An in-depth look at the tire rubber hardness influence on tire/road noise measurements

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ABSTRACT

When assessing the acoustic quality of a road pavement with the close-proximity (CPX) or the on-board sound intensity (OBSI) method, the rubber hardness of the reference tire substantially affects the measurement. Practical experience shows that measurement tires can get significantly harder within a single measurement season. This is why one would like to normalize measurements to a reference rubber hardness. The recently published technical specification defining the reference tires for CPX measurements (ISO/TS 11819-3), therefore, includes a new correction for tire rubber hardness. Early experiences with this new correction procedure raised questions about its accuracy. This paper takes an in-depth look on the influence of tire rubber hardness on CPX measurements for both reference tires P1 and H1. It analyses existing and new data and summarizes the research from several scientific contributions on this topic. It provides evidence that the effect of rubber hardness is tire specific and that separate correction factors for the P1 and the H1 tires lead to accuracy gains and improved repeatability and reproducibility of the method. The study concludes by proposing a revised tire-specific approach for the tire rubber hardness correction of CPX measurement results.

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1 INTRODUCTION

Measurements involving rubber tires can be a delicate matter as it is well known that over time the physical properties of rubber undergo significant changes. This is also the case for controlled tire/road noise measurements, e.g. CPX, OBSI and controlled pass-by or coast-by measurements. A substantial number of studies have investigated and documented the influence of tire properties on tire/road noise measurements suggesting that it constitutes one of the largest sources of error in the measurements[1–5]. The properties of the rubber can influence the measurements in different ways: 1. by the momentary variation of the tire property due to varying temperature conditions (referred to as temperature effects); 2. by the gradual change of the tire properties due to chemical and mechanical ageing of the rubber compounds (referred to as rubber hardness effects); and 3. by varying tire properties between different tires of the same or different production batches (referred to as acoustic non-conformity of measurement tires).

Whilst there has been substantial research on temperature effects, which has led to consolidated correction approaches in recent standards, limited amounts of data have been presented on the rubber hardness effects and on the acoustic conformity of measurement tires. Even though good storage practices of a measurement tire can mitigate the rubber ageing process[6–8], several studies[3,9] suggest that rubber hardness increases significantly over a year under medium to extensive usage while respecting good storage practices. Bühlmann et al.[3] reported an increase of up to 0.1 unit Shore A per measurement day for a new (run-in) reference tire. This means that if an operator with high usage replaces the reference tires every year while performing, say, 50 to 100 measurement days, the rubber hardness is likely to increase by 5 to 10 units Shore A. An operator with medium usage with around 20 to 30 measurement day will still experience a substantial rubber hardness increase by 2 to 3 units Shore A. If not accurately corrected, this is likely to lead to systematic errors in the measurement results. The recently published technical specification for CPX reference tires ISO/TS 11819-3:2017[10] takes account of the rubber hardness effect by including a new correction term, based on available data at that time. Recent experiences with this new correction method, however, raised questions about its accuracy. An obvious way of avoiding rubber hardness effects is the frequent replacement of reference tires. However, this practice may be costly and will only lead to satisfying improvement of measurement accuracy if there is acoustic conformity between the reference tires.

This paper takes an in-depth look on the influence of tire rubber hardness on tire/road noise measurements. It also investigates acoustic conformity issues when replacing a reference tire with a new one. It analyses existing datasets and summarizes research from several scientific contributions on this topic. Moreover, it examines new and unpublished data from substantial measurement campaigns undertaken in Switzerland by Grolimund + Partner AG and in Poland by the Gdansk University of Technology. The study then uses a validation dataset to test the determined Shore hardness vs. noise slopes, using data provided by the Dutch road authorities Rijkswaterstaat. The study concludes by presenting recommendations for standardization with the ultimate aim to further improve both repeatability and reproducibility of tire/road noise measurements. The focus in this paper is on reference tires P1 (here indicated as SRTT) and H1 (here indicated as Avon AV4) which are specified in ISO/TS 11819-3:2017.

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2 MATERIALS AND METHODS

2.1 Data collection and measurement set-up

Reliable quantification of tire rubber hardness effects can be empirically investigated under free-field conditions or on a laboratory drum. We distinguish between two main approaches when undertaking measurements to isolate and quantify rubber hardness effects: firstly, the “multi-tire” approach, which constitutes essentially of a series of identical measurements that are carried out with two or more sets of reference tires with different rubber hardness; or, secondly, the “single-tire approach” in which a series of measurements are carried out under the same conditions in an early and a late stage of a reference tire’s lifespan. With both approaches the data are ideally acquired on different road pavements (to investigate whether the effect varies significantly for different pavement types), at different speeds (to check for speed-dependent behavior) and at different temperature ranges (to check whether the effect is different at low or high ambient temperatures).

The “multi-tire approach” requires that measurement runs with two or more sets of tires are undertaken within a very narrow time window so that the measurement conditions do not significantly vary during the measurement series. As this most frequently used approach for determining rubber hardness effects always uses different set of reference tires, the determined rubber hardness effects always incorporate possible tire-related acoustic non-conformity issues other than those linked to rubber hardness.

The “single-tire approach”, on the other hand, requires a certain time shift in order for the tires to age. Under real world circumstances and normal usage this takes at least a few months to a year or more. An alternative approach is oven ageing, which requires a considerably shorter time but has certain limitations regarding the representativeness of the artificially aged tire in comparison to a tire aged under conventional environmental conditions. Although the “single-tire” approach is free of possible non-conformity issues linked to the “multi-tire approach”, it also has its downside: practical experience shows that it is difficult to find congruent measurement conditions on two days a year or more apart. Even if the ambient air temperature is similar, other possible influencing factors such as solar radiation or air humidity etc. may vary, which may make it difficult to properly isolate the rubber hardness effects. Besides, the properties of the road surface may change between the two time windows, even on rarely used test tracks due to mechanical and/or climatic strains. All these practical limitations make it a real challenge to measure rubber hardness effects with high accuracy.

An alternative to free-field measurements constitutes measurements on a drum in the laboratory. The laboratory environment can be controlled far better than outdoors and, hence, makes drum measurements easier to repeat under exactly the same conditions. The downside of the drum measurements is that the general applicability of laboratory results may be compromised by the fact that not all surfaces and replicas used on the drum are entirely representative of pavements common on roads.

2.2 Data requirements

Whenever rubber hardness effects are presented, data on the exact measurement conditions should also be provided as it constitutes the basis for uncertainty assessment. In order to qualify and cross-compare datasets obtained by various researchers, it is essential to provide data on ambient, road surface and tire temperature, exact measurements of speed as well as detailed information on the road surface. In addition, it is useful to document as much information on the assessed tires as possible, e.g. production date, time in use, number of measurement days, mileage, profile depth, measurements of rubber hardness on tread and sidewall.

2.3 Rubber hardness measurements in this study or its referenced studies

In all datasets/studies tire rubber hardness was measured using a Shore A durometer device (sometimes together with other measures). The measurement procedure of Shore A is simple and only requires a limited amount of equipment. The procedure, however, can lead to systematic differences between operators. As rubber hardness is strongly influenced by the rubber temperature (Wehr et al. 2018 determined a consistent decrease of around -0.25 Shore A/°C), the ASTM standard and ISO standards[11,12] require the rubber hardness measurement to be carried out in a climate controlled room at 23 °C. In order for the tires to adopt a homogeneous temperature, they need to be kept in the room for at least 2 hours prior to the measurement. If the tires cannot be measured at the prescribed temperature, the Shore hardness measurement can be corrected for temperature influence. Due to the measurement's strong dependency on temperature it is, however, recommended to carry out the measurement at the prescribed conditions.

The Shore A measurements of the tire tread were carried out in accordance to the ISO/TS 11819-3:2017[10] with a series of 3x2x2x3 (left outer rib, left inner rib, right inner rib, right outer rib) well distributed measurements over the tire tread. The hardness of the tire sidewall was acquired with three measurements on the right and the left sidewall each (see Table 1).

Table 1 – Rubber hardness measurements

Illustration of the rubber hardness measurements with a Shore A durometer			
Investigated tires	Dimensions	Tread	Sidewall
SRTT Uniroyal Tiger Paw M+S (P1)	P225/60 R16		
Avon Supervan AV4 (H1)	195 R14C		

2.4 Data preparation and analysis

The data found in the literature and considered by the authors was compiled into one single data sheet. The datasets usually contained multiple entries of overall and spectral tire/road noise levels for tires with different rubber hardness, with measurements undertaken under similar environmental conditions. The information on the road pavement was categorized by distinguishing between the main types dense asphalt concrete (DAC), stone matrix asphalt

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(SMA), surface dressing (SD), porous asphalt (PA), porous or semi-porous thin layers (TL), and several replica surfaces installed on laboratory drums. For measurements performed under similar conditions (see also Section 2.4), linear regressions between shore A rubber hardness and overall noise levels as well as third-octave band levels between 315 Hz and 5000 Hz were calculated. Each Shore hardness-to-noise relationship corresponds to one data point in the datasheet prepared for analysis.

Multivariate linear regression analysis was used to assess rubber hardness effects' main sources of variability. The dependent variables considered in the analyses were the Shore hardness-noise slope obtained for the overall noise levels (averaging the microphone positions to the front and rear of the tire/pavement contact area). For the analyses, only Shore hardness-noise relationships were considered which met the criteria for non-contaminated measurement data (coefficient of determination $R^2 > 0.7$, see also section 2.5). Parameters for which data were available for most datasets, such as tire, speed, pavement type, measurement method, data source and ambient temperature during measurements were used as ordinal or nominal independent variables. Variables were entered or removed from the model depending on the significance level of F (probability p): probability to remove greater than 0.10 and probability of F to enter smaller than 0.05. Based on the obtained multivariate models, the primary and secondary influencing variables were determined.

2.5. Limiting the effects of sources of error

The isolation and quantification of the rubber hardness effect through measurements is generally a rather challenging and delicate matter as other sources of variation can easily dilute or offset the effect we are aiming to determine. We call such sources of variation parasitic phenomena. Detailed analysis of our data with poor correlation between rubber hardness and noise levels showed that poor correlation is mainly a result of parasitic phenomena or poor design of testing, rather than due to noise-generation mechanisms being independent of tire rubber hardness. A major cause for poor correlation is the limited repeatability and reproducibility of the measurement methods in relation to the magnitude of the studied effect. As an example, with standard uncertainties of 0.7 dB in the CPX levels[2] and a magnitude of the rubber hardness effect of 1.5 dB, a maximum value of R^2 of 0.5 may be expected.

A frequently observed source of variation is temperature. Both the single-tire and the multi-tire approach require repeated measurements carried out in different times. Already a slight deviation in temperature of merely 5 °C will lead to an error in the estimated Shore hardness effect of 0.5 to 1 dB depending on the frequency range. In order to reduce the influence of temperature in the analyzed data, the maximum deviation of temperature was set to ± 2 °C for single measurement runs to be included in the analysis. Another frequent source of parasitic phenomena is deviating speed in measurement runs. As already small speed deviations will lead to measurement errors, the maximum tolerated speed deviation between measurement runs was set to 2 km/h.

Other parasitic phenomena may be the acoustic inhomogeneity of pavements (e.g. due to void content, or due to road markings, manhole covers etc. present in the wheel track). Whenever an analysis requires the comparison of several repeated measurements, the slightest deviation in the measurement process (e.g. if not following exactly the same warming-up procedure) may lead to erroneous data. Another source of error may be insufficient run-in of the reference tire. Especially when newer sets of tires are compared and analyzed, it is critical that they are sufficiently run-in (ISO/TS 11819-3[10] specifies a minimal run-in distance of 400 km for trailer systems) as poorly run-in tires may exhibit unrepresentative behavior.

3 RESULTS AND DISCUSSION

3.1 Why is there a need for correction?

Various studies have shown that the rubber hardness properties of a reference tire change significantly within the tire's typical lifespan, with negative implications on the accuracy of CPX and OBSI measurements (see below). The speed of this process varies dependent on the reference tires' usage and duration of usage as well as on the conditions in which they are stored (between usages). To allow operators to predict these changes, some empirical data on the ageing process has been assembled in Table 2.

Table 2 – Estimating the process of reference tire ageing

Empirical data on the ageing process of reference tires		
Usage	Ageing in ordinary lab storage	Ageing in good practice storage
based on measurement days: SRTT: 0.05 Shore A / usage day Avon AV4: 0.1 Shore A / usage day *Source: Bühlmann et al. 2013* [3] In function of total meas. distance: SRTT: 1 Shore A / 1000 km Avon AV4: 1 Shore A / 1000 km *Source: Grolimund + Partner AG*	based on duration after run-in: 1.1 Shore A / 100 days* *non-used (but run-in) tires stored in laboratory (around 20 °C) *Source: Ejsmont et al. 2017* [7]	based on duration after run-in: 0.66 Shore A / 100 days** *non-used (but run-in) tires stored in dark cold conditions (5-10 °C) *Source: Ejsmont et al. 2017* [7]

From Table 2 we can conclude that even with the best storage practices it will be impossible to sufficiently control the rubber hardness properties of a reference tire during its lifespan of typically 1 to 3 years. Hence, to produce comparable tire/road measurements during such a period, there is no straightforward alternative to the correction of rubber hardness influences.

3.2 Rubber hardness effects based on data of various researchers

In this study. 12 data sets, summing up to 247 different Shore hardness-noise relationships, were analyzed. Table 3 summarizes the characteristics of these datasets and presents the number of Shore hardness-noise relationships obtained in each of these studies. As Table 3 shows, most studies followed the multi-tire approach when investigating rubber hardness effects. The fact that the present data compilation involves data from in total more than 50 SRTT and 50 Avon AV4 tires and tire sets (in case of two wheeled trailers), reduces the risk that the obtained Shore hardness effects are skewed by possible non-conformity issues of tires. The obtained statistical distribution of Shore hardness effects are displayed in boxplots in *Fig. 1*. The Figure also shows a separate evaluation for the tires SRTT and Avon AV4. To exclude data points corrupted by parasitic phenomena from data analysis, we only incorporated Shore hardness-noise relationships with minimum R^2 of 0.7. By taking R^2 into consideration as a selection criterion, the dataset was reduced from 247 to 171 data points which corresponds to around 70 % of all data. It should be stated, that with this approach the removal of parasitic phenomena remains incomplete, since on around 40 % of the data sets the rubber hardness effects were derived on merely two data points (yielding a R^2 of 1). Moreover, there remains the risk that applying a selection criterion based on R^2 may lead to an overestimation of the rubber hardness effects. The selection criterion, however, mainly reduced the spread in obtained shore-hardness-noise relationships without significantly altering the median values: if a selection criterion of $R^2 \geq 0.5$ is applied, for instance, the median values remain unchanged.

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Table 3 – Characteristics of the 12 datasets on rubber hardness effects incorporated in this study

Authors / Data source	Country	Short title	Speeds in km/h	Tires (No. of)	Pavements (No. of)	No. of measurements	No. of noise rubber hardness relationships	Measurement approach	Average rubber hardness effect
Bühlmann et al 2013	Switzerland	Ageing reference tires during a measurement season	50	SRTT (2), Avon AV 4 (2)	AC (1)	4	2	CPX, single-tire	0.3 dB/Shore A (SRTT) 0.15 dB / Shore A (Avon AV 4)
Grolimund + Partner (unpublished)	Switzerland	Tire comparison at different temperatures	50	SRTT (2) Avon AV 4(2)	Thinlayer (4), SMA (1), AC (2)	201	56	CPX, multi-tire	0.12 dB/ Shore A (SRTT) 0.25 dB / Shore A (Avon AV 4)
Grolimund + Partner (unpublished)	Switzerland	Tire comparison at different speeds	30, 50, 80, 100	SRTT (2) Avon AV 4(2)	AC (1), Thinlayer (1)	48	10	CPX, multi-tire	0.09 dB/ Shore A (SRTT) 0.14 dB / Shore A (Avon AV 4)
Grolimund + Partner (unpublished)	Switzerland	Tire evaluation at start and end of season	50	SRTT (12) Avon AV 4(12)	AC (1), SD (1)	57	10	CPX, multi-tire	0.17 dB/ Shore A (SRTT) 0.18 dB / Shore A (Avon AV 4)
Grolimund + Partner (unpublished)	Switzerland	Tire changes from start to end of season	50	SRTT (12) Avon AV 4(12)	AC (1), SD (1)	24	12	CPX, single-tire	0.10 dB/ Shore A (SRTT) 0.17 dB / Shore A (Avon AV 4)
Oddershedde and Kragh (2014)	Denmark	Changes in noise levels from SRTT due to increasing tire tread hardness	80	SRTT (4)	AC (3), SMA (3), ISO (3)	58	14	CPX, multi-tire	0.09 dB /Shore A (SRTT)
Rijkswaterstaat (unpublished)	Netherlands	Round-robin CPX 2017	80	SRTT (9)	SMA (1), PA double layer (1)	18	-	CPX, multi-tire	-
Sandberg & Ejsmont 2007	Sweden / Poland / Germany	Influence of tire tread rubber hardness on t/r noise emission	80 (CPX) 70, 90 (market tires)	CPX tires A (5), B (7), C (5) and D (4); Market tires (100)	ISO (1), SD (1); market tires: ISO (1), SW (1), SD (1), DAC (1)	42 (CPX) 800 (Drum)	4 (CPX) 8 (Drum)	CPX, multi-tire market tires: multi-tire	0.2 dB/ Shore A (CPX) 0.1 to 0.26 dB/ Shore A (market tires)
Schubert et al. 2016	Germany	Influence of tire age and wear on t/r noise emission	80	SRTT (11), Avon AV 4 (5)	SMA (1), PA (2), Thinlayer (1)	64	8	CPX, multi-tire	0.05 dB/ Shore A (SRTT) 0.11 dB/ Shore A (Avon AV 4)
TU-Gdansk (unpublished)	Poland	Rubber hardness effect - Laboratory drum measurements of different tires	30, 50, 80, 100	SRTT (7), Avon AV 4 (11)	APS (2), DAC (2), ECE (1), ISO (1), Pers (1), SMA (1)	490	105	Drum, multi-tire	0.16 dB/ Shore A (SRTT) 0.11 dB/ Shore A (Avon AV4)
TU-Gdansk (unpublished)	Poland	Rubber hardness effect - Road measurements	50, 80	SRTT (6)	DAC(3), HRA (1), SMA (4), Thinlayer (1)	36	11	CPX, multi-tire	0.16 dB/ Shore A (SRTT) 0.11 dB/ Shore A (Avon AV4)
Wehr et al. 2018	Austria	Combined approach for correcting tire hardness &temperature on t/r noise	80, 100	SRTT (4)	SMA	46	4	CPX, multi-tire	0.12 dB / Shore A (SRTT)

Then all data sets listed in Table 3 were combined into one large data set and jointly analyzed. The resulting statistical distribution of rubber hardness effects is displayed as box plots in *Fig. 1*.

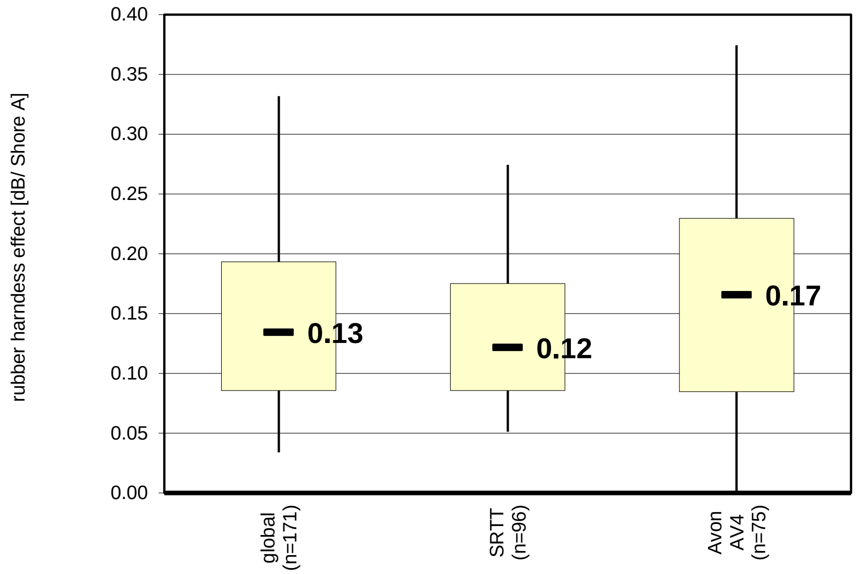

Fig. 1– Rubber hardness effect based on 12 datasets and 171 different relationships.

For the analyzed 171 data points, *Fig. 1* shows a median Shore hardness effects of 0.13 dB/ Shore A while yielding in a lower effect of 0.12 dB/ Shore A for the SRTT tire as opposed to 0.17 dB/ Shore A for the Avon AV4 tire. The rather large spread of the obtained Shore hardness-noise relationships either suggests the presence of measurement errors in the datasets or the manifestation of underlying influencing factors that may lead to a variation in the magnitude of the effect. These causes for variation will be further examined in Sections 3.3 and 3.4. Note that in ISO/TS11819-3:2017 the constants are given as 0.20 for both tires. The following *Fig. 2* shows the spectral characteristics of the rubber hardness effect.

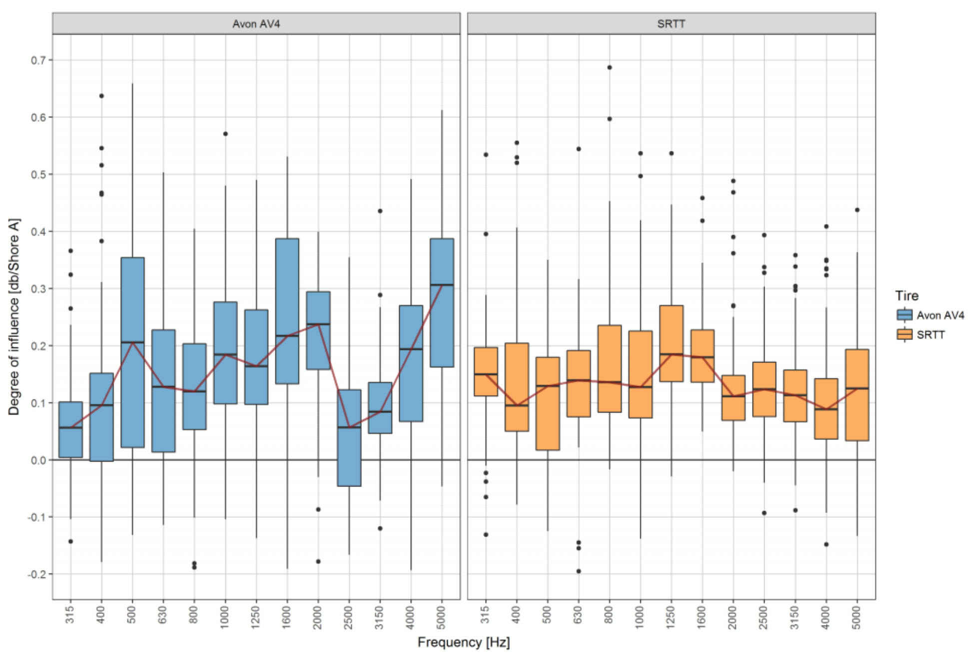

Fig. 2 – Spectral characteristics of rubber hardness effects.

As *Fig. 2* illustrates, the Shore hardness effect varies over the noise spectrum: it shows its peak around the mid-frequencies while plummeting at higher frequencies before it rises again. Similar spectral characteristics were determined by Wehr et al. (2018)[5] in their measurements. Besides, the results for the SRTT tire are highly congruent with the simulation results (but to a lesser degree with the measurement results) of Schubert et al. (2016)[9] using tire mobility measurements to simulate rubber hardness effects. The rubber hardness effects, moreover, show strong tire specific characteristics. Such a tire specific behavior has also been detected in an earlier study by Sandberg & Ejsmont (2007)[13]. In this respect, Shore hardness effects are different from temperature effects, which do not deviate in such a degree for different tires[14].

3.3 Sources of variation: influence of acoustic non-conformity between tires

As we learnt from Table 3, the overwhelming part of the data analyzed in this study stems from studies which used the multi-tire approach to determine rubber hardness effects. To get a better understanding of the degree that the observed spread of spectral rubber hardness effects may be influenced by acoustic non-conformity different tires, datasets of tires with the same Shore hardness measured under the same conditions on the same surface are compared. The obtained tire/road noise spectra and the corresponding standard deviation are shown in *Fig. 3*.

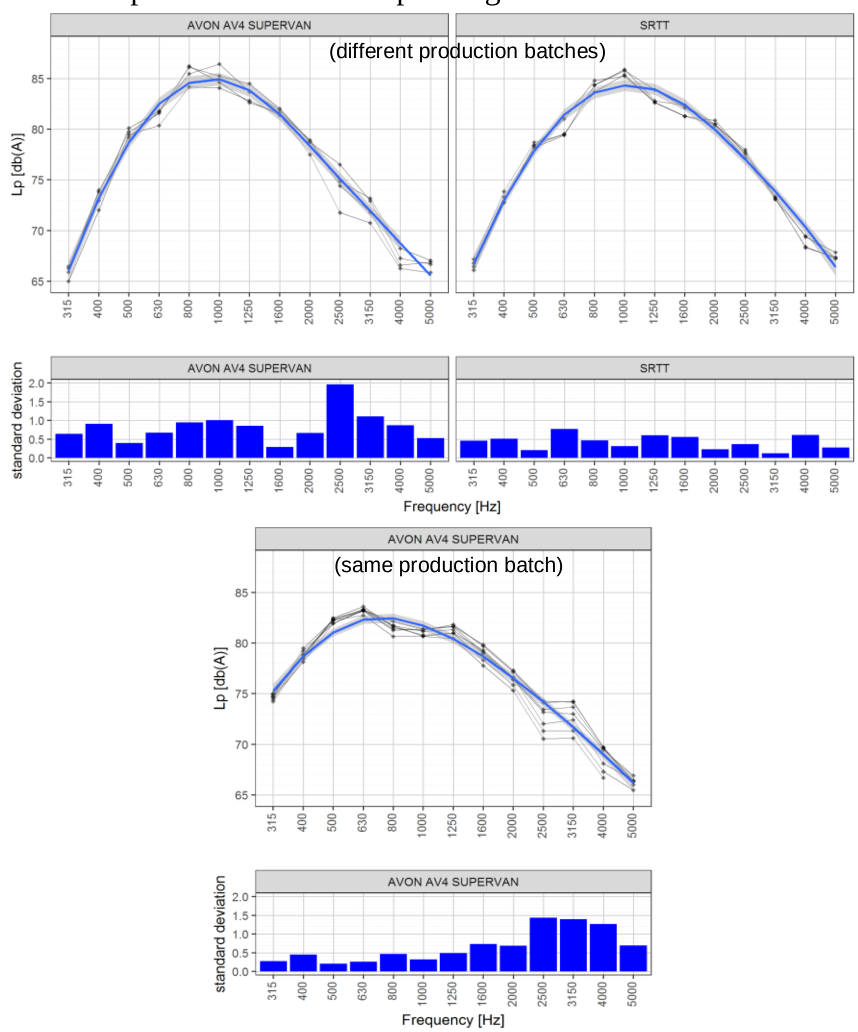

Fig. 3 – Acoustic conformity of tires from different production batches (measured by Grolimund +Partner AG) and from the same batch (measured by the Gdansk University of Technology).

Fig. 3 shows that the standard deviations for spectral noise levels for the SRTT are rather small and homogeneous over the noise spectrum and lay near the expected measurement accuracy for CPX measurements. Those for the Avon AV4 tire, in contrast, are substantially larger and increase towards the high frequency range. This can only partially be mitigated when tires of the same production batch are used (see lower figure). With regard to the rubber hardness effects presented above, this implies that indeed a part of the observed variation in the effect may be attributed to the rather limited acoustic conformity of different Avon AV4 tires. In practice this means that one should conduct conformity tests (ideally with several tires and then select the most conform one) before replacing a reference tire.

3.4 Sources of variation: investigating the main influencing variables

In order to investigate the sources of variation of rubber hardness effects, a multivariate linear regression analysis was undertaken, adding independent variables in a stepwise forward process. The primary and secondary influencing variables were then determined based on the multivariate models for rubber hardness effects on the overall and spectral noise levels.

Table 4 – Primary and secondary influencing variables of rubber hardness effects

	LP	Frequencies [Hz]												
		315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Primary**	*Speed*	*Tire*	*Speed*	*Tire*	*Speed*	*Pav.*	*Pav.*	*Pav.*	*Drum*	*Tire*	*Tire*	*Drum*	*Tire*	*Tire*
Secondary*	-	*Pav.*	*Pav.*	*Speed*	-	*Tire*	-	-	*Tire*	*Drum*	*Pav.*	-	-	-

** significance level $p<0.001$

* significance level $p<0.05$

LP = Overall noise level, Pav. = pavement type, Drum = measurement on laboratory drums, Tire = SRTT, Avon AV4

As the results of the statistical analysis displayed in Table 4 reveal, *Speed* is the only variable significantly causing variation of the rubber hardness effects on overall noise levels. If the primary and secondary influencing variables of the rubber hardness effects on the third-octave band frequencies are considered, the variable *Tire* contributes 8x (all frequency ranges), variable *pavement type* 6x (mainly in the low and mid frequency ranges), and speed *Speed* 4x (low frequency range) to the variation of rubber hardness effects. In the higher frequency range measurements performed on the laboratory drum seem to cause some variability in the rubber hardness effect. Interestingly, the ambient temperature during measurements did not appear as a factor of influence in any of the models, implying that rubber hardness effects remain constant over different temperatures. Further examination of the data indicates that there are some combinations of tires and pavements which may be considered as outliers regarding rubber hardness effects. Such outliers are: Thin layers (high, Avon AV4), PERS (high, Avon AV4), APS (low, Avon AV4), APS (high, SRTT), PERS (high, SRTT). The pavements that feature outliers on the high side have the attribute of being rather smooth (exception: APS with SRTT tire, APS is a replica of a surface dressing 8/11). This may be explained by the fact that on smoother surfaces the tire induced noise generation mechanisms become more important and that the property of the tire (i.e. rubber hardness) in turn becomes more influential.

3.5 Validation with Dutch Round Robin Test data

To validate the Shore hardness-noise slopes determined in Section 3.2, an independent dataset is used consisting of a series of measurement runs performed by 9 different CPX trailers in the scope of a round robin test ordered by the Dutch road authorities Rijkswaterstaat. The round robin test involved a number of measurement runs performed on a test track by each operator in a relatively short time frame under the same measurement conditions. The tests were performed at 80 km/h on two surfaces (a porous asphalt and an SMA) with each operator using his own set of SRTT tires of varying age and rubber hardness. This study uses the calculated standard deviation of the overall noise levels obtained by the 9 measurement systems while systematically increasing the applied rubber hardness correction (see *Fig. 4*).

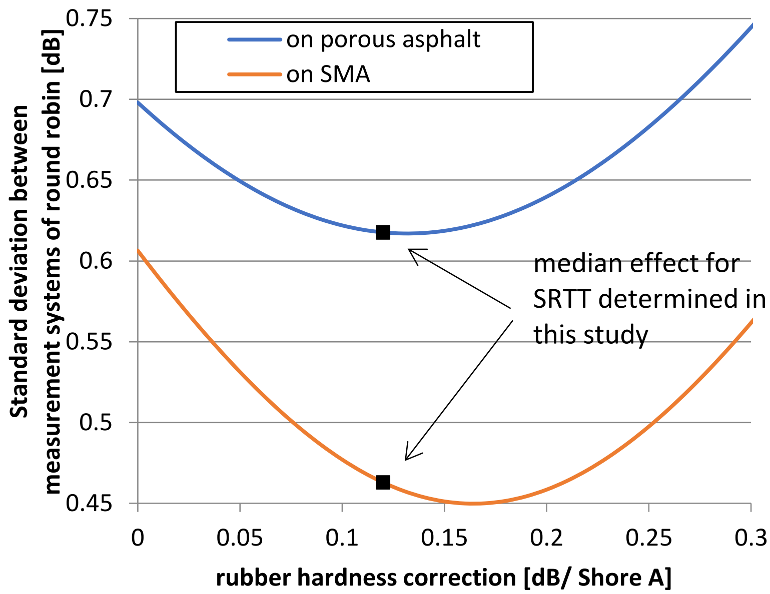

Fig. 4 – Standard deviation of overall noise levels determined by 9 measurement systems in function of the applied Shore hardness correction vs. the median rubber hardness effect obtained in this study

A first validation undertaken in *Fig. 4* indicates that the suggested rubber hardness correction for the SRTT tire works really well for the 9 sets of tires used in the study.

4 CONCLUSIONS

This study reviewed new and existing data to gain a better understanding of the way rubber hardness influences tire/road noise measurements. 13 different data sets altogether yielded 172 valid data points of rubber hardness effects. Based on this large amount of data, a median rubber hardness effect of 0.13 dB/ Shore A was determined with a rather large spread in magnitude. When investigating the sources of variability, it was found that the effects substantially vary for different tires. If separate values for different reference tires are calculated, a somewhat lower factor, 0.12 dB/Shore A, is obtained for the SRTT (reference tire passenger cars for the OBSI and CPX method) as opposed to 0.17 dB/A for the Avon AV4 tire (heavy vehicle reference tire H1 for the CPX method). Note that in ISO/TS11819-3:2017 the constants are given as 0.20 for both tires. While it was found that acoustic conformity issues between tires of the same type contributed to the observed variation of the effect, statistical analysis revealed that the main sources of variation are road pavement and measurement speed. In addition, rubber hardness effects seem to remain constant over different temperatures.

The authors strongly recommend correcting tire/road noise measurements OBSI and CPX for rubber hardness effects. The results suggested that this should be done using tire specific correction factors. In order to further increase the reproducibility and repeatability of tire/road noise measurements, the authors advise carrying out conformity testing before replacing reference tires.

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