



Tyre-road noise measurements: influence of tyre tread and road characteristics

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ABSTRACT

Traffic noise is a well known problem. For speeds above approximately 40 km/h the noise is mostly tyre-road noise. The noise level depends on the tyre, the road and the interaction between the tyre and the road. There are various well-known methods to measure tyre-road noise and in this paper the measurement results of CPX, impedance tube and road roughness measurements are combined to investigate the relation between the radiated noise and the tyre tread design and road characteristics.

All measurements have taken place on a special test area at Airport Twente, where 8 different type of asphalt surfaces were constructed. Two these tracks are based on new models for sound absorption and grip. Six of the tracks are porous asphalt concrete.

To investigate the relation between tyre tread design and the sound radiation, three simple parameters are defined based on properties that are commonly considered when researching the influence of tyre tread. However, the parameters defined in this paper are simplified, such that they can be applied when no detailed knowledge of the tyre properties is available.

The relation between road characteristics and sound radiation is investigated using the properties of the road, such as stone size, porosity and sound absorption, and some texture parameters as defined by the International Organisation of Standardization (ISO).

The correlation between the tyre and road parameters and the sound radiation is investigated, both for the root mean square values and the octave bands of 500 Hz, 1000 Hz and 2000 Hz. The results show that both the tyre parameters as the road characteristics, such as porosity of the road and the sound absorption by the road, are important for a decrease in sound radiation. The influence of the porosity of the road and the sound absorption by the road on the radiated sound is more significant for the frequencies in the octave band of 2000 Hz than the influence of the investigated tyre treads on the radiated sound. However, in the octave band of 1000 Hz, the influence of the tyre tread parameters on the sound radiation is larger. Furthermore, a relation is found between the radiated sound and the maximum stone sizes in the asphalt concrete.

The measurements show a clear correlation between the sound absorption of the tested tracks and the radiated sound: for an increasing sound absorption coefficient the sound radiation decreases. Moreover, the total sound radiation decreases more when the sound absorption of higher frequencies is increased.

Keywords: Sound, Tyre-road noise, Measurements I-INCE Classification of Subjects Number(s): 51.4

1. INTRODUCTION

Tyre-road noise is caused by the interaction between the tyres of a car and the road. The main cause is the variation in contact force between tyre and road while driving. Tyre-road noise is investigated intensively and there are various well-known methods to measure the noise. However, the tyre characteristics are determined using standardized roads – conform the EC legislation R1222 – while the road characteristics are determined using standardized tyres – for example ISO11819-2.

The roads and tyres, as defined in the standards, are rarely used nowadays, which hinders innovation.

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In 2011, the project 'Stil Veilig Wegverkeer' (translated in: 'Silent and Safe Road Traffic') was started by the University of Twente, Province Gelderland, Apollo Tyres Global R&D B.V., Reef Infra B.V. and Stemmer Imaging. The project is sponsored by the partners and subsidised by the Regio Twente, Province Overijssel and European Regional Development Fund. The project led to an integral approach of the tyre-road interaction, both for noise and wet grip. Within this project, multiple simulation tools and test procedures were developed for the optimisation of a silent and safe tyre and road combination. An overview of the different aspects of this project are given in (1).

Apart from new simulation tools and test procedures, a special test area was developed at Airport Twente, a regional and out-of-service airport in the eastern part of the Netherlands. At this site, 8 different type of asphalt surfaces were constructed based on new models for sound absorption and grip. Six of these surfaces are porous asphalt concrete.

The focus in this paper is on the tyre-road noise measurements carried out within the project 'Silent and Safe Road Traffic' at Airport Twente. The measurement results of impedance tube measurements, road roughness measurements and CPX measurements are combined to investigate the relation of the tyre tread design and road characteristics on the noise radiation. Other aspects of this project are described in (1), (2), (3) and (4).

1.1 Outline

The relation between tyre tread design and road characteristics is investigated using so called input parameters. The tyre input parameters defined in this paper are based on commonly investigated properties, such as the air ratio and impact of the tread blocks. However, the parameters defined here are simplified, such that they can be derived also when there is no detailed knowledge of the tread pattern of the tyre.

The road input parameters are chosen from generally used parameters to describe concrete asphalt surfaces, such as stone size, layer height, porosity and sound absorption coefficient. The road roughness parameters are chosen from the 'Characterization of pavement texture by use of surface profiles' by the International Organisation of Standardization (ISO) (5).

The relation between the tyre tread design and the road characteristics – the input parameters – and the noise radiation measured by close-proximity (CPX) measurements – the output parameters – is shown in a matrix form, similar to a correlation matrix.

In the second section of this paper, the input parameters for this correlation matrix are discussed. In Section 3 the CPX measurements are discussed as well as the results of the correlation study between the output parameters and the input parameters. The CPX measurements are discussed in more detail in Appendix A.

2. TYRE TREAD DESIGN AND ROAD CHARACTERISTICS

Various existing and prototype tyres have been tested within the project 'Silent and Safe Road Traffic', but in this paper only the measurement results of a selection of the tyres is presented. These are the Uniroyal SRTT Tigerpaw (also known as ASTM tyre), the Vredestein Ultrac Cento and a slick tyre, as shown in Figure 1.



Figure 1 – The SRTT Tigerpaw (left), Ultrac Cento (center) and the slick (right).

2.1 Tyre tread design parameters

There are many properties of the tyre which can be considered, such as the width of the tyre, the material properties (like stiffness and damping), the contact pressure or the area of the tyre which is in contact with the road, the randomisation or pitch sequence of the tyre design. Those and more tyre characteristics are discussed by (6), (7) and many others.

In this paper we limited ourselves to three input parameters for tyre tread design: (a) the air ratio; (b) the pattern continuity factor and (c) the true contact ratio. These parameters are based on commonly investigated tyre properties. However, the purpose of this paper is to give simple parameters which can also be used when no detailed knowledge of the tread pattern is available.

The tyre input parameters are used to describe the tyres used in the measurements. For each tyre, an estimate is made of the footprint of the tyre, based on pictures of this footprint. These schematically rendered footprint areas, shown in Figure 2, are used to calculate the air ratio and the pattern continuity factor, as listed in Table 1. The true contact ratio also depends on the porosity of the road surface. The parameters are explained below in more detail.

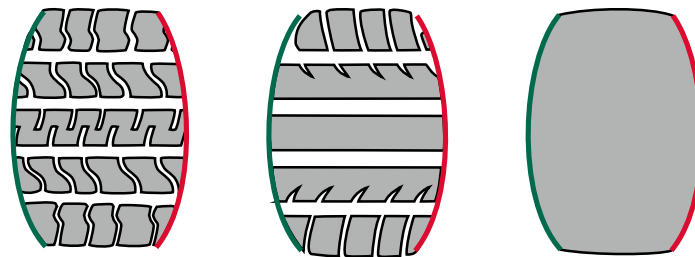


Figure 2 – Schematic rendering of footprint area of SRTT Tigerpaw (left), Ultrac Cento (center) and the slick (right), where the green line indicates the leading edge and the red line the trailing edge.

			SRTT	Ultrac Cento	Slick
Air ratio	R_{air}	[-]	0.38	0.37	0
Pattern continuity	$C_{pattern}$	[-]	0.75	0.83	1

Table 1 – Input parameters for tyres used in the correlation study.

2.1.1 Air ratio

The air ratio R_{air} is defined as the relation between the area of the grooves $S_{grooves}$ and the total footprint area S_{total} of the footprint (7):

$$R_{air} = \frac{S_{grooves}}{S_{total}} \tag{1}$$

where $S_{total} = S_{grooves} + S_{tread}$, with S_{tread} is the area of the apparent contact between the tyre and a smooth surface. This schematically displayed in Figure 3, where the area of the grooves is shown in dark green and the total area is equal to the sum of the yellow and dark green area. The air ratio gives some insight in the pressure inside the footprint. However, this factor only gives the ratio between the open and total area, and not the real contact area, since this also depends on the road surface.

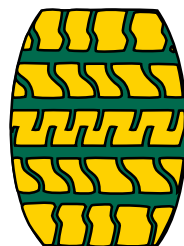


Figure 3 – Schematic representation of air ratio.

2.1.2 Pattern continuity

The second tyre parameter we used in the correlation study describes the continuity of the tyre pattern. We defined this parameter C_{pattern} as the variation in contact during rolling. The contact during rolling is described as the sum of the width of the tyre blocks in apparent contact W_{tread} . The variation in contact is then described by the variation of the ratio between this total width in contact and the total width of the tyre footprint W_{total} , along the circumference of the tyre:

$$C_{\text{pattern}} = 1 - \left[\max\left(\frac{W_{\text{tread}}}{W_{\text{total}}}\right) - \min\left(\frac{W_{\text{tread}}}{W_{\text{total}}}\right) \right] \tag{2}$$

This is illustrated for a section of the tyre tread pattern in Figure 4.

This continuity factor is based on the tread pattern height factors discussed by Bekke (7), page 72–81. However, for the parameter defined by Bekke, a detailed knowledge of the tyre has to be known, whereas the pattern continuity as defined in this paper can easily be derived if only an estimation of the tread pattern is known.

Furthermore, this continuity parameter is slightly related to the tread pattern geometry description, as discussed by Sandberg and Ejsmont (6), chapter 10. The authors argue that the shape or contour of the tread design is very important, because if the contour of the tread coincides with the contour of the footprint of the tyre, noise will be generated. Therefore, both the pattern continuity and the tread design layout give an indication of the variation of pressure and impact when the tread blocks come into contact with the road.

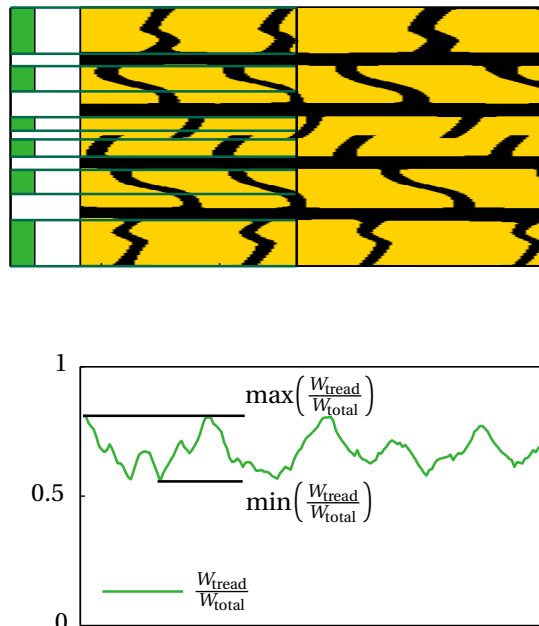


Figure 4 – Schematic representation of pattern continuity for section of tyre circumference.

2.1.3 True contact ratio

Another parameter that we defined depends on both the road properties and air ratio of the tyre. This parameter is defined as the true contact ratio R_{tc} and is related to the real contact area of the tyre with the road surface. It would be best to determine this parameter using footprint images of the tyres on every road surface, but we do not have this information.

Therefore, the true contact ratio is estimated in this paper using the apparent contact area of the tyre S_{tread} , the total area of the footprint S_{total} and the porosity of the road Ω_{road} :

$$R_{\text{tc}} = 1 - \frac{S_{\text{true contact}}}{S_{\text{total}}} = 1 - \frac{(1 - \Omega_{\text{road}})S_{\text{tread}}}{S_{\text{total}}} \tag{3}$$

where $S_{\text{true contact}}$ indicates the area of the true contact, taking into account the structure of the road. this is illustrated in Figure 5. The true contact ratio is listed in Table 5 for all combinations of tyres and road surfaces, using the porosity of the road as listed in Table 3. This true contact ratio is connected to the

ventilation of the tyre, as discussed by Sandberg and Ejsmont (6), in chapter 10, and gives information about the formation of air pockets inside the contact area.

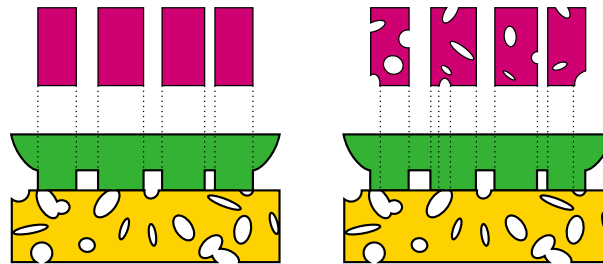


Figure 5 – Schematic representation of apparent contact (left) and true contact (right), where the road is indicated in yellow, the tyre in green and the contact area in pink.

		Track 1	Track 2	Track 3	Track 4	Track 5	Track 6	Track 7	Track 8
R_{tc} SRTT	[-]	0.45	0.47	0.50	0.40	0.43	0.40	0.53	0.53
R_{tc} Cento	[-]	0.44	0.46	0.50	0.39	0.42	0.39	0.53	0.53
R_{tc} Slick	[-]	0.12	0.15	0.20	0.03	0.08	0.03	0.25	0.25

Table 2 – True contact ratio.

2.2 Test area and road characteristics

Within the project ‘Silent and Safe Road Traffic’, a total of 8 test tracks were constructed at Airport Twente. This out-of-service airport is located in a quiet and rural area in the eastern part of the Netherlands. An impression of the test area is shown in Figure 6.



Figure 6 – Test area at airport Twente, photo taken during pass-by measurements.

The first 6 tracks were constructed in 2013, these were existing road surfaces with various characteristics, such as porosity, type and size of stone. In the years 2013 and 2014, research was done to find the properties of the test sections and the behaviour of various tyre road combinations. This research was done by in-situ measurements, by measurements in the lab and by developing predictive models and design tools.

A novel modelling approach to predict the sound absorption coefficient of porous asphalt concrete for oblique incidence (3) is used to define design parameters for a road surface which will minimise the sound radiation. The design parameters given by the model have been combined with parameters based on measurement results from CPX measurements, pass-by measurements and sound absorption measurements.

Combining the models and measurement results, two new test sections with porous asphalt concrete were developed and constructed in 2015. These roads were optimised for the best grip and minimum noise radiation. One of these new roads is a double layered open porous asphalt with small stones in

the top layer (2–4mm) and larger stones in the second layer (8–11mm). The porosity of both layers is approximately 25%. The other new road surface is a single layer of open porous asphalt with stones of 2–6mm. A different type of stones is used for both test sections, such that the influence of the material on noise and wet grip could be investigated further.

Again some characteristics are defined to describe the most important properties of the road surfaces, these are explained below and listed in Table 3.

2.2.1 Road roughness

An important property of a road surface is the roughness of this surface. Within the project ‘Silent and Safe Road Traffic’, a 3D laser scanner with two sets of lasers using triangulation is developed, which can acquire a depth image of a surface with texture of 140 mmx200 mm, with a resolution of 50µm. This scanner is used to obtain the roughness information of all the road surfaces at Airport Twente. The output can be used to show the texture spectrum of the surfaces, but can also be translated into commonly used parameters, such as the mean profile depth, texture depth, profile envelope, profile amplitude distribution and so on. Moreover, the spectrum of the texture can be analysed by the texture level divided into three groups:

- microtexture (<0.5mm),
- macrotexture (0.5–50mm),
- megatexture (50–500mm),

as defined by the ISO standard 13473-2:2002 (5).

An example of the depth image of track 2 is shown in Figure 7.

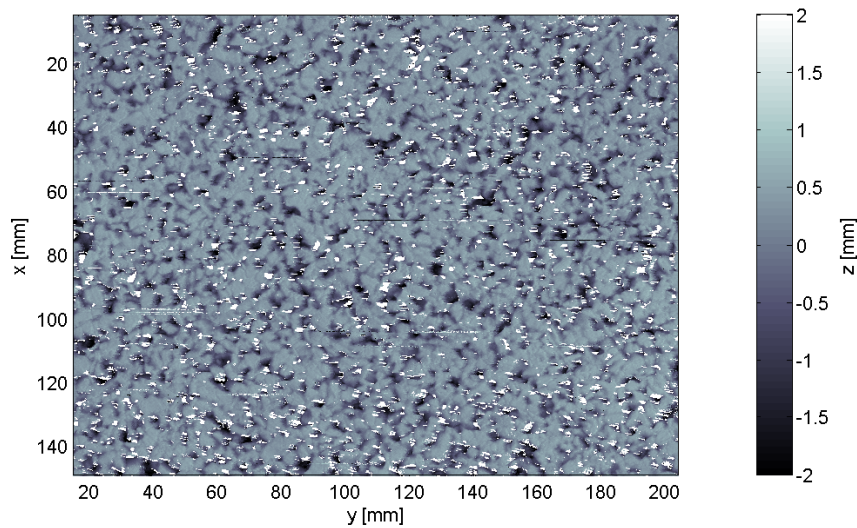


Figure 7 – Example of depth image by 3D laser scanner of track 2 (8).

In this paper, we only considered the mean profile depth (MPD) and root mean square value of the texture levels to determine the correlation between road surface characteristics and the measured sound pressure level. The MPD is defined as:

$$MPD = \frac{1^{st} \text{ peak level} + 2^{nd} \text{ peak level}}{2} - \text{average level} \tag{4}$$

where the peak levels are defined as indicated in Figure 8. However, the method prescribes a total measurement length of 100 m. Using the 3D scanner, the measured surface is approximately 140 mmx200 mm. Therefore, we used a variation of the official method, in which we assumed that the acquired image shows a representative distribution of the surface texture and we divided the surface scan into line segments. These line segments of 200 mm each are pasted one after the other up to a length of 100 m, forming the profile curve $z(x)$. For this approach, 3 scans per road surface are used.

The values for the MPD are listed in Table 3. It can be seen that the values are around 0mm, which could be explained by the bitumen removal procedure applied to the test tracks. In this procedure, the top layer of the surface is removed using rotating diamond discs.

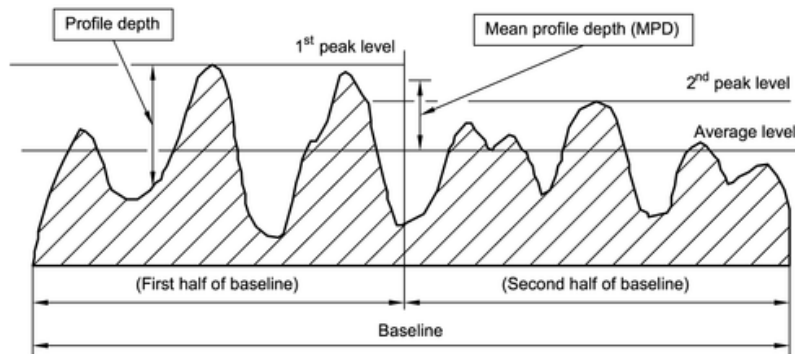


Figure 8 – Illustration of definitions to determine MPD (5).

The second roughness parameter we considered, is the root mean square value (z_{rms}) of the profile curve $z(x)$, which is evaluated for segments of length l :

$$z_{rms} = \sqrt{\frac{1}{l} \int_0^l z^2 dx} \quad (5)$$

The root mean square values for each track are listed in Table 3.

2.2.2 Properties mixture

The properties of the asphalt and stone mixtures are also considered in the correlation study. Again, some parameters are selected. These are the minimum and maximum stone size of the mixture ($D_{s,min}$ and $D_{s,max}$, respectively), the porosity of the road (Ω_{road}) and the layer thickness (H_{road}). These four characteristics are listed in Table 3 for all 8 test tracks.

		Track 1	Track 2	Track 3	Track 4	Track 5	Track 6	Track 7	Track 8
MPD	[mm]	0.07	0.04	0.11	0.03	0.09	0.02	0.03	0.02
z_{rms}	[mm]	1.1	0.7	1.4	0.5	1.0	0.4	0.9	0.8
$D_{s,min}$	[mm]	2	2	4	2	4	2	2	2
$D_{s,max}$	[mm]	5	5	8	16	8	8	4	6
Ω_{road}	[%]	12	15	20	3	8	3	25	25
H_{road}	[mm]	25	30	57	40	35	35	75	40

Table 3 – Road roughness and properties of the mixtures.

2.2.3 Sound absorption coefficient

The sound absorption coefficient of all road surfaces is determined using the impedance tube technique. The sound absorption is measured in-situ. The absorption coefficient is averaged over at least 10 measurements at various positions in longitudinal direction of the road. The variation in the other direction is measured and has good agreement with the measurements in the longitudinal direction. The repeatability of the measurements was tested at several roads and measurement locations.

The sound absorption coefficient is determined in the continuous frequency spectrum, but for the purpose of this paper, only the results in the octave bands of 500 Hz, 1000 Hz and 2000 Hz are considered. The results are listed in Table 4.

3. CORRELATION RESULTS

In this section a summary of the CPX measurement results and the correlation study are presented. The focus of this paper is to show the relations between the tyre and road characteristics and noise radiation. Therefore, a correlation study is done, using sound pressure level determined by CPX measurements. Only the measurement results for a velocity of 80km/h are included here.

		Track 1	Track 2	Track 3	Track 4	Track 5	Track 6	Track 7	Track 8
500 Hz	[-]	0.12	0.26	0.59	0.02	0.19	0.03	0.62	0.62
1000 Hz	[-]	0.14	0.25	0.40	0.02	0.18	0.03	0.50	0.55
2000 Hz	[-]	0.17	0.28	0.33	0.04	0.19	0.06	0.46	0.44

Table 4 – Sound absorption coefficient per octave band.

3.1 CPX measurements

The CPX measurements have been performed with a special device attached to the car, shown in Figure 14. Since the microphones of this device are in open air and the distance between the microphones and the tyres is larger than for a standardized CPX trailer, the correlation between this device and the standardized CPX measurements with a closed trailer is investigated, as discussed in in Appendix A. The found correlation is:

$$CPX_{trailer} = 0.97CPX_{car} + 5.50 \tag{6}$$

where CPX_{car} is the root mean square (rms) value in dB(A) for the CPX device attached to the car and $CPX_{trailer}$ is the rms value in dB(A) for the CPX trailer. This relation is used to find the corrected values of the CPX measurement results as shown in this paper.

3.2 Correlation study

The correlation for all input parameters and output parameters are considered. A quick overview of the results is shown in Table 5. For every combination in this table the correlation and the coefficient of determination (R^2) of a linear fit through the measurement points is checked. A good R^2 is indicated in green (75% gray in black and white print), a moderate R^2 in yellow (25% gray in black and white print) and when R^2 is low, the color is red (95% gray in black and white print). In the situation of good or moderate R^2 , the correlation is represented by the slope of the black line.

Some of the found correlations are shown in more detail in this section.

3.2.1 Sound absorption and porosity of the road

In Figure 9 the correlation between the sound absorption of the test tracks and the measured sound pressure level are shown per octave band. The CPX measurements for four tyres are compared with the sound absorption coefficients of the test tracks. It can be seen that the total sound pressure level varies with the tyres, but the overall correlation is good. Interesting is that the effect of sound absorption by the test tracks is more important for the higher frequencies. The same trends are seen when the porosity of the road is considered, though the influence of the porosity on the sound radiation is much larger.

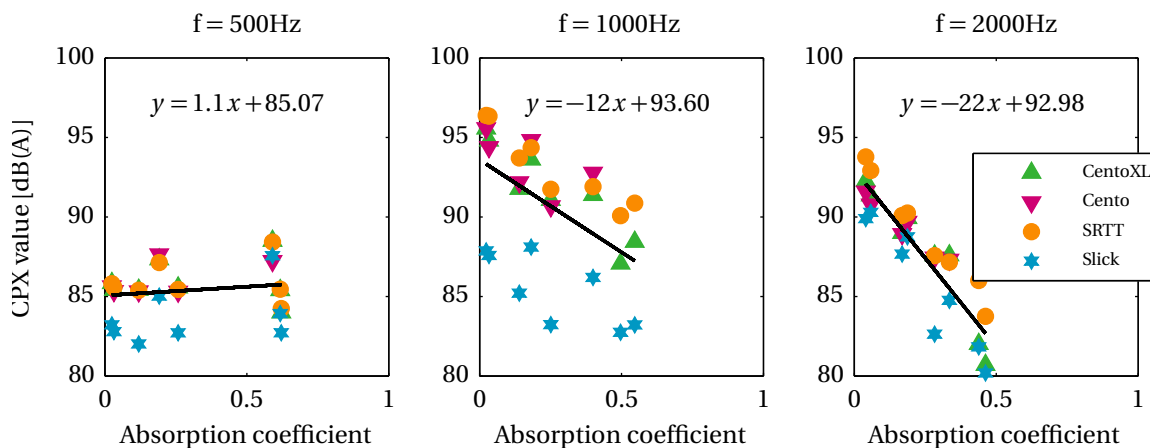


Figure 9 – Correlation between sound absorption and sound pressure level per octave band.

3.2.2 Stone size

Figure 10 shows the correlation between the maximum stone size in the asphalt mixtures of the top layers and the CPX values. The figure shows a good correlation between the maximum stone size and the

CPX values, when the variation in results for the measurements with the four different tyres is considered. It can be seen that a larger maximum stone size in the mixture has a negative influence on the radiated sound. Influence of the minimum stone size in the asphalt mixture is not seen. However, this could also be explained by the small variation in minimum stone size for these tracks.

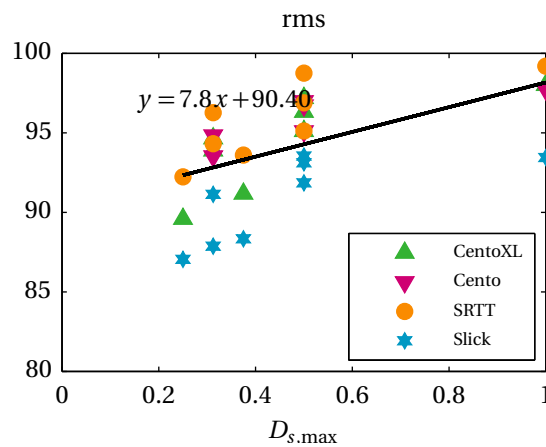


Figure 10 – Correlation between maximum stone size and CPX sound pressure for rms value of spl.

3.2.3 Tyre tread design

The influence of the first two tyre parameters is shown in Figure 11 and 12. Only three different tread patterns are included in the measurements described in this paper. In the future, more tyre tread patterns will be included in this analysis.

However, the results already show the influence of the tyre parameters. The influence of the air ratio of the tyre tread is shown per octave band in Figure 11. An increasing air ratio of the tyre has a positive influence on the sound radiation. Note that this influence is largest for the octave band of 1000 Hz. The correlation between the pattern continuity and the radiated sound is also shown per octave band, in Figure 12. For tyres with a larger pattern continuity, the sound radiation decreases. Again, this effect is largest for the octave band of 1000 Hz.

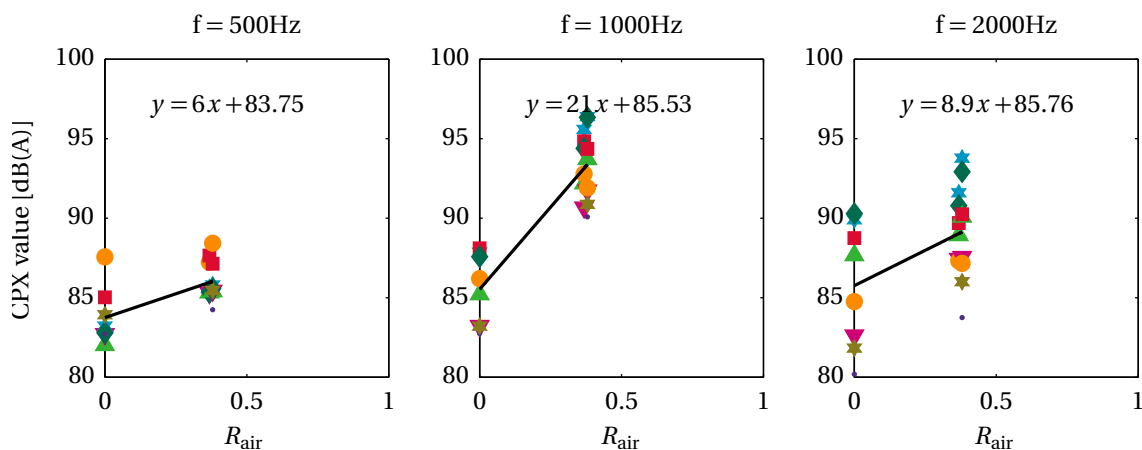


Figure 11 – Correlation between air ratio and CPX sound pressure per octave band, where the different markers indicate the different tracks.

4. CONCLUSIONS

A total of 8 test tracks were constructed at Airport Twente. Two of these tracks were developed based on measurements, predictive models and design tools carried out within the project ‘Silent and Safe Road Traffic’.

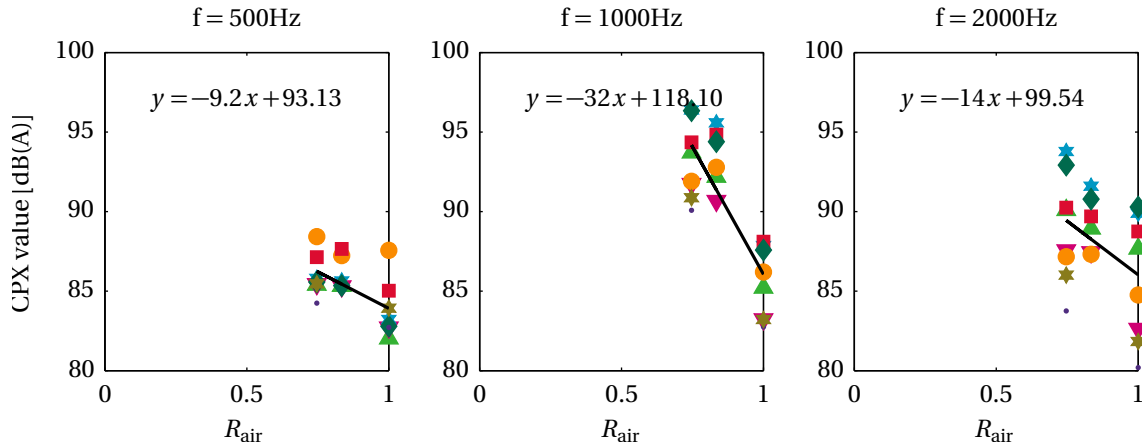


Figure 12 – Correlation between pattern continuity and CPX sound pressure per octave band, where the different markers indicate the different tracks.

	INPUT PARAMETERS											
	Tyres			Road						Absorption		
	R_{air}	$C_{pattern}$	R_{tc}	MPD	z_{rms}	$D_{s,min}$	$D_{s,max}$	Ω_{road}	H_{road}	500Hz	1000Hz	2000Hz
rms	■	■	■	■	■	■	■	■	■	■	■	■
500 Hz	■	■	■	■	■	■	■	■	■	■		
1000 Hz	■	■	■	■	■	■	■	■	■		■	
2000 Hz	■	■	■	■	■	■	■	■	■			■

Table 5 – Correlation matrix.

In this paper, the results of impedance tube measurements, road roughness measurements and CPX measurements carried out within this project at Airport Twente were summarised. The results are combined to investigate the influence of several tyre tread design parameters and road characteristics on the noise radiation.

It is found that the sound absorption and porosity of the road have a large influence on sound radiation for higher frequencies, but not so much for the octave band of 500Hz. Furthermore, the largest stone size in the asphalt concrete mixture is also important for the sound radiation. For increasing stone sizes, the sound radiation is worse. Again, this influence is larger for the higher frequencies.

Considering the tyre tread design parameters, it can be concluded that the continuity of the pattern is important. A tread pattern with large continuity has less sound radiation. Also, an increasing air ratio of the tyre has a positive influence on the sound radiation. Both correlations show the largest influence of the parameters on the noise radiation for the octave band of 1000 Hz. It should be noted that only three tyres are considered. In the future, measurements with different tyre tread patterns will be included in this correlation matrix. Also, the results for measurements with a velocity of 50 km/h and 100 km/h will be included.

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APPENDIX A: CORRELATION CPX MEASUREMENT METHODS

The CPX measurements with a trailer, which is closed and padded with foam (Figure 13), are compared to CPX measurements with a device attached the car, as shown in Figure 14. The main differences are listed below:

- distance from microphone to tyre;
- microphones in open air or inside closed trailer;
- measurement position at outside of tyre or inside (between center road and tyre).



Figure 13 – Closed CPX trailer, padded with foam.

To find the correlation between the two measurement methods, two sets of tyres (ASTM SRTT 225/60R16 and Vredestein Ultrac Cento 225/55R16) are tested on six different test tracks (track 1 – 6) at two velocities, 50 km/h and 80 km/h. The total number of measurements for each method were 24. All tracks sections have a length of approximately 100m and a width of approximately 3m.

For all measurements the rms value (root mean square value) per road section is determined. These values are shown in Figure 15. The correlation between the measurements is given by:

$$CPX_{\text{trailer}} = 0.97CPX_{\text{car}} + 5.50 \quad (7)$$

where CPX_{car} is the rms value in dB(A) for the CPX device attached to the car and CPX_{trailer} is the rms value in dB(A) for the CPX trailer.



Figure 14 – CPX device attached to car.

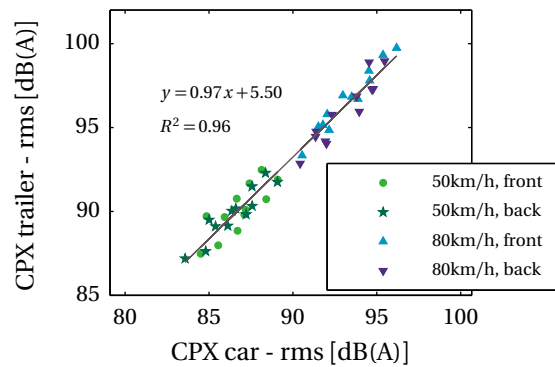


Figure 15 – Correlation between closed CPX trailer and open CPX device attached to car.

Furthermore, the correlation for the octave bands of 500Hz, 1000Hz and 2000Hz are determined and listed in Table 6. The correlation for the octave band of 500Hz is $R^2 = 0.66$, which is low. It can be explained by the disturbances of the wind, since the microphones of the device attached to the car are more exposed to the wind effects as the microphones in the closed CPX trailer.

Octave band	Correlation	R^2
500Hz	$CPX_{trailer} = 0.64CPX_{car} + 31.2$	0.66
1000Hz	$CPX_{trailer} = 1.00CPX_{car} + 0.3$	0.89
2000Hz	$CPX_{trailer} = 0.93CPX_{car} + 5.4$	0.91

Table 6 – Correlation relations for trailer and car for octave bands