature below the reference temperature and at least one set with road surface temperature above the reference temperature. The sound level at 20 °C is then obtained by a linear interpolation of the sound levels at the two different temperatures to obtain the sound level at 20 °C. As an alternative, if it is not possible to obtain results with surface temperature above and below the reference temperature, a linear regression can be used to obtain the sound level at 20 °C. In this case, there should be at least three different measurements with surface temperatures differing from one another by at least 2 °C and within a range of at least 5 °C. The standard limits the meteorological conditions for the measurements to air temperatures in the range 10–30 °C, road surface temperatures within 5–40 °C and wind speeds less than 18 km/h.

Before measuring, it is required that the tyres are subjected to a break-in period of at least 80 km at typical highway speeds. Additionally, it is required that the tyres are at normal operating temperature during test. It is not, however, clear how to achieve the normal operating temperature.

The repeatability and variability of the procedure in J57 was analysed by [Thompson, 1995]. Measurements were performed with two different C3 tyre sets, a set of 11x24.5 bias traction tyres, and a set of 11R22,5 radial steer tyres with ribbed design. The tyre warm-up was shown to be a key factor that affects the precision. When testing began with cold tyres, an increased number of tests were needed to obtain the required five measurements within 0.5 dB. As it was pointed out by the author, even though J57 requires the tests to be carried out with the tyres at operating temperature, it does not specify the means for achieving this condition. It was suggested that at least 32.2 km (20 miles) of warm-up distance should be necessary.

3. What temperature should be used?

There are three different temperatures that can be considered for the correction procedure: (i) tyre, (ii) road (or test track) surface, and (iii) ambient air. The selection of a temperature comes with different advantages and disadvantages. While it is generally recognized that the tyre temperature is the most relevant temperature for correction purposes, there is still no good agreement as to where and how this temperature should be measured [ISO/TS 13471-1, 2017].

For all three types of temperature, it must be further specified where these temperatures shall be measured. Tyre temperatures vary dramatically depending on where in or on the tyre they are measured and are even subject to variations in time depending on tyre operation. Road or test track surface temperatures may be quite different depending on how far from the surface they are measured, and air temperatures are likewise dependent on how far above the road surface they are measured. There is a discussion about this below.

Even when it is decided not to use the tyre temperature and carry out a correction using air or road temperature, it is important to warm up the tyres so that the temperature stabilizes, and the tyre temperatures may be considered in steady state before measurements are taken. In other words, even when the tyre temperature is not directly used in the correction, it will affect the results. As it was shown in section 2, it is not clearly standardized how the warm-up process should be.

The temperature effects are relevant not only for noise measurements, but also for measuring other properties, such as rolling resistance. For this reason, some previous investigations that focused on rolling resistance and temperature are also included there. Ejsmont et al analysed the effects of tyre temperature (external tread surface temperature) on rolling resistance and pointed out that typical warming-up periods for passenger car tyres are 20–30 min, while for truck tyres this period is at least 30–40 min [Ejsmont et al., 2018]. The authors also point out that, even though it is possible to achieve a proper steady state on drums or on closed-loop test tracks, it is normally not possible to achieve steady state on open roads. For test methods, such as the SPB method, it is impossible to even have information on the tyre temperatures unless the vehicles are equipped with tyre temperature sensors and share this data during measurement. Sandberg, who also focused on rolling resistance, modelled truck tyres considering that, in steady state, the tyre shoulder and the inflated air are approximately at the same temperature [Sandberg, 2001]. This assumption was based on the results obtained by [Janssen and Hall 1980] who showed that the curves for shoulder and air cavity temperatures as a function of time have approximately the same shape under laboratory conditions. Sandberg also considered that C3 tyres reach this steady state when driven at constant speed for a time of 1–2 hours.

Another approach is to measure the bulk temperature with sensors in the tyre, which was done by [Corollaro, 2014]. Even though the author was focusing on tyre/vehicle handling performance, it is interesting to note that the author obtained a saturation temperature that depended on the loading and velocity. Given some simplifying hypotheses the author modelled the influence of temperature on cornering stiffness. The model was then validated obtaining satisfactory results. Even though measuring bulk temperature presents the difficulties of having multiple sensors in the tyre, which may not be practical for more routinely measurements, for applications were higher precision is required, this approach could be of interest. Another relevant obstacle to be considered for sensors embedded in the rubber is the limited lifetime, which will depend on the test manoeuvres.

Some systems measuring with the CPX method are equipped with tyre temperature measuring equipment. The most common is then that an IR sensor measures the temperature on the tyre tread over an area with a diameter of around 50 mm. Noise emission is coming from areas close to the tyre/road contact. Therefore, the parts of the tyre most influenced by temperature should be the tread and the shoulders. Since the shoulder temperatures vary substantially over small areas which are different for different tyres, the only reasonable part to measure on with a fair reproducibility and simple sensors seems to be the tread.

Another possibility is to use the road temperature. This may be measured on the surface or with sensors a bit down into the pavement. As discussed by [Lodico, 2015], the road surface temperature shows considerable scattering when compared to the air temperature. The road surface temperature was observed to vary within a range of 11–17 °C for the same air temperature. The effects are dependent on meteorological conditions and a correction based on surface temperature generally led to lower slopes for the temperature correction when compared to the slopes based on air temperature. As indicated above, another question that arises when using road temperature is whether to measure the surface temperature, which can easily be done by an infra-red or contact sensor, or to use a sensor in the road structure, but near the surface. The later approach can potentially lead to more stable results as the sensor is not exposed to winds, shifting shadows caused by passing clouds and other meteorological effects. However, the tyre/road contact may be at a different temperature than the temperature a bit below the surface.

Air temperature in most cases is considered more stable and easier to measure, which was one of the reasons why it is often used in different standards. Nevertheless, air temperature varies with the sensor's height above the surface; especially on sunny days when the road surface may be hot and there may be a substantial temperature gradient with vertical height. When measured according to the ISO standards mentioned above, therefore, it will not be affected by sun exposure or excessive radiation from the road surface since the sensor is at approx. 1.5 m above the road surface.

The problem with using air temperature, road temperature or even a combination of both is that the noise generation mechanisms are dependent on tyre viscoelastic properties, thus dependent on tyre temperatures. If such temperatures are not available, a more conservative warm-up process could potentially be used, however, it is difficult to guarantee a temperature saturation without having access to advanced tyre temperatures.

Ongoing research (publishing expected later in 2021) in the STEER project shows that combining air and road surface temperatures, with somewhat greater weight on air temperature, provides a good model to estimate tyre temperature measured on the tread. Therefore, an intermediate model for temperature correction to noise may be based on a weighted average of air and surface temperatures. But this is premature to suggest at this time.

4. Data collected in earlier projects

When the ISO Technical Specifications ISO/TS 13471-1 and 13471-2 (the last one is still a draft) were developed, the work relied on data compiled by various researchers and organizations. The following is a list of significant documents for this purpose:

- Bühlmann E., & van Blokland G. Temperature effects on tyre/road noise – A review of empirical research. Proc. of Forum Acusticum 2014. Krakow, Poland, 7–12 September 2014
- Sandberg U., & Mioduszewski P. Temperature influence on measurements of noise properties of road surfaces and possible normalization to a reference temperature. Deliverable D2.2 of project ROSANNE. Available at http://rosanne-project.eu/
- Sandberg U. Standardized corrections for temperature influence on tire/road noise. Proc. of Inter-noise, San Francisco: 2015
- Bühlmann E., & Ziegler T. Temperature effects on tyre/road noise measurements and the main reasons for their variation. Proc. of Inter-noise 2013, 15–18 September, Innsbruck, Austria
- Bühlmann E., Sandberg U., Mioduszewski P. Speed dependency of temperature effects on road traffic noise. Proc. of Inter-noise, San Francisco: 2015
- Mioduszewski P., Ejsmont J., Taryma S., Woźniak R. Temperature influence on tire/road noise evaluated by the drum method. Proc. of Inter-noise, San Francisco: 2015
- Lam Y. K., Leung R. C. K., Hung W. T. Air and road surface temperature corrections for tyre/road noise measurement with Close-Proximity (CPX) method. Article in the Chinese journal Technical Acoustics TA_Vol33_No1_pp56_60 (February 2014)

Those references are cited from the ISO TS documents. They have been used as the basis for determination of the temperature corrections in the ISO TS documents. They are not further reviewed or summarized here.

5. Recent results that have not yet impacted the ISO documents

5.1. Road surface and air temperature data from Nissan Motor Co.

Both air and road temperature data are relevant for the temperature procedures presented in Section 2 of this document. The relationship between road and air temperature can be significantly affected by weather conditions and lead to a higher variability in the results, as discussed in Section 3. As an alternative to measuring the road surface temperature with an infra-red or contact sensor, it is also possible to measure the road surface temperature. Data provided by Nissan Motor Company [Shirahashi, 2020] shows how the air temperature changes simultaneously with the road temperature, which was measured with a sensor located 40 mm below the ISO road surface, see Figure . The road sensor was thus not directly exposed to meteorological conditions, such as wind or direct solar radiation, which is likely to have contributed to more stable measurements. The air and temperature data were provided as readings every 10 minutes for 24-hour periods in 7 different days (Table 4 and Figure 3). In addition, for every temperature reading, the barometric pressure and the air humidity were also provided.

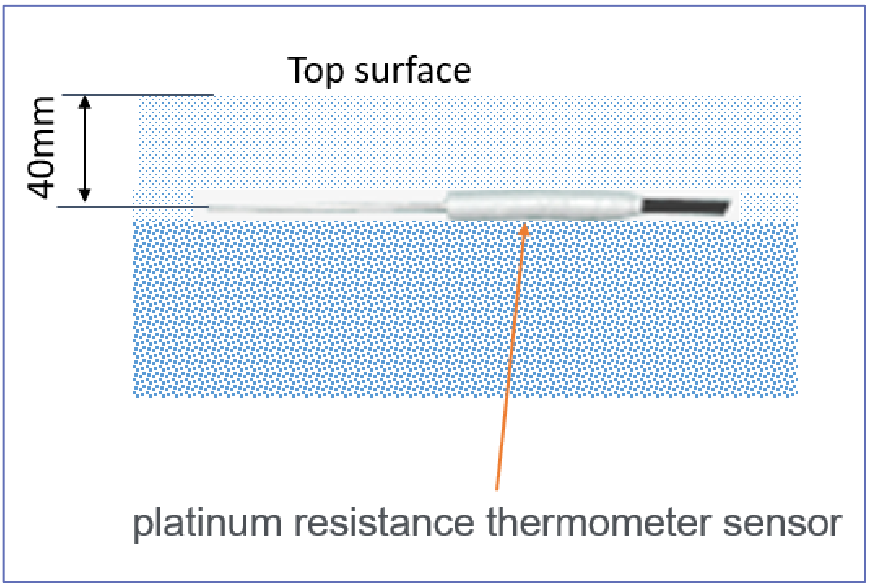

Figure 2: Road temperature sensor used by Nissan Motor Co. Based on information from [Shirahashi, 2020].

A linear regression was calculated using air temperature to predict road temperature. The data was split, by using 70 % to calculate the model and 30 % to test it. The resulting linear regression is shown in Figure 4 and its metrics are shown in Table 4. These data are based on information from [Shirahashi, 2020] but processing has been made by the authors. Table 6 shows the results when multiple regression was applied, including air temperature, barometric pressure and air humidity.

Table 4: Measured dates and reported weather conditions. Based on information from [Shirahashi, 2020].

Date	Weather
06 January	Sunny
21 April	Sunny
25 June	(data not available)
26 June	(data not available)
05 July	Cloudy
11 August	Sunny
16 August	Sunny

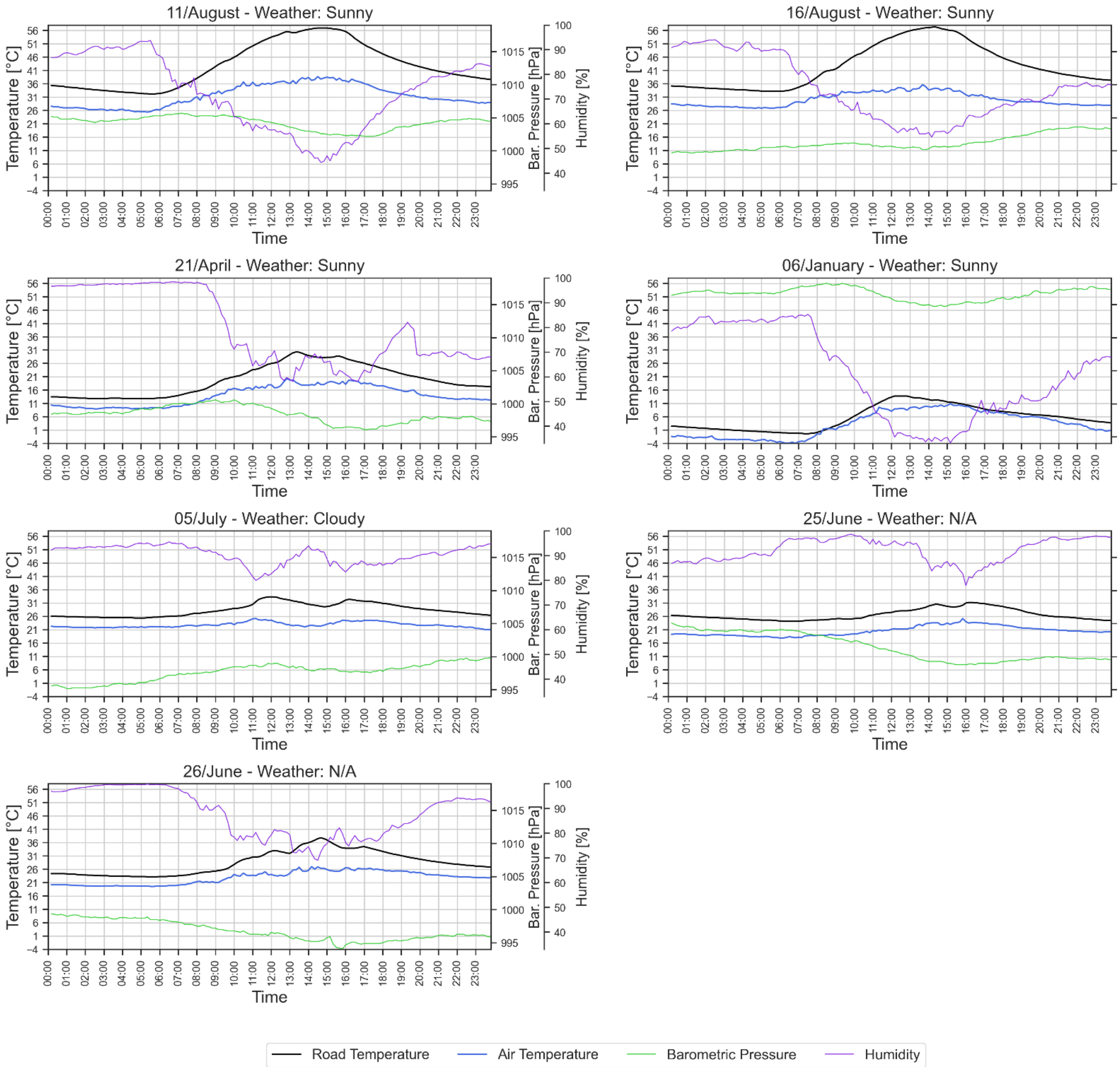

Figure 3: Meteorological variations for seven different days, sampled every 10 minutes. Based on information from [Shirahashi, 2020].

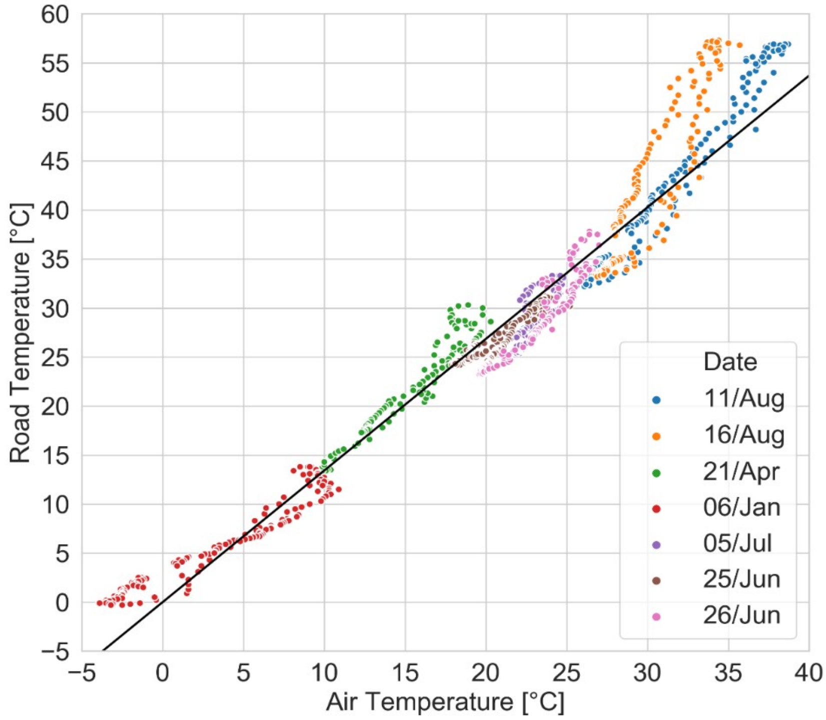

Figure 4: Air and road temperature in linear regression with zero intercept. Based on information from [Shirahashi, 2020] but data processed by the authors.

Table 5: Linear regression with air temperature as predictor for road temperature. The R^2 is adjusted (from the test data) by the Bayesian Information Criterium (BIC).

Predictor	Coefficient	Std. error	P value	95 % conf. int.	R^2 adjusted	BIC
Air temperature [°C]	1.345	0.005	<0.001	[1.335; 1.355]	0.946	3558

Table 6: Multiple linear regression having air temperature, barometric pressure and humidity as predictors for road temperature. The R^2 adjusted (with the test data) and the Bayesian Information Criterium (BIC).

Predictor	Coefficient	Std. error	P value	95 % conf. int.	R^2 adjusted	BIC
Air temperature [°C]	1.359	0.011	<0.001	[1.337; 1.380]	0.965	3378
Barom. pressure [Pa]	0.78	0.001	<0.001	[0.007. 0.009]		
Humidity [%]	-0.1030	0.006	<0.001	[-0.115.-0.091]		

Multiple linear regression leads to a decrease in BIC and slight increase in R^2 adjusted, which means that if data regarding barometric pressure and humidity are available, it is possible to obtain a marginally better prediction of road temperature. If, however, only air temperature is available, it is also possible to estimate the road temperature. Note, however, that the available data encompasses only 7 days; albeit spread over 8 months. It would be desirable to have a larger dataset and different weather conditions to obtain more robust conclusions.

It is especially interesting to note the non-linearity of the regression (the increased slope at high temperatures in Fig. 4). The slope seems to be appr. double as high as for the major part of the slope. This is a manifestation of the increasing solar energy absorption in warm and sunny weather on the generally dark asphalt surfaces of ISO test tracks. One might take this into consideration when establishing a relation between road and air temperatures but using a slope which is lower up to a certain air temperature (say 30 ^{o}C) and a much higher slope at higher air temperatures (say 30-40 ^{o}C). Not doing so might create an uncertainty of up to 10 ^{o}C at the higher end. A complication is that the temperature where the slope changes might depend on a number of factors, such as climate zone, sun height above the horizon and albedo of the road surface.

5.2. Round Robin Test on ISO test tracks in 2005, by M+P

Consultant company M+P in 2005 performed several coast-by and accelerated pass-by measurements on nine different surfaces using four different tyres as part of a Round Robin Test (RRT) for test tracks complying with ISO 10844:1994. Seven of the nine surfaces were supposed to comply with ISO 10844 and were designated ISO1, ISO2, …ISO7. The other two surfaces were SMA surfaces designated SMA1 and SMA2. Four car tyres 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. The tested surfaces were located in Northwestern Europe. It is worth noting that it is unclear how the tyres were warmed up and if the warmup process was long enough; something which is important for the results.

Based on a compilation of data supplied to us [M+P, 2006], VTI has processed the results of this test focusing on the effects of temperature; something that has not been done before, in order to see if it may reveal some significant results.

First, the authors analyzed the raw data for coast-by noise and temperature results, with and without temperature corrections. Two correction procedures were applied: ECE R117 based on road temperatures and ISO/DTS 13471-2:2021, based on air temperatures. The results were:

- For the three tyres (the slick one was excluded), the uncorrected difference between the surfaces was 2.8-3.9 dB (depending on tyre).
- The difference between the surfaces in air temperature was 7-16 ^{o}C and 18-35 ^{o}C in road temperatures.
- Temperature corrections thus ranged between 0 - 1.5 dB for air and 0 - 1.1 dB for road temperatures.
- Applying the temperature corrections did not reduce the differences between the surfaces; on the contrary, there were tendencies for somewhat greater differences between surfaces with temperature corrections applied (but statistically not significant).

The authors think that the results of this disappointing study are due to the difference between the surfaces being much greater than the temperature corrections, despite a rather wide range of temperatures. Thus, the deviations were dominated by surface differences and the temperature-caused differences were “drowned” compared to the former. There is also not known how, where and when the temperatures were measured.

Further results are presented extensively in Annex 1. A summary of the results in the Annex is presented here:

- It must be recognized that the tests were made in different geographical locations with measurements in different weeks and in different weather conditions at each location.
- Noise measurements were made with both the coast-by method (ISO 13325) and the pass-by maximum acceleration method (ISO 362) in the versions existing at that time. Note that only the coast-by measurements are relevant for STEER, since this is the method used for tyre noise labelling purposes.

- It does not help considering all temperature vs noise data together in multiple regression for all surfaces, because then the ISO surface noise differences is the dominating variable which will obscure the temperature effects, as was discussed above.
- Consequently, reasonable and consistent correlations between noise and temperatures were not obtained. And that is what we see in Figs A7 to A9, where the correlations vary all over the scale with no consistent picture.
- The correlations between air, road and tyre temperatures should, however, be relevant and interesting for STEER. In those correlations, the surfaces' noise properties is a parameter of much less importance as we can forget the noise influence and imagine that it "just" influences the road temperature somewhat from location to location (due to sun height over the horizon, month and surface albedo). But such influence is acceptable, as measurements are actually made under such different conditions.
- The results of the temperature relations (air/road/tyre) are presented in Table 7 and in Figure 5. It is notable that the slope of the relation between road and air temperature is approx. 1.57, which is not far from that presented in Fig. 4 where the slope is 1.35. The residual variation is much larger in Figure 5 than in Figure 4, which is logical since the measurements were conducted at different locations on slightly different surfaces.
- Finally, it is worth noting that the multiple correlation study in Table A4, between the three temperatures, reveal that the air temperature affects tyre temperature more than the road surface temperature. It may not be surprising if one considers that the tyre area in contact with the road is in the range 0.01-0.02 m^2, while the area of the tyre surrounded by mainly turbulent air flow is more than 20 times larger. Of course, there is a difference in heat transfer efficiency, but probably not as large as a factor 20.

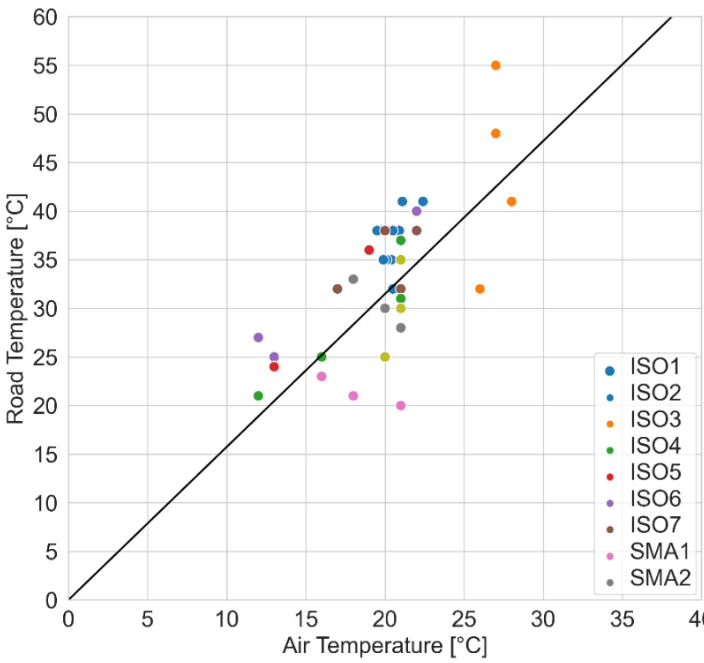

Figure 5: Correlation between road and air temperatures for all (4) tyres and all (9) test tracks during coast-by and pass-by measurements.

Table 7: Relations between tyre, road and air temperatures as recorded during coast-by and pass-by measurements in the RRT in 2005. It is not known exactly how and where the measurements were taken.

Relation considered	Regression equation	R^2	P value
Road vs air	$T_{road} = 1.57 \cdot T_{air}$	0.964	< 0.001

Air vs road	$T_{air} = 0.61 \cdot T_{road}$	0.964	< 0.001
Road vs tyre	$T_{road} = 0.98 \cdot T_{tyre}$	0.972	< 0.001
Tyre vs road	$T_{tyre} = 0.99 \cdot T_{road}$	0.972	< 0.001
Tyre vs air	$T_{tyre} = 1.62 \cdot T_{air}$	0.987	< 0.001
Air vs tyre	$T_{air} = 0.61 \cdot T_{tyre}$	0.988	< 0.001

5.3. Tests and views presented by tyre and vehicle industries

The European Tyre and Rim Technical Organization (ETRTO) has presented data relating noise levels for vehicle cruise-by (i.e., constant speed) at 50 km/h (on ISO surfaces) vs road surface temperature [ETRTO, 2020]. Since at 50 km/h constant speed, tyre/road noise is clearly dominant for A-weighted overall levels, one may consider it is tyre/road noise. They report that “Based on data from multiple C1 summer tyre designs and sizes an average value of -0.07 dB(A)/°C surface temp. is found for 50 km/h constant speed”. Figure 6 shows the data reported by ETRTO.

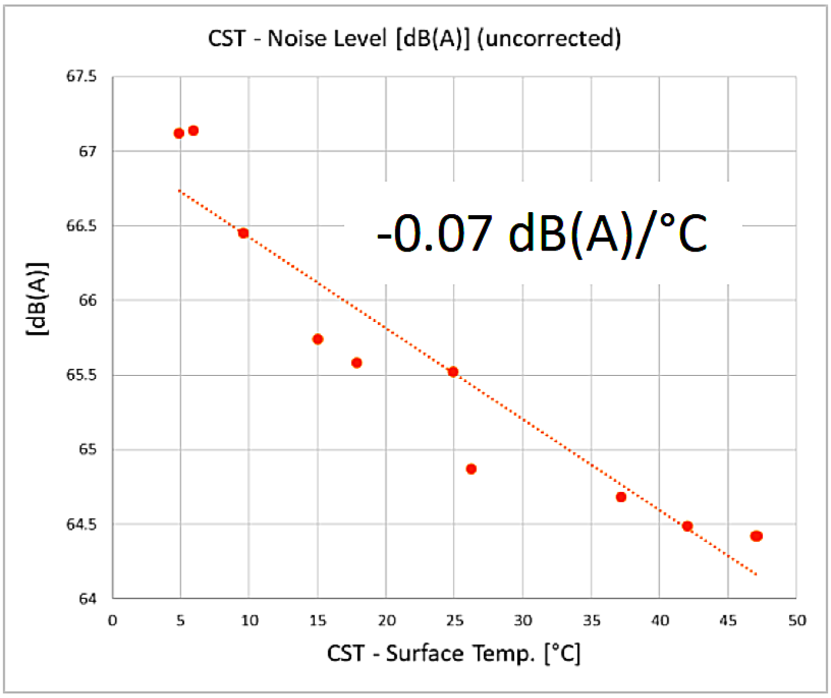

Figure 6: Relation between cruise-by noise of cars equipped with multiple summer tyre designs and test surface (ISOI 10844) temperature. From [ETRTO, 2020].

The regression results in a slope -0.07 dB/°C which ETRTO suggests being linear, with an R^2 of 0.84, However, one can fit a non-linear line better, which will be consistent to what is proposed later in this report for the case of using road or test surface temperature as the basis for correction.

Simultaneously, the vehicle industry, through its International Organization of Motor Vehicle Manufacturers (OICA) has suggested that the temperature range should be limited to air temperatures of 5 – 40 °C, while road temperatures should not be as high as 60, but a value is not yet proposed [OICA, 2020]. It should be noted that the ECE R 51 (which is the regulation for vehicle noise, but which has tyre/road noise as a component) specifies air temperature and it seems that the vehicle industry wants to have a temperature correction for the tyre/road noise part and prefers to base temperature corrections based on air rather than road surface temperatures [GRBP, 2020].

6. Data specific for temperature effects for C3 tyres

No new data has been found related to C3 tyres. Therefore, we must rely entirely on what came out of the work made by ISO/TCF 43/SC 1/WG 27, which resulted in ISO/TS 13471-1:2017 and in ISO/DTS 13471-2:2021. This is summarized in the selection of temperature correction coefficients for C3 tyres.

7. Conversion between temperature coefficients based on air and road temperatures

7.1. General issues and the choice of temperature for correction

On a global scale, road surface temperatures are generally quite well correlated with air temperatures. Nevertheless, significant deviations include but are not limited to wind, rain, intensive sunshine on dark surfaces and short-term fluctuations in air temperature due to shadows or air turbulence. When there is intensive and unobstructed sunshine, road temperatures can by far exceed the air temperatures, but at temperatures considerably lower than the reference temperature, road surface temperatures can sometimes be lower than air temperatures [Sandberg & Mioduszewski, 2015], [Mioduszewski et al, 2015]. The true relation is, therefore, probably non-linear; at least when one considers the full (practical) range of testing temperatures. More about the relation between the various temperatures appear in [Bühlmann, Schlatter and Sandberg, 2021].

Evidently, cloudiness (or clear weather) influences the relation between the air and road temperatures. The relation also depends on the angle of incident sun radiation since the energy absorbed by the road depends on this radiation impact. Consequently, the relation depends on season, the latitude of the test location and even the time of the day. It becomes even more complicated due to the phase shift between air and road temperatures due to the thermal capacity of the pavement, and the fact that the temporal history of the road temperature depends on where (on or in the pavement) where the measurements are taken.

Recognizing that the most relevant temperature is the tyre temperature and that this depends on both air and road surface temperatures, it seems that basing the temperature correction on only one of the variables (air or road temperature) is a bit risky. This is especially for the road temperature-based correction, since the road temperature depends on so many and rather complicated factors, as described above.

Note also that the results of the M+P study mentioned above and further analyzed in the Annex suggests that tyre temperature is more influenced by air than by road (test) surface temperature. This is a strong indication that it would be better to base temperature corrections on air than on road (test track) surface temperatures. The problem is that this needs more study with independent data to be considered as robust information.

If the correction is based on air temperature, the suggested coefficients in ISO/DTS 13471-2 (summarized in Table 3 in this report) should be used; i.e., a correction coefficient of 0.10 dB/^{o}C. This fits well with the data in Figure 6, if a conversion factor of 1.45 is used to convert between road and air temperatures as discussed below. Such an approach has two practical consequences:

The coefficient is an even number, very easy to remember, which should reduce the risk of human errors. It is also a linear correction, which further reduces the risk of human errors and the discussion of how the non-linearity should be.

7.2. Conversion between air and road temperatures

In certain standards, such as those based on measurements on a reference surface specified by ISO [ISO 10844, 2014], due to the stationary location on test tracks, it has become common practice and also the standard (while not necessarily better) to use the road temperature from permanently mounted sensors for correction to noise levels. In order to use the temperature corrections in this document, which are based on air temperatures, a conversion of the temperature coefficients need to be made to road surface temperatures. For this reason, one must define a conversion factor:

$$\gamma_{tr} = K\,\gamma_{ta} \qquad \text{(Eq. A1)}$$

where

γ_{tr} is the temperature coefficient for tyre (or vehicle) t, based on road temperature

γ_{ta} is the temperature coefficient for tyre (or vehicle) t, based on air temperature

K is the conversion factor for air-to-road coefficients

The conversion factor is currently subject to studies. The size of this varies within the range from 1.2 to 2.6 according to [Sandberg & Mioduszewski, 2015]. That document lists a number of suggested conversion factors listed in Table 8.

Table 8: Compilation of data reporting the regression of road temperature on air temperature. The slope coefficient k in this relation is shown here. Note that the last reference in itself is based on a compilation of data collected in 1992-1997. The factor K has no dimension. The table is copied from [Sandberg and Mioduszewski, 2015].

Reference	Factor K reported	No. of surfaces	Assigned weight	Weighted K factor
Anfosso & Pichaud, 2006	1.73	6	2	3.46
Beckenbauer et al, 2002	1.23	4	1	1.23
Bendtsen et al, 2009	1.52	1	1	1.52
Bühlmann & Ziegler, 2011	1.91	112	5	9.55
Hung et al, 2012	2.6	1	1	2.6
Watts et al, 2004	2.08	1	1	2.08
Bergiers, 2015	2.3	1	1	2.3
Mioduszewski et al, 2014	1.4	1	1	1.4
WG27, 1997 (conclusion based on data coll.)	1.7	several	3	5.1
Weighted sum				29.24
Average (middle) / Weighted average (right)	1.83			1.8275

Provisionally, when one wants to compare temperature correction based on air with corresponding corrections based on road surface temperatures, a K factor of 1.8 was suggested in [ROSANNE] and is also used in [AASHTO, 2013]. However, this single value for the factor may be an over-simplification and better conversion should be developed.

The Nissan data described above finds that the conversion factor is 1.36 while in the M+P data the factor was found to be 1.57. The large discrepancy between these and the 1.8 mention above may be due to the range of temperatures considered. As discussed above, the Nissan data suggest approx. a doubling of the factor above 30 °C.

Table 9 shows the temperature coefficient for an ISO surface based on road temperatures if the air temperature coefficients are converted by the conversion factors discussed above. The last example is for a conversion factor 1.4 below 30 °C and 2.0 above 30 °C. For C1 and C2 tyres.

These coefficients are illustrated in Figure 7, where also the correction used in ECE R117 and related regulations are included for comparison.

It may be noted that a document expected to be published in the first part of 2021, based on a large database, presents the relation between road surface and air temperatures as a linear relation with a slope of 1.56. The range of road surface temperature is 0 to 60 °C. This is well in line with Table 8 and the choice made for rows 2 and 4 in Table 9.

Table 9: Some different conversion factors (K) considered in this report. Note that noise corrections will have the opposite sign to the temperature coefficients.

Coeff. based on air temp.	Conversion factor	Coefficient based on road temp.	Notes
- 0.10 dB per °C	1.36	- 0.074 dB per °C	Similar to the Nissan data
- 0.10 dB per °C	1.5	- 0.067 dB per °C	Arbitrary chosen intermediate factor
- 0.10 dB per °C	1.8	- 0.055 dB per °C	Recommended by ROSANNE
- 0.10 dB per °C	1.44 and 2.0	- 0.070 and – 0.050	Factors rounded to get practical coefficients

7.3. Discussion of potential non-linearity in temperature corrections based on road temperatures

The relations between noise and air temperature are assumed in this document to be linear. This is because there is no firm evidence of a nonlinear behavior that has been published. It has so far been considered that this is the same for road temperature, since published data suggesting nonlinearity are not known.

However, if it is accepted that the relation between air and road temperatures is non-linear (due to the extra warm-up of dark ISO surfaces in intensive sunshine), if conversion is made from air to road temperature corrections, there will be a corresponding non-linearity in the correction based on road temperatures. In Fig. 7 the “knee” temperature is at 30 °C.

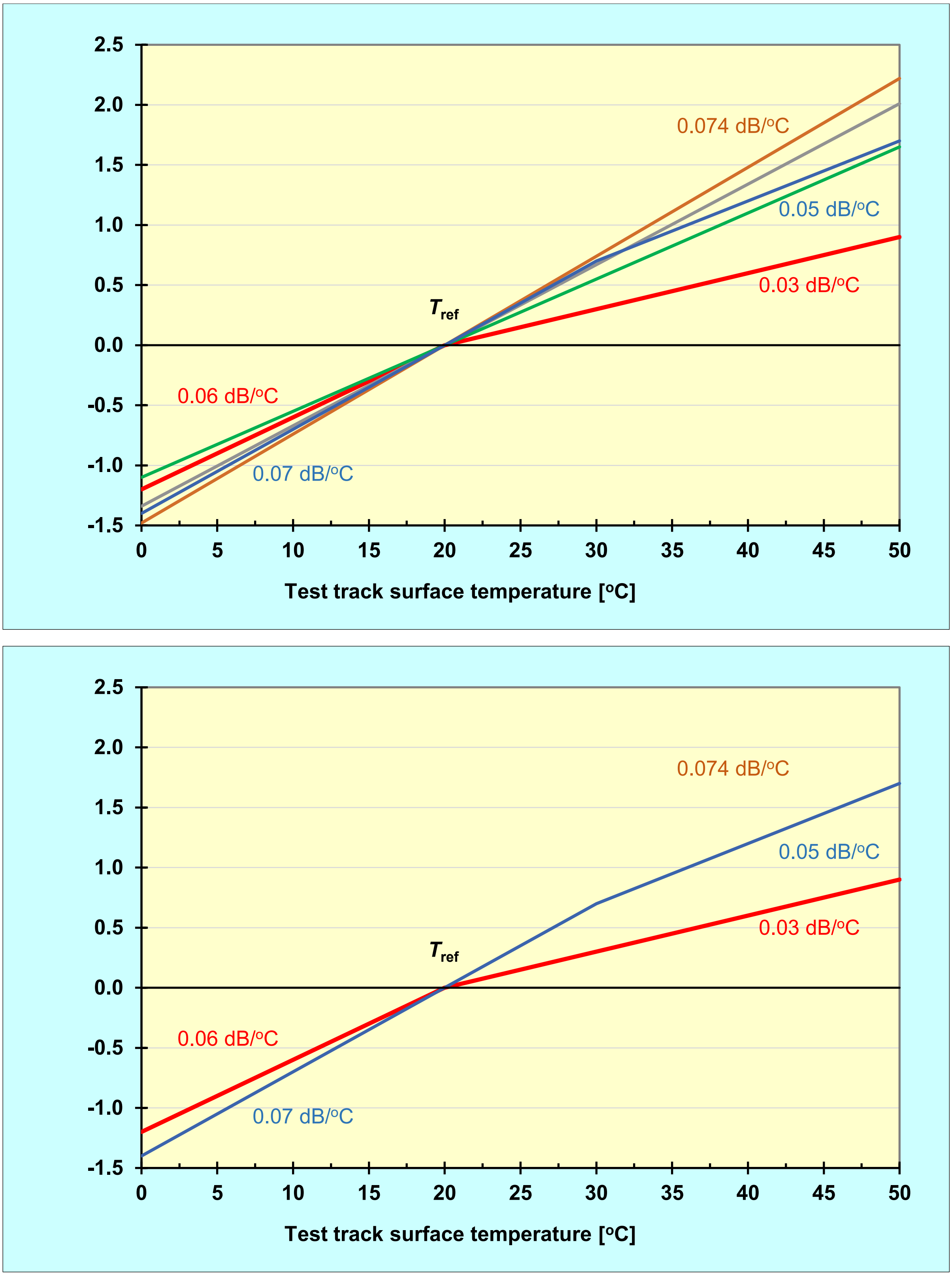

Figure 7: Illustrations of the noise level corrections according to the alternatives in Table 9 (above). The red curve is the existing correction in ECE R117, brown is K = -0.074, grey is K= -0.067, green is K = -0.055 and blue is K = -0.07 and -0.05. The diagram below shows our recommendation compared to the existing correction in ECE R117.

As stated in an earlier chapter, it is the tyre temperature that should be the relevant temperature for corrections, since noise is emitted by the tyre and not the road surface. Air temperature does not influence the noise propagation directly at the distances applicable in coast-by tests (7.5 m); although it is possible at longer distances. Road temperature may marginally influence the stiffness of the test surface which may influence tyre noise emission, but such influence for an asphalt pavement like to ISO 10844 pavement should be at most marginal.

Test surface (“road”) temperature is influenced by ambient (air) temperature, and by solar energy influx, where the latter very much depends on the angle between the surface and the solar radiation angle. In certain weather and climate conditions, the generally dark ISO surfaces may absorb exceptional energy from the sun; something not reflected in air temperature increases. When the tyre is heated or cooled by air and surface together, the very high temperatures of the surface are not fully reflected in tyre temperatures; at least not as well as at lower solar energy influx.

Therefore, it is rather logical that there is a non-linear relation between noise emission from the tyre and the test surface (road) temperature, which is not seen for air temperatures; at least not for air temperatures at higher heights than near the tyre centre. This is reflected in the fourth option in Table 9.

It is hoped that this non-linearity would be easier to accept for the tyre industry than just a linear correction, as it is less different from the one applied in the present ECE R117 and related regulations. If one would put the “knee” at 25 instead of 30 °C, the change compared to ECE R117 would be even smaller.

7.4. Acceptable temperature range and temperature regulation of ISO test tracks

The ECE R117 specifies that “Measurements shall not be made if the air temperature is below 5 °C or above 40 °C or the test surface temperature is below 5 °C or above 50 °C”. In the vehicle industry, a discussion is ongoing where the maximum road (test surface) temperature should be set. A range of 40 to 60 °C is considered.

An air temperature limited to 35 °C and a road surface temperature limited to 40 °C would be desirable for reducing uncertainties. However, it would seriously limit possibilities to test in many hot areas of the world which are already used for tyre or vehicle testing. But this problem could be reduced if one will allow the ISO surface to be much lighter, ISO surface are black when new and stay “blackish” all their life as they are not normally exposed to such intensive traffic that the binder gets worn away fully. It is ideal for absorbing sunshine energy. A higher albedo would mean that the surface would reflect the sunshine instead of absorbing its energy in the test surface, air temperature would be somewhat reduced too, and the air and surface temperature would be more similar over the entire year.

Can one colour the asphalt surface to become (for example) light grey? Yes, there are commercial products that can be added to the asphalt mix at a small quantity that will give the surface a desired colour. One example appears in [Asphaltcolor, 2021]. They are UV resistant powdered mineral pigments and chemical polymers that can be added either in the mix or be applied as a sealing. In this case, probably adding it into the asphalt mix would be the best. What would the effect be on the noise emission? The authors think that the noise influence will be nil or at most marginal since the texture and sound absorption properties need not be influenced. If this technology is applied it will mean a marginally increased cost, but this may be more than balanced out by the reduced risk of surface changes due to melting binder in extremely hot weather.

This or a similar technology is already used in paving management. In Japan, a solar heat-blocking pavement technology has been developed [Iwama et al, 2017]. It has three components that together give a 1 mm thick coating (which is too thick), but probably one can skip the friction-increasing particles in it to get a much thinner coating. This is already implemented in some Japanese cities (like Tokyo and Osaka), where asphalt pavements in light grey colour are laid on streets with the purpose to reduce the urban heat island effect; i.e., to reduce the street’s surface temperature. They have achieved a surface temperature reduction of 12 °C [Iwama et al, 2017]. Two examples from central Tokyo are shown in Figure 8. Note that in principle it is possible to make them even brighter but the contrast with the street markings would then be too low.

There are also some spray paints that give an extremely thin coating with light colour; see e.g. Fig. 11.23 in [Sandberg & Ejsmont, 2002]. There should be much more advanced materials available today.

Figure 8: Two streets in Tokyo paved with asphalt with an additive that colours the surface grey. The purpose is to reflect sunshine energy and thus reduce the thermal energy absorbed in the asphalt pavement. The upper picture shows a dense asphalt and the lower a porous asphalt, both of which normally would look “blackish”. Photos in 2016 and 2018 by Sandberg.

It is suggested that the proposed technology is tested, including comparing it to a pavement of a similar mix except not using the colouring material. If this turns out positive, the ISO 10844 specification should be revised to allow this additive, which will reduce uncertainties in warm weather by providing a lower surface temperature that needs less temperature correction.

In Sweden, Germany and probably also in some other northern countries, it is common that ISO test tracks are built with a heating facility built into the test track, so that measurements can be made on a dry and not too cold surface, in season(s) when humidity is very high and sunshine is rare, or even to get the track free of snow before snow is melting in the natural way. This is a good way to extend the number of days in a year when measurements are possible which has a great economic value.

In principle it should be possible to cool down an ISO test track that has been heated by sunshine to (say) 60-70 degrees in a hot summer day by operating the system in the opposite way (like a fridge). The authors are not aware of such a system, but it should be possible and feasible.

When using such temperature regulating systems the normal test track temperature would be quite different from the actual one. On hot days, the test track temperature may be below that of the air, and in wintertime the opposite may be the case. Such conditions may complicate the temperature correction if it is based on surface temperatures since tyre temperature is more affected by air than surface temperatures.

Nevertheless, test track temperature regulation may be an effective way to avoid excessively low or high surface temperatures, in this way reducing the needed temperature correction and thus contribute to reduction of uncertainties.

Furthermore, avoiding extremely high temperatures of a test track surface may have a favourable effect also on the useful lifetime of the test track surface, since it will avoid bleeding of the surface and make it less sensitive to rutting.

7.5. New analysis of relations between air, road and tyre temperatures

A new analysis of the relations between air, road and tyre temperatures will be published in August 2021 [Bühlmann, Schlatter & Sandberg, 2021]. This may be considered in an update to this report, when available.

8. Discussion of the relevance of testing winter tyres at “summer” temperatures

Currently, all tyres are tested at certain temperatures, often around or above 20 °C, irrespective of whether they are intended for normal (“summer”) or winter or M+S use. Winter tyres are intended for use at substantially lower ambient temperatures than normal tyres; in practice it could be for the range -30 to +10 °C, while normal tyres are not supposed to run at temperatures below (say) 5 °C. and may run at ambient temperatures up to (say) 45 °C. Yet, there is no distinction between tyres and noise testing temperatures. If winter tyres are tested at (say) 20-30 °C air temperature, they are operating at a condition for which they are not intended. Therefore, the noise levels they produce at common testing conditions may not be fair and relevant for such tyres. All-season tyres are in a grey zone between the normal and winter tyres and shall operate satisfactory over the entire temperature range.

The situation calls for a change in testing conditions. Ideally each tyre type shall be tested at an ambient temperature which represents a common operation of the tyre type; i.e., for winter tyres around 0 °C (for example) and normal tyres in the range of 15-30 °C; i.e. essentially as is currently common. All-seasons tyres should be tested in both temperature ranges, or maybe at an average temperature (say around 10 °C).

9. Conclusions

This report has examined different regulations, standards and measurement methods, as well as different datasets focusing on relationships between tyre, road and air temperature as well as noise, including maximum values and values in different frequency bands. Despite a huge number of measurements having been made during tyre/road noise measurements related to regulations, data relating noise levels to test surface temperature have very rarely been published. This is in contrast to tyre/road noise measurements on road pavements related to air temperatures. In this report we have assessed the temperature corrections, mainly based on air temperature, but converted to road surface temperatures using relationship reported about the air-road surface temperatures.

The amount of data thus available is far from satisfactory. Nevertheless, we conclude that by using our recommendations below, the uncertainty in the labelling procedure will be reduced. These recommendations should be considered as preliminary and should be refined in the future, but for the time being they are the best that we can offer and absolutely better than the present situation.

Consequently, our assessment shows that the correction used in the regulations based on road temperature appears to be underestimated and can be improved by following the recommendations in this report that are based on a multitude of different research projects.

The correction we suggest will have an influence of up to 0.15 dB at the lowest temperatures and 0.75 dB at the highest temperatures. Overall, considering the range of testing temperatures, in an uncertainty calculation, we estimate that this adjustment will reduce the uncertainty due to the temperature correction by a standard error of 0.1 dB and a maximum error of 0.75 dB (at the highest temperatures).

In ECE R117 it is written about "Test surface temperature", after it has first been stated that measurements shall be taken in the wheel tracks, that

"If an instrument with a contact temperature sensor is used, heat-conductive paste shall be applied between the surface and the sensor to ensure adequate thermal contact.

If a radiation thermometer (pyrometer) is used, the height should be chosen to ensure that a measuring spot with a diameter of ≥ 0.1 m is covered".

As discussed above, "test surface temperature" is not an unambiguous definition; temperatures vary from the road surface down below the surface; and this has both a temporal and surface-dependent effect. The authors know that some ISO test tracks have sensors embedded a bit into the surface since this is much more practical than a sensor pasted on the surface which may be damaged by the tyres. Therefore, the way to measure road surface temperature shall be better specified.

A possibility to verify the condition for steady state of tyre temperature is that tyre shoulder temperature should be approximately equal to inflated air temperature. Approximate time to reach this condition is in the range of two hours for C3 tyres and 30 to 40 minutes for C1 tyres. The present text in ECE R117 is not sufficiently strict, nor clear on this.

In the recommendations below we suggest some measures making it possible to limit the allowed temperature range to 5 to 40 °C for both air and surface temperatures. This upper limit for surface temperature would mean a serious restriction for some regions in the world in their warmer seasons. However, the measures recommended will reduce this problem. No region in the world can count on having measuring conditions at all times of the year and all times of the day and night. Northern countries in Europe, North America and Asia already have such a restriction that does not usually allow measurements during at least one-third of the year as it is too cold and humid. It is not unreasonable that also the hottest regions will face restrictions during the warmest season and/or the warmest parts of the day and night.

10. Recommendations

The following recommendations are suggested with the aim to reduce uncertainties in the labelling test procedure:

The warm-up time of tyres to be tested shall be increased to 40 minutes for C1 tyres, 1 hour for C2 tyres and 2 hours for C3 tyres. In the future, such warm-up may be better defined by recording tyre temperature time profiles.

The data analyzed herein seems to indicate that tyre temperature is more influenced by air than by road (test) surface temperature. Air temperature also varies less in both space and time than surface temperature as the surface is partly or fully exposed to sunshine. Therefore, our preferred recommendation is that the noise testing for labelling of tyres is revised from being based on road surface (test track) temperature to being based on air temperature, using the linear correction specified in ISO/DTS 13471-2, issued in 2021 and expected to be published in 2021.

However, as it may be difficult, politically, to change the current relevant regulations to use air temperature instead, our less preferred but acceptable recommendation is that test surface temperature can continue to be the basis for temperature corrections in the tyre noise limit and labelling regulations, provided "political" reasons makes it impossible changing to air temperature.

Nevertheless, for purposes of reporting ambient conditions, both air and test surface temperature should be reported. In the future it may be that the temperature for correction of noise would be a mix of air and road surface temperatures, so in the meantime both should be collected. Air temperature should be measured at a height of 1.2 to 1.5 m above the propagation area of the test track. In addition, it is suggested to report the weather, as being sunny, mixed sunny and cloudy or mainly cloudy.

For long-term purposes, the preferred correction is based on tyre temperatures. Therefore, it is recommended to develop and specify a way to make relevant tyre temperature measurements. As tyre temperatures vary dramatically in both time and location one must find the best way of characterizing tyre temperature. It may then be that for noise purposes one might want another location on (or inside) the tyre than for rolling resistance purposes. For rolling resistance purposes, probably the shoulder area is the most important part of the tyre since it is where most of the energy is transferred into heat. Measuring on the innerliner near the shoulder areas will probably be a proper way for rolling resistance but will require that each tyre to be tested is equipped with an advanced internal temperature measuring system. This will be both complicated and expensive. At least for noise purposes, it will be preferred with a compromise making measurements with an IR sensor on the outer part of the tyre, such as the shoulders and the tread, although these are difficult to define. Until more data is available, the tyre tread seems to be a reasonable choice for noise purposes.

The ISO test surface temperature shall be measured on the test surface of the wheel track, using infrared thermometer technology or a similar non-contact method (as already specified in ECE R117); in order to avoid using different temperatures depending on the sensor's mounting and depth under the surface.

If the current basis for temperature correction (test surface) is retained, the temperature correction for C1 and C2 tyres shall be changed to the correction shown as the 4th case in Table 9 and Figure 7, i.e., with coefficients -0.07 below 30 °C and -0.05 above 30 °C. This implies higher corrections than in the current ECE R117.

If the air temperature is used as the basis for temperature correction, the correction specified for dense asphalt in ISO/DTS 13471-2:2021 shall be used. Refer to Table 3 for the case of dense asphalt. Also in this case it means that, compared to the present time, temperature corrections will be higher.

For C3 tyres, the temperature correction should be approx. 60 % of the correction for C1 and C2 tyres. This would correspond to -0.04 below 30 °C and -0.03 above 30 °C in the case of using test surface temperatures.

In the long-term, the testing temperatures of winter and all-seasons tyres shall be re-considered. Each type of tyre, be it normal, winter or all-seasons, should be tested in a temperature range for which the tyres are optimized and not outside such a range. This will be more practical in the future if noise testing can be made indoors.

To reduce the uncertainty created by the temperature influence on tyre/road noise emission, three measures are recommended. The first one is to reduce the highest temperatures reached during hot and sunny days on ISO test tracks by constructing the pavement to appear in light greyish colour. There are some means of doing so, such as spraying the surface with a very thin paint, putting a thin grey coating on top of the surface, or mixing mineral pigments into the mix. These measures require some experimentation and testing before they can be applied in standards, and such work is proposed here.

The second measure is to build a heating and/or cooling system into the pavement in which case both the lowest and the highest temperatures can be shifted into the more normal range. For heating purposes this is already used in some countries. It has the extra advantage of extending the measuring season and to make it possible to measure sooner after a rain has ceased by drying up the surface.

The third measure is to limit the allowed range of surface temperatures. For example, when applying the measures above it will be feasible to limit the range of surface temperatures to 10 to 40 ^{o}C. However, as 10 is not far from 20 and 5 ^{o}C would still be allowed for air temperatures, it is more practical to limit both air and surface temperatures to be within 5 and 40 ^{o}C.

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ANNEX 1: Analysis of M+P data from ISO surface RRT conducted in 2005

A.1 Introduction

In 2005, a Round Robin Test (RRT) to check how tyre/road and vehicle pass-by noise are influenced by the test track surface formally meeting ISO 10844:1994 was conducted in Europe and Japan. The data compilation was made by M+P in the Netherlands. The data file has been accessed by SINTEF in Norway (via Mr Truls Berge), who in turn (in 2020) has allowed VTI to explore the data [M+P, 2006].

The analysis at VTI was conducted by the first author of this report and the results are presented in this Annex. A summary of the findings appears in the main body (Section 5.2). Note that more information regarding how the tyre warm-up process was carried out was desirable; however, not available to the authors at the time of writing.

Table A1. The four different tyre models used and the respective tyre designations

Tyre Designation	A	B	C	D
Tyre model	Pirelli slick	Pirelli P6000	Goodyear Eagle Ultra Grip	Goodyear Wrangler MT/R

A.2 Correlations

This section can be used to discuss, among other things, the relationship between different temperatures and different frequencies. Inconsistencies observed here could be due to different tyre warm-up processes as well as tyres that had not reached a steady state.

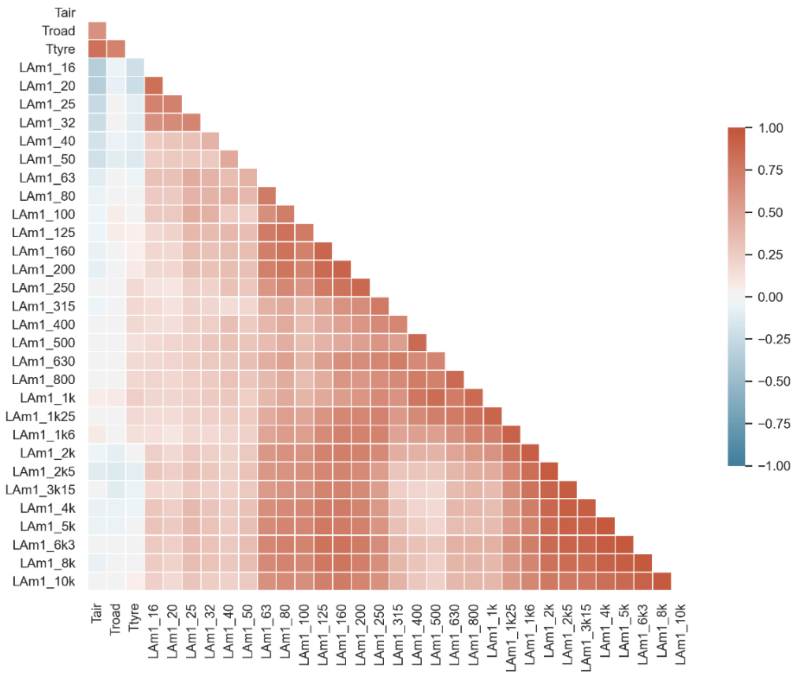

Figure A1. Correlation matrix for coast-by measurements showing the correlations between noise levels in the different frequency bands, where noise levels are the averages for the four test tyres. The three leftmost columns show correlations between either the tyre, road, or air temperatures and the noise levels in the respective, third-octave bands.

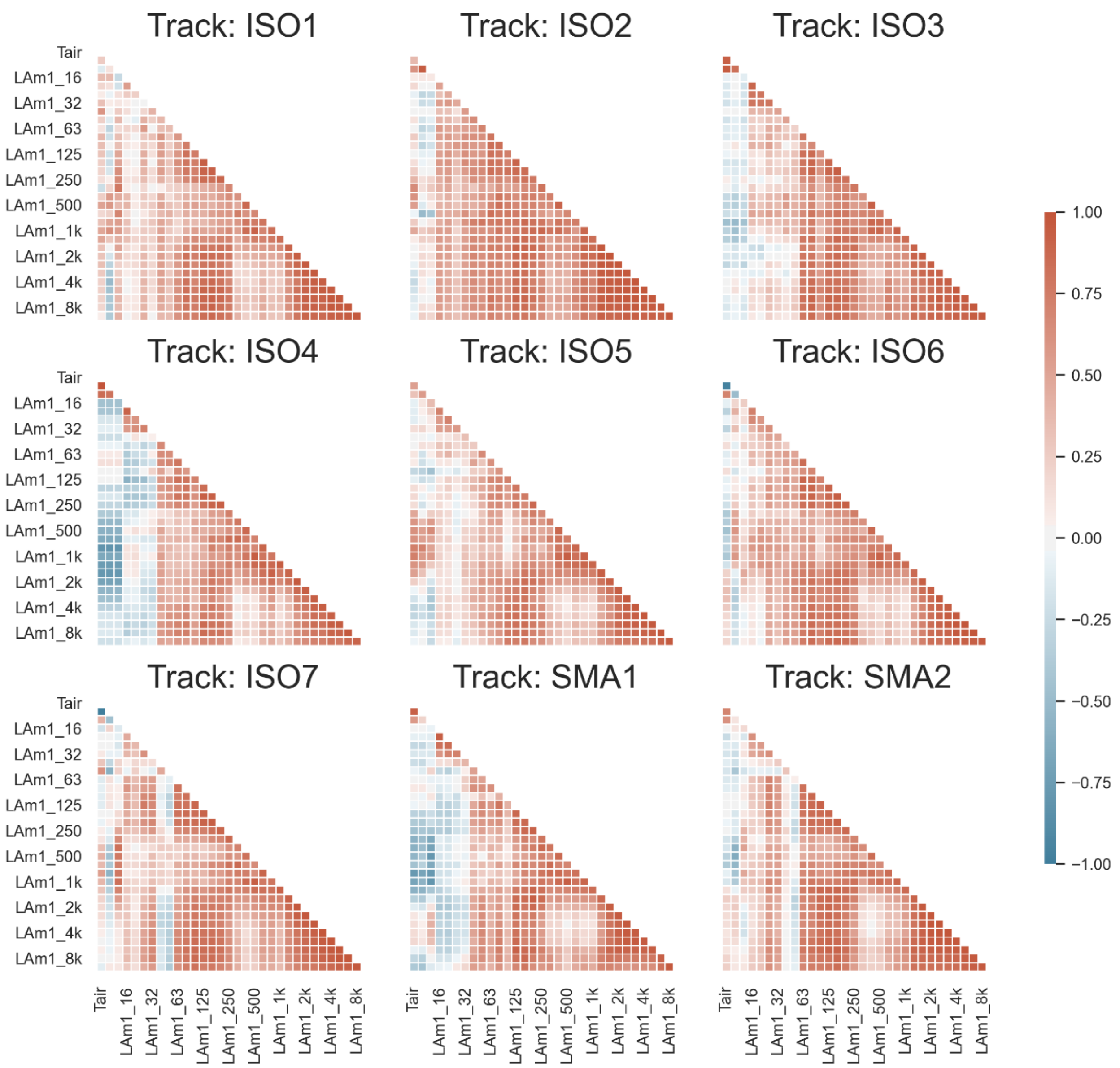

Figure A2. Same as the previous figure but split up for each separate test track. Due to the compression, only some of the data on the Y and X axles are indicated; refer to the previous figure for full resolution of the Y and X axle scales.

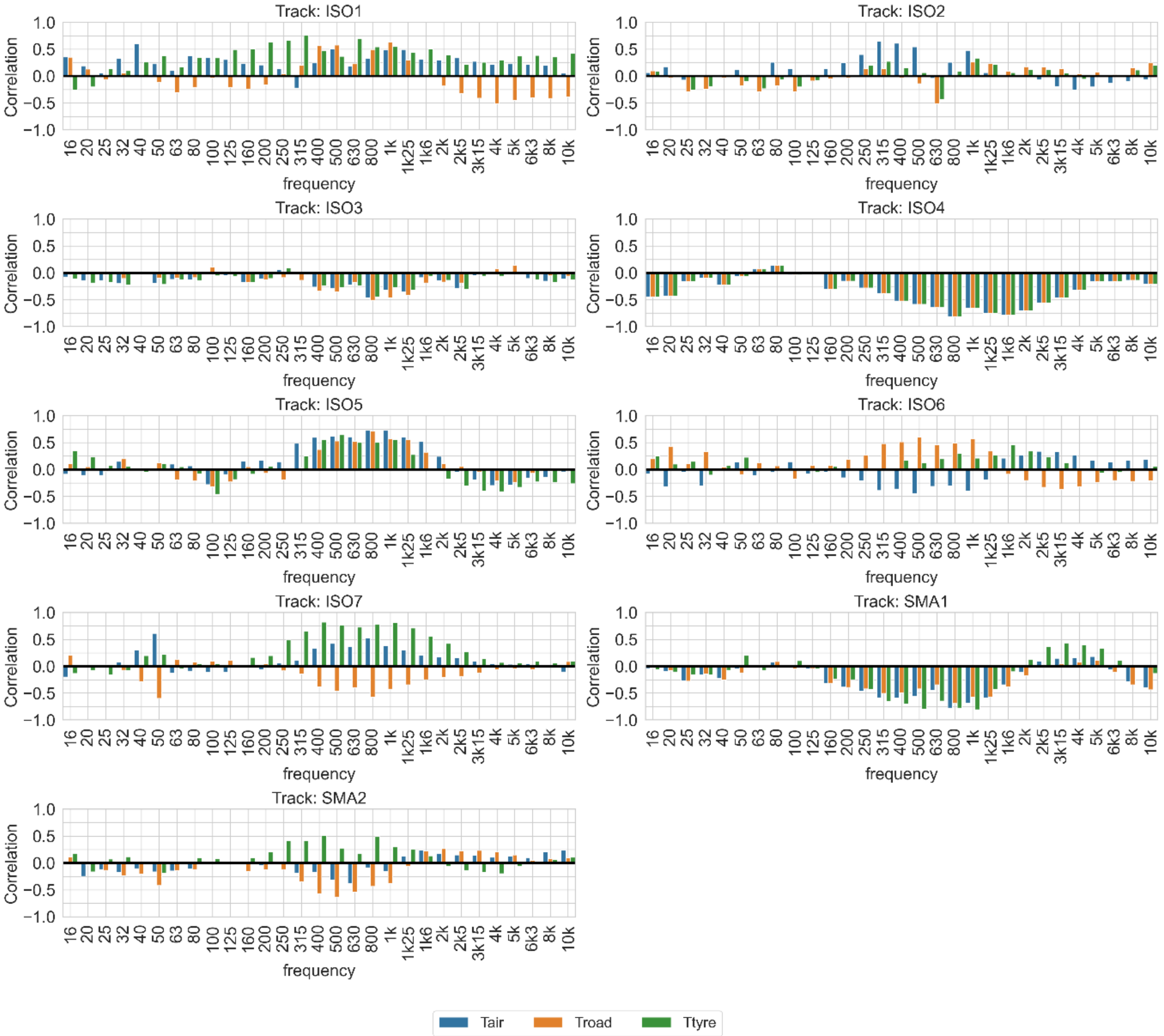

Figure A3. Correlations for each test track between coast-by third-octave band levels and each of the three temperatures.

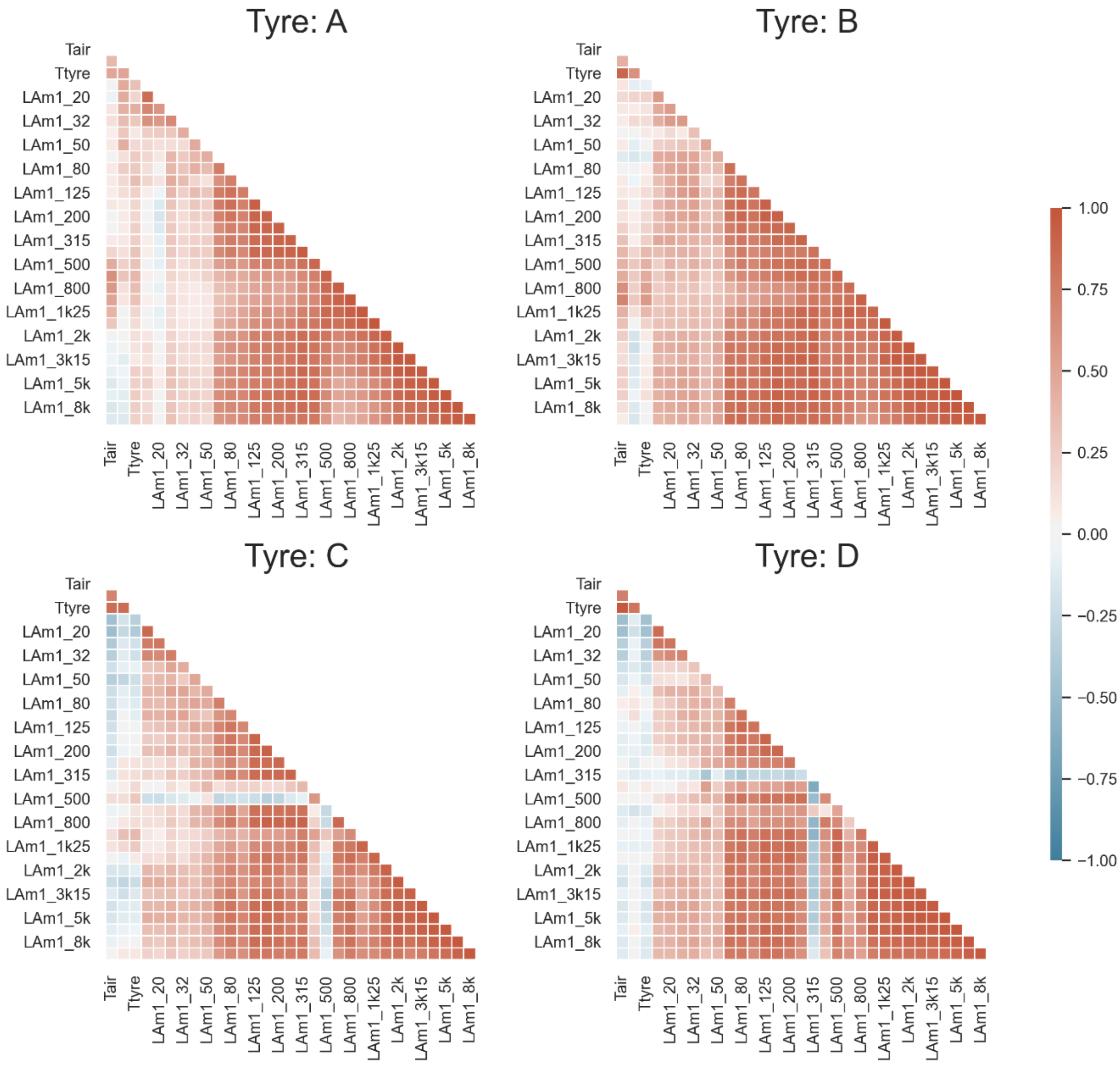

Figure A4. The same as Figure A1 but split between each of the four tested tyres.

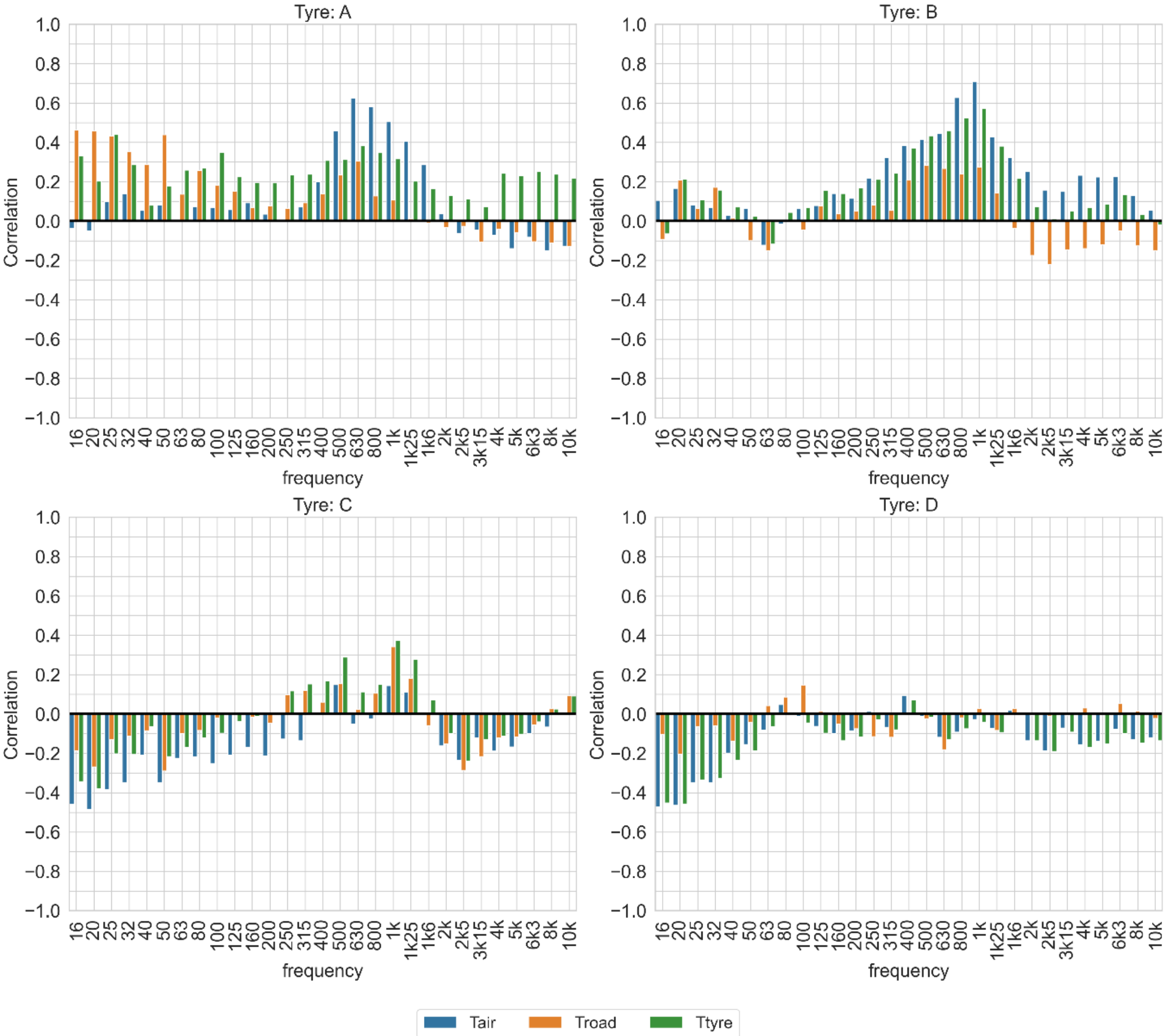

Figure A5. Coast-by temperatures (air, road, and tyre) and spectral correlations for each tyre.

A.3 Temperature models

Table A2. Linear regression having air temperature as predictor for road temperature, showing the R^2 adjusted (from the test data set) and the Bayesian Information Criterium (BIC).

Predictor	Coefficient	Std. error	P value	95 % conf. int.	R^2 adjusted	BIC
Air temperature [°C]	1.5732	0.020	0.000	[1.533; 1.613]	0.404	1477

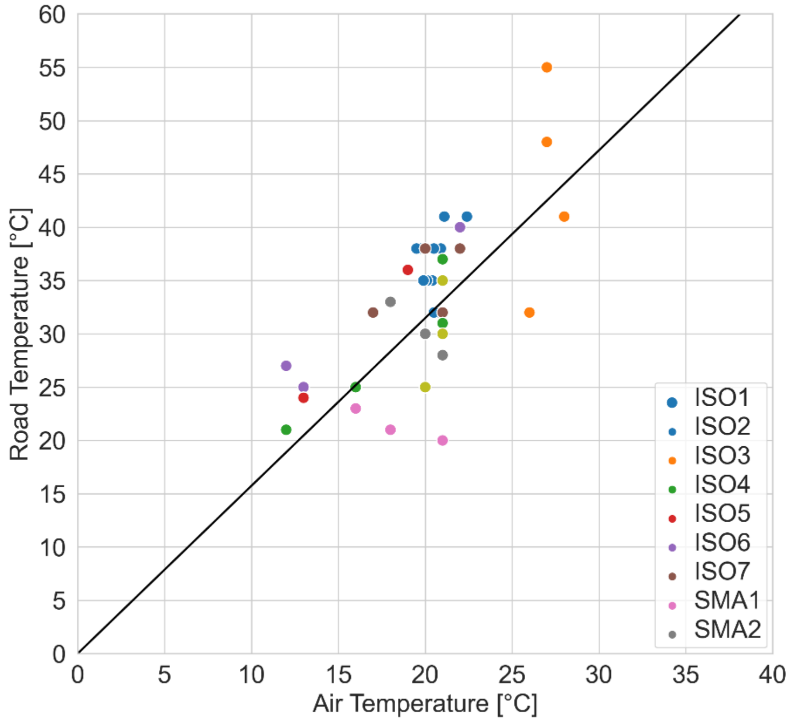

Figure A6. Linear regression for road temperature predicted by air temperature (during cost-by measurements) on different road surfaces indicated by different colours.

Table A3. Linear regression having tyre temperature as predictor for road temperature. The R^2 is adjusted (from the test data set) and the Bayesian Information Criterium (BIC).

Predictor	Coefficient	Std. error	P value	95 % conf. int.	R^2 adjusted	BIC
Tyre temperature [°C]	0.9897	0.010	0.000	[0.970; 1.010]	0.471	1588

A multiple linear regression using the air and the road temperatures as predictors in order to predict the tyre temperature was also attempted; see Table A4.

Table 7. Multiple linear regression for coast-by results having air and road temperatures used to predict tyre temperature.

Predictor	Coefficient	Std. error	P value	95 % conf. int	R^2 adjusted	BIC
Air temperature [°C]	1.1276	0.052	<0.001	[1.025; 1.230]	0.53	1223
Road temperature [°C]	0.3112	0.033	<0.001	[0.246; 0.376]		

Note that this suggests that tyre temperature is more influenced by air than by road temperature.

A.4 Noise and temperature data

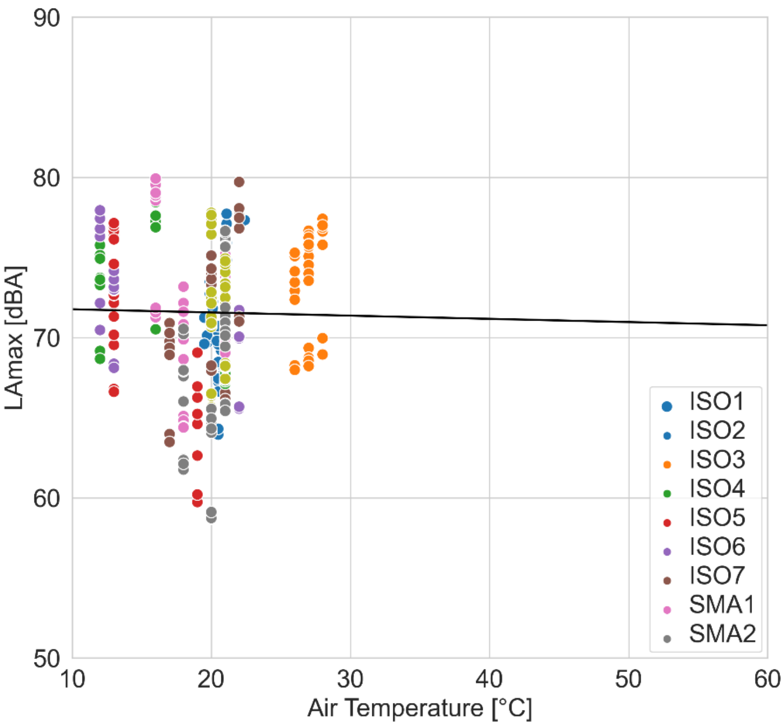

Figure 1. Linear regression for coast-by measurements, LAmax predicted by air temperature on different test surfaces, indicated by different colours.

Table 8. Linear regression having air temperature as predictor for LAmax for coast-by measurements. Results are presented as R^2 adjusted (from the test data set) and the Bayesian Information Criterium (BIC).

Predictor	Coefficient	Std. error	P value	95 % conf. int.	R^2 adjusted	BIC
Air temperature [°C]	-0.0262	0.079	0.740	[-0.182; 0.129]	<0.01	1212
Constant	71.9657	1.571	<0.001	[68.869. 75.062]		

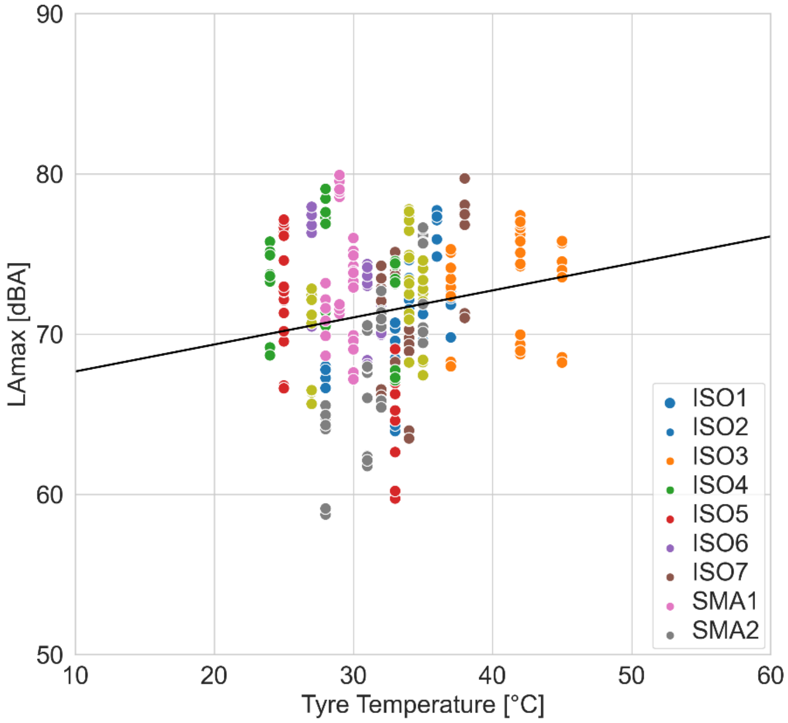

Figure A8. Linear regression for coast-by measurements, LAmax predicted by tyre temperature on different test surfaces indicated by different colours.

Table A6. Linear regression having tyre temperature as predictor for LAmax for coast-by measurements. Results are presented as R^2 adjusted (from the test data set) and the Bayesian Information Criterium (BIC).

<table>
<tr><td>Predictor</td><td>Coefficient</td><td>Std. error</td><td>P value</td><td>95 % conf. int.</td><td>R² adjusted</td><td>BIC</td></tr>
<tr><td>Tyre temperature [°C]</td><td>0.1273</td><td>0.067</td><td>0.059</td><td>[-0.005; 0.260]</td><td rowspan="2">0.03</td><td rowspan="2">226</td></tr>
<tr><td>Constant</td><td>67.1024</td><td>2.190</td><td>0.000</td><td>[62.785.71.419]</td></tr>
</table>

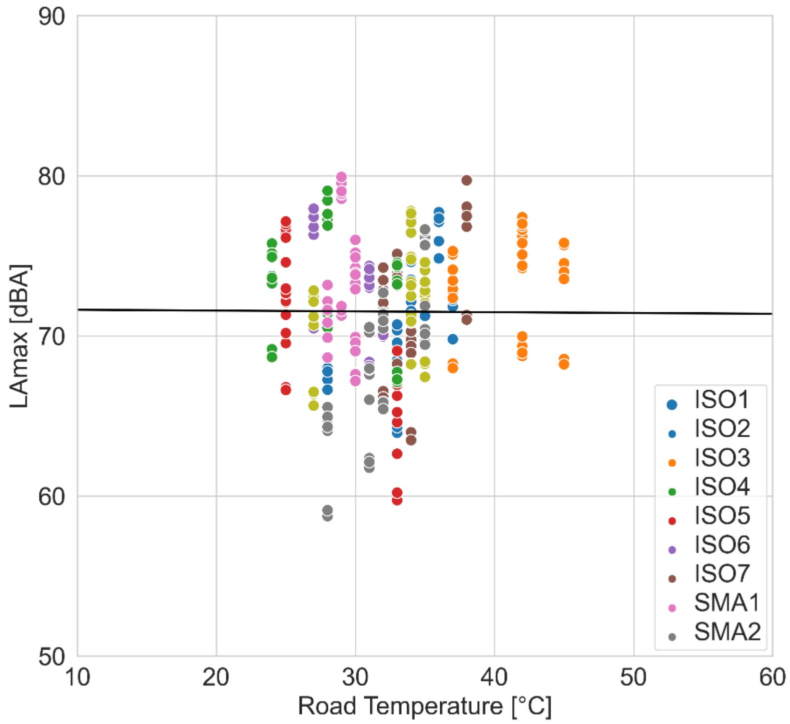

Figure 2. Linear regression for coast-by measurements, LAmax predicted by road temperature on different road surfaces indicated by different colours.

Table A7. Linear regression having road temperature as predictor for LAmax for coast-by measurements. Results are presented as R^2 adjusted (from the test data set) and the Bayesian Information Criterium (BIC).

<table>
<tr><td>Predictor</td><td>Coefficient</td><td>Std. error</td><td>P value</td><td>95 % conf. int.</td><td>R² adjusted</td><td>BIC</td></tr>
<tr><td>Road temperature [°C]</td><td>-0.0012</td><td>0.038</td><td>0.974</td><td>[-0.076; 0.073]</td><td rowspan="2">0.02</td><td rowspan="2">226</td></tr>
<tr><td>Constant</td><td>71.4131</td><td>1.233</td><td><0.001</td><td>[68.982.73.844]</td></tr>
</table>