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The influence of lateral road surface resolution on the simulation of car tyre rolling losses and rolling noise

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ABSTRACT

CO_2 emissions and traffic noise are two major environmental issues associated with road traffic. Increased efforts are made to develop suitable simulation tools for the prediction of tyre rolling losses and rolling noise. The accurate description of the tyre/road interaction under rolling conditions is crucial for these simulations. Besides an accurate contact model, input data of sufficiently high quality is required. Accordingly, the measurement effort for the road roughness profiles is high: in the rolling direction distances of several meters need to be scanned at positions less than a millimetre apart. While in the lateral direction a lower resolution can be accepted, still between ten and twenty parallel profile tracks are required under perfect conditions. Yet, in reality road surface scans are typically restricted to very few lateral tracks due to limited resources. This study evaluates how rolling resistance and rolling noise simulations are affected if the number of independent lateral road scans is less than the number of lateral tracks in the contact model. Different schemes for extrapolating the missing lateral information from the available data are tested for several tyre/road combinations. It is shown that a certain number of parallel road surface scans is necessary for accurate prediction of rolling noise and rolling resistance.
Keywords: Tyre/road interaction, Road surface profile, Simulation

1 INTRODUCTION

In recent years there has been an increasing public awareness for greenhouse gas emissions and exterior traffic noise as two major environmental issues associated with the road transportation sector. In 2006 the fuel consumption in the road transportation sector was responsible for 23 % of the CO_2 emissions in the European Union (EU) [1], with absolute emission values remaining constant or even increasing since 1990. One possible way of reducing CO_2 emissions is by finding ways to increase the energy efficiency of existing means of transportation. Depending on vehicle type and driving conditions, about 5 % to 30 % of the fuel consumption are due to hysteretic losses in the tyres, i.e. rolling resistance [2]. Accordingly, decreasing energy losses due to rolling resistance has a strong potential of reducing a vehicle's overall fuel consumption.

Besides being a significant source of greenhouse gas emissions, the road transportation sector places a further severe burden on a large part of the population in form of road traffic noise. A recent report by the World Health Organization (WHO) [3] estimates that within the EU about 50 % of the population are

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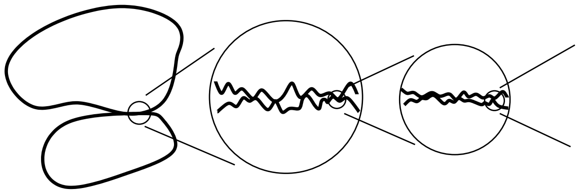


Figure 1 – The difference between *apparent* and *real area of contact*. Due to small-scale surface roughness only discrete parts of the bodies are in contact.

regularly exposed to A-weighted road traffic noise levels exceeding the WHO guideline value for outdoor sound levels of $55\,\mathrm{dB}$, and about $10\,\%$ to A-weighted road traffic noise levels exceeding $65\,\mathrm{dB}$, i.e. levels with an increased risk of suffering from cardiovascular problems. At the most common driving speeds of $30\,\mathrm{km/h}$ to $100\,\mathrm{km/h}$ tyre/road noise is the dominating road traffic noise source [4].

As there is sustained demand for personal mobility and transportation services in most societies, it seems unlikely that a decrease in noise levels or CO_2 emissions can be achieved by traffic reduction. Instead roads, vehicles and tyres have to be optimised with regards to noise generation and rolling resistance. This has been acknowledged by policy makers, leading to a set of new, tightened regulations (e.g. [5, 6]). In view of this, an increasing effort is made to model tyre/road noise (e.g. [7–11]) or rolling resistance (e.g. [12–14]). For all these models the accurate description of the tyre/road interaction under rolling conditions is a crucial part of the simulation process.

Modelling the interaction between a rolling tyre and the road is a complex task. One of the main challenges is the extent of relevant length scales, ranging from several meters (road unevenness) down to microscopic (road asperities) or even molecular levels (adhesion effects). The size of a typical contact patch is too big to allow a full discretisation down to the smallest relevant length scales. As a consequence, the distinction between the *apparent* and the *real area of contact* between tyre and road becomes important. At small scales, both road and tyre have a certain roughness; contact will only be made between certain parts of the asperities, see Figure 1. Hence, the area which is in contact is only a fraction the size of what it appears to be at a macro-scale level.

On a larger length scale another aspect has to be taken into consideration: the tyre is an elastic continuum where the deformation due to a point force at location A will not be limited to just that point. A certain area of the material will be affected, perhaps considerably changing the conditions at another contact point B. Due to inertia, this effect does not happen instantaneously, meaning that past contact forces and deformations influence the contact conditions at the current time. This dynamic interaction can put some constraints on the achievable resolution for the contact area. Tyre models require a much lower spatial resolution to simulate the dynamic behaviour than what is needed to accurately capture the complex contact processes. Because of the computational costs and the fact that the finer resolution would only be needed in a very small part of the tyre, increasing resolution is typically not an option. Many simpler tyre models do also not explicitly include the tread, in these cases a separate contact law is required to describe the local interaction between road asperities and tread rubber.

The dynamic part of many models for rolling tyre/road contact is based on a time-domain formulation in which the dynamics of the contacting bodies are described by their Green's functions. These are convolved with the contact forces to give the response at a specific time due to present and past contact forces. Kropp [7] was the first to use this technique to simulate tyre/road interaction, albeit only for two-dimensional conditions (i.e. one lateral roughness profile line). The approach was extended to a fully three-dimensional contact by Larsson *et al.* [15] and Wullens and Kropp [16].

All these models do not explicitly handle the microscopic change of contact area during contact. To account for the change in contact area, non-linear contact springs between each matching point of tyre and road were introduced in [17]. The same paper also describes a method for obtaining stiffness functions from measured road roughness data. Several authors presented further variations of the convolution approach [8, 10, 14].

FEM approaches have also been widely used to simulate tyre/road interaction. Biermann *et al.* [9], for example, used harmonic excitation functions based on road surface data for the contact formulation in their FEM simulations of a rolling tyre. Sound radiation could be correctly calculated for shaker excitation of the tyre, however not for real tyre/road contact. This is most likely due to considering only linear steady-state rolling in the contact implementation. To overcome some of the spatial resolution limitations in FE modelling, Lopez [18] proposed an approach in which the tyre/road interaction is split up into two parts: the large scale tyre deformations are obtained from an FE model of a tyre rolling on a smooth road, while the tread/road surface interaction is calculated separately using the convolution technique. The technique seems to work quite well for the determination of rolling losses, it is however not clear if the individual calculation and subsequent superposition of large- and small-scale contact effects adequately captures the complex contact dynamics.

Despite all the advances made in modelling tyre/road interaction, input data of sufficiently high quality is required for all models. While it is straightforward to include the tyre profile, the measurement effort for the road roughness profiles is high: in the rolling direction distances of several meters need to be scanned (e.g. by a laser) at positions less than a millimetre apart. While in the lateral direction a lower resolution can be accepted [16], still a certain number of parallel profile tracks is required, as has been shown for tyre/road contact by Wullens [19] or the SPERoN project [20] and for railway wheel/track contact by Pieringer *et al.* [21]. Yet, in practice road surface scans are typically restricted to very few lateral tracks due to limited resources. Though techniques for synthesising road surface data have been proposed [22, 23], these have not yet proven to be adequate replacements for measured data. In an effort to determine the necessary lateral resolution of road surface scans, this study evaluates how an existing model for the prediction of rolling resistance and rolling noise (cf. [11, 24]) is affected if the number of unique and independent lateral road scans is less than the number of lateral tracks in the contact model. Different schemes for extrapolating the missing lateral information from the available data are tested for combinations of two different tyres and five different road surfaces.

In Section 2 the rolling noise/rolling resistance simulation tool is introduced. The properties of the road surface scans used in this study are discussed in Section 3. The study methodology is presented in Section 4. Simulation results are presented in Section 5, and discussed in Section 6. The paper closes with some final remarks and suggestions for future work in Section 7.

2 THE ROLLING NOISE AND ROLLING RESISTANCE MODEL

The simulation framework is identical to the one described in [24]. The tyre dynamics are modelled using a waveguide finite element approach which combines FE modelling of the cross-section with a wave ansatz for the circumference [13, 25, 26]. Tyre/road interaction is modelled using a convolution based non-linear 3D approach which accounts for the alternating relation between contact forces and tyre vibrations [24]. The contact problem formulation reads

$$\mathbf{u}(t_N) = \mathbf{G}_0\mathbf{F}(t_N) + \mathbf{u}_{\text{old}}(t_N) \tag{1a}$$

$$F_e(t_N) = k\, d_e(t_N)\, \mathcal{H}(d_e(t_N)) \tag{1b}$$

$$\mathbf{d}(t_N) = \mathbf{Z}_\mathbf{R}(t_N) - \mathbf{Z}_\mathbf{T}(T_N) - \mathbf{u}(t_N)\,. \tag{1c}$$

$\mathbf{u}$ and $\mathbf{F}$ denote the normal tyre displacements and contact forces at time step t_N. $\mathbf{G}_0$ contains the values of the tyre's Green's function for $t_N = 0$. $\mathbf{u}_{\text{old}}$ is the displacement given by the contribution from previous time steps, and $\mathbf{Z}_R$ and $\mathbf{Z}_T$ are the road roughness and tyre profiles. $\mathcal{H}$ is the Heaviside function and the subscript e denotes one individual contact point. To account for small-scale roughness phenomena and the resulting difference between the apparent and real area of contact, contact springs are introduced between the tyre and the road [24]. This is reflected by the spring stiffness k in (1b).

Due to energy conservation, rolling losses can be calculated as input power P_{in} for steady-state rolling conditions [13]. The rolling resistance coefficient C_r is then defined as $C_r = P_{\text{in}}/(F_z V)$, where F_z is the axle load and V the rolling speed.

Radiation calculations are based on a half-space BEM approach [11]. Rolling noise is evaluated as

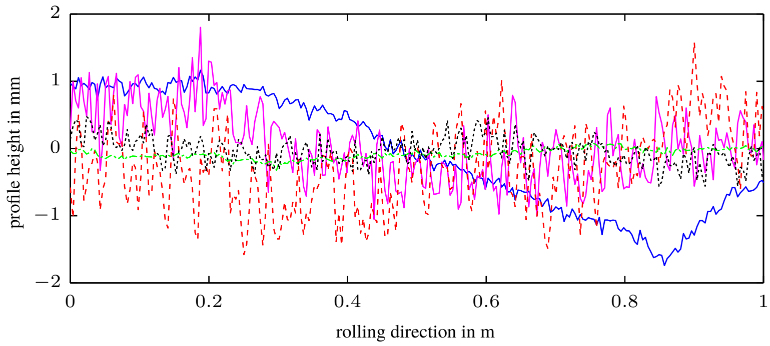


Figure 2 – Average of road surface profiles over all lateral tracks for the first meter in rolling direction. A (—), B (– –), C (–·–), D (· · ·) and E (—).

mean sound pressure on a half-sphere of radius 1 m around the contact point between tyre and road. A-rated sound pressure levels $L_{p,A}$ are calculated for the third-octave bands from 100 Hz to 2.5 kHz.

Simulations are performed for two different tyres: a slick 205/55 R16 tyre and a 175/65 R14 tyre with three circumferential grooves. For both tyres information about the construction and material properties was provided by the manufacturer. The cross-sectional mesh for the 205/55 (175/65) tyre consists of 20 (12) solid elements for the tread and 46 (37) shell elements for the sidewalls and belt. The tyre circumference is discretised into 512 intervals. The rim and the air cavity are accounted for by blocking the tyre motion at the bead and including the pre-tension due to inflation. Losses are implemented as frequency dependent proportional damping. The inflation pressure is 200 kPa, the axle load is 3415 N, and the rolling speed is 80 km/h. Rolling is calculated for seven full tyre revolutions of which the last two are evaluated, giving a frequency resolution of roughly 6 Hz. More details about the simulation process can be found in [24].

3 ROAD PROPERTIES

The considered road surface profiles are based on detailed laser scans of the following road surfaces:

(A) Drum-mounted ISO 10844 road replica surface,

(B) drum-mounted generic rough road surface,

(C) ISO 10844 road surface,

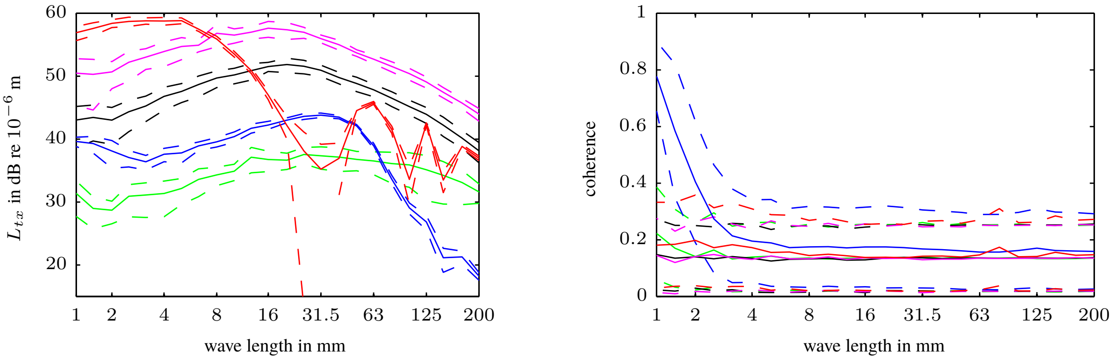
(D) 0/8 stone mastic asphalt (SMA), and

(E) 5/8 surface dressing.

For the surfaces A and B scans of 15 lateral tracks with a length of nine tyre revolutions exist. For surfaces C to E 20 lateral tracks of length 2.95 m and a lateral spacing of 0.01 m are available. The resolution in rolling direction is 0.2 mm for all road surfaces. Due to the limited data in lateral direction, detailed analysis of the surfaces is only possible in the rolling direction. Assumptions about the properties in lateral direction can only be made based on differences or similarities between parallel tracks.

The lateral profile average for the first meter of all scans is shown in Figure 2. The highest amplitudes are as expected recorded for the generic rough (B) and surface dressing (E) surfaces and the smoothest surface is the ISO surface (C). The drum mounted surfaces A and B are both characterised by a pronounced unevenness.

The amplitude differences are also visible in Figure 3a where road surface spectra L_{tx} calculated according to ISO 13473-4 [27] are given as mean values over all lateral tracks. The additionally shown standard deviations reveal that for most of the surfaces a quite pronounced variation between the individual lateral tracks exists. This is further emphasised by Figure 3b which for each road surface shows the



(a) road surface spectra

(b) coherence

Figure 3 – Third-octave band averages (—) and standard deviations (– –) of (a) road surface spectra over all lateral tracks and (b) coherence between lateral tracks. A (—), B (—), C (—), D (—) and E (—). Missing data denotes outlier.

Table 1 – Lateral averages (incl. standard deviations) of mean profile depth (MPD), estimated texture depth (ETD), and root mean square deviation (R_{ms}).

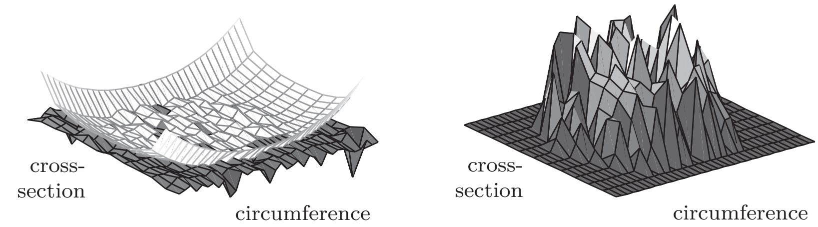
surface	$\overline{MPD}$, mm	$\overline{ETD}$, mm	$\overline{R_{ms}}$, mm
A	0.48 ± 0.08	0.59 ± 0.06	0.66 ± 0.04
B	2.28 ± 0.70	2.02 ± 0.56	2.16 ± 0.21
C	0.28 ± 0.04	0.42 ± 0.03	0.22 ± 0.02
D	0.80 ± 0.17	0.84 ± 0.13	0.90 ± 0.08
E	3.30 ± 0.67	2.84 ± 0.54	1.88 ± 0.19

mean and standard deviation of the coherence between the lateral tracks (calculated according to [21]). Apart from the shortest wave lengths for surface A, coherence between the parallel tracks is bad and standard deviations are large. The assessment of the road surface properties is finalised by Table 1, where according to ISO 13473-2 [27] the mean profile depth MPD, the estimated texture depth ETD, and the root mean square deviation R_{ms} are given. The amplitude differences are in accordance with the previous observations. The standard deviations are in the range of $10\,\%$ to $25\,\%$ which underlines the observation that large differences exist between parallel tracks on the same surface.

For the contact simulations, all surface scans are resampled to match the resolution of the tyre model. The tyre is divided into 512 intervals over the circumference, giving a circumferential contact revolution of slightly less than $4\,\mathrm{mm}$. In lateral direction, the contact size is associated with the size of the solid elements in the WFE model. Depending on tyre size, this gives ten (205/55) or twelve (175/65) contact tracks, which is a sufficiently high number for rolling noise calculations [19, Paper C]. An example for a calculated tyre/road contact is given in Figure 4.

4 STUDY METHODOLOGY

The influence of the available lateral road surface data on the calculation of rolling noise and rolling resistance is examined by replacing individual distinct tracks in the reference configurations of ten (205/55 tyre) and twelve (205/55 tyre) independent, unique lateral tracks with already present tracks. The number of available unique lateral tracks is assumed to range from one to half of the full data. Additionally, the repeated tracks are taken from different lateral locations in the reference configuration, and the beginning and end of the scan might be reversed. The scans of surfaces A and B are several tyre revolutions long; this allows for yet another repetition scheme in which later segments in rolling direction are used as lateral segments instead, e.g. if the scan is four revolutions long, then the second revolution is used as second



(a) road surface and deformed tyre (b) contact forces

Figure 4 – Example for tyre/road interaction.

Table 2 – Arrangements of lateral tracks used in the simulations. Arabic numerals denote the position of a lateral track with regard to the reference contact simulation with complete lateral information. * denotes a reversed track. Alphabetic characters denote that longitudinal segments from surface scans being longer than one tyre revolution are used as lateral tracks.

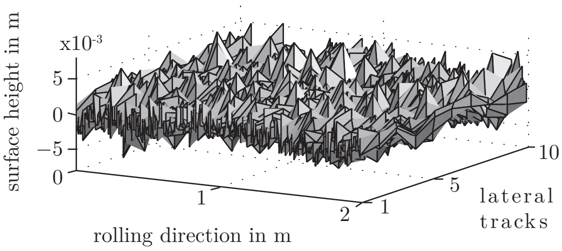
configuration	arrangement lateral tracks	
	175/65 R14	205/55 R16
reference	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10
I.a	1 1 1 1 1 1 1 1 1 1 1 1	1 1 1 1 1 1 1 1 1 1
I.b	6 6 6 6 6 6 6 6 6 6 6 6	5 5 5 5 5 5 5 5 5 5
II.a	1 2 1 2 1 2 1 2 1 2 1 2	1 2 1 2 1 2 1 2 1 2
II.b	5 6 5 6 5 6 5 6 5 6 5 6	5 6 5 6 5 6 5 6 5 6
III.a	1 2 3 1 2 3 1 2 3 1 2 3	1 2 3 1 2 3 1 2 3 1
III.b	5 6 7 5 6 7 5 6 7 5 6 7	4 5 6 4 5 6 4 5 6 4
IV.a	1 2 3 4 1 2 3 4 1 2 3 4	-
IV.b	5 6 7 8 5 6 7 8 5 6 7 8	-
V	1 2 3 4 5 6 1 2 3 4 5 6	1 2 3 4 5 1 2 3 4 5
VI.a	1 1* 1 1* 1 1* 1 1* 1 1* 1 1*	1 1* 1 1* 1 1* 1 1* 1 1*
VI.b	6 6* 6 6* 6 6* 6 6* 6 6* 6 6*	5 5* 5 5* 5 5* 5 5* 5 5*
VII.a	a b c d e f a b c d e f	a b c d e a b c d e
VII.b	a b c d e f f e d c b a	a b c d e e d c b a

lateral track, the third revolutions as third lateral track and so forth. A complete overview of all repetition schemes is given in Table 2 and an example for one case is shown in Figure 5.

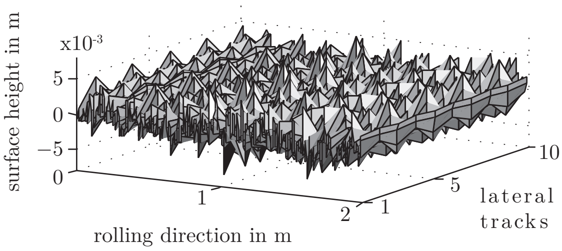
Results are expressed as differences to simulation outcomes for the reference case. For rolling losses this is done in terms of the rolling resistance coefficient C_r and for rolling noise the overall or third-octave band A-weighted sound pressure level $L_{p,A}$ is used.

5 RESULTS

In total, 108 cases are calculated for the two tyres, five road surfaces and the different repetition schemes. In general, no large differences are observed between the results for the different tyres. Results for the rolling loss calculations are given in Figures 6a and b. For the two ISO road surfaces A and C and the SMA surface D, the variations of the rolling resistance coefficient C_r with respect to the reference case are less than $5\,\%$ regardless of the number of unique lateral tracks and the applied repetition scheme. Considerably higher deviations are obtained for the rough surface B and the surface dressing E if only one or two tracks are repeated (schemes I, II and VI). The deviations are in the order of $5\,\%$ to $40\,\%$ and vary depending on which lateral tracks are repeated (a or b configurations). For surface B four or more surfaces are necessary to reliably keep the variation below $5\,\%$. In the case of surface E, deviations of more than $10\,\%$ are still obtained even when half of the lateral tracks are unique (scheme VI). Finally, results for cases



(a)



(b)

Figure 5 – Surface E with (a) complete lateral information and (b) reduced lateral information (III.b).

where the lateral tracks are taken from longitudinal scans being longer than one revolutions, scheme VII, show an accuracy which is approximately between that obtained with three or four repeated tracks.

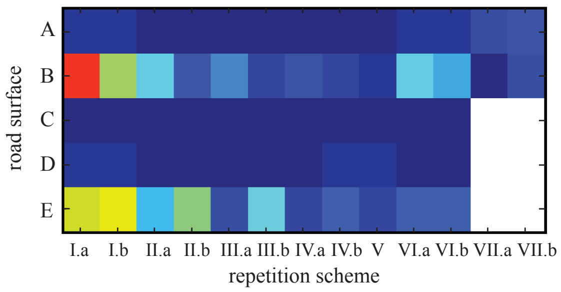
For rolling noise calculations the dependency of the total A-weighted sound pressure level $L_{p,A}$ on the lateral track data is even more pronounced, see Figures 6c and d. Independent of road surface, plain repetition of just one lateral track (scheme I) leads to a gross overestimation of the sound pressure levels. While the introduction of some lateral variation by reversing every other track, scheme VI, considerably reduces the deviations, the error is still more than $1\,\mathrm{dB}$ for all surfaces but the drum-mounted ISO surface A. Using two or more unique tracks, deviations are less than $1\,\mathrm{dB}$ for both ISO surfaces (A/C). For surface D, the same accuracy is achieved with three or more original tracks. In the case of the generic rough and surface dressing surfaces B and E, variations of less than $1\,\mathrm{dB}$ can only be obtained reliably when at least five or six (depending on the tyre) independent lateral scans exist. Similar to the results obtained for the rolling losses, the accuracy obtained with scheme VII is better than for just one lateral track (I), but not particularly better than that for scheme VI which is also based on only one lateral track. Moreover, results for a particular scheme again vary strongly depending on which tracks are repeated (a or b configurations).

The rolling noise simulation results can be further analysed if third-octave band spectra are considered. Deviations of less than $1\,\mathrm{dB}$ in all of the most relevant third-octave bands (i.e. those dominating the overall level) are only observed in five cases as shown by the white frames in Figures 6c and d. All of these cases are for surfaces C and E. No clear attributions to particular repetition schemes can be made. An example for the third-octave band deviations is shown in Figure 7 for the 205/55 tyre and road surface D. Though the differences to overall reference sound pressure level are less than $2\,\mathrm{dB}$ for all of schemes II to VI (and less than $1\,\mathrm{dB}$ for most of them), see Figure 6d, only configuration III.b deviates by less than $1\,\mathrm{dB}$ from the reference value in all of the most relevant third-octave bands. All other schemes show larger deviations which partly cancel each other out in the overall level.

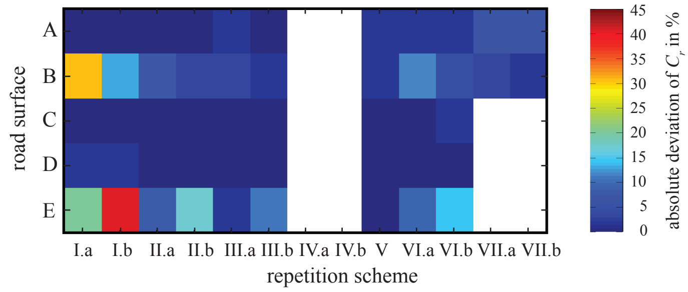
6 DISCUSSION

In order to answer the question whether an adequate simulation of rolling noise and/or rolling losses is possible if the number of available lateral road surface scans is limited, two different aspects have to be considered. The first one being how representative one particular track is for the whole surface. In Section 3 it could be shown that for typical road surfaces considerable differences exist between scans on parallel lines of the same surface. This is reflected in the rolling noise and rolling resistance simulations, where huge differences can be observed for results obtained with the same basic repetition scheme, but different initial lateral tracks, e.g. II.a and II.b. The influence of the chosen individual track becomes the smaller the larger the number of unique tracks is, as a larger lateral section of the surface is covered. Though it could intuitively be assumed that variations between lateral scans are smaller for smoother surfaces, there is no indication of this in this study.

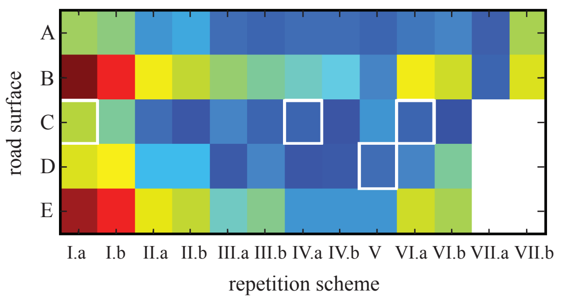
The second aspect which has to be considered is which possibilities exist to extend the lateral data if only a limited number of parallel scans is available. The results indicate that for rolling loss simulations of smooth surfaces only very few tracks are necessary to obtain adequate results. This is because rolling



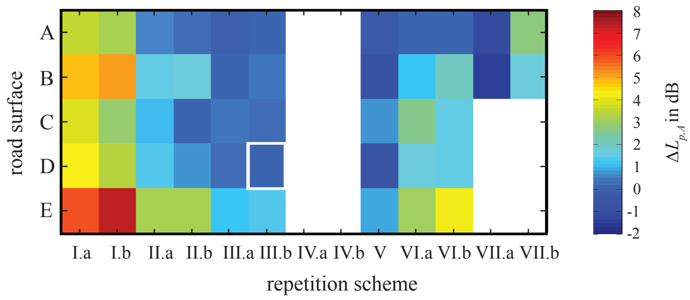
(a) 175/65: rolling losses



(b) 205/55: rolling losses



(c) 175/65: rolling noise



(d) 205/55: rolling noise

Figure 6 – Deviations of rolling loss and rolling noise calculations from reference case. White areas denote omitted calculations. Rolling noise only: White frames denote cases where the deviation in all dominating third-octave bands is $< 1\,\mathrm{dB}$.

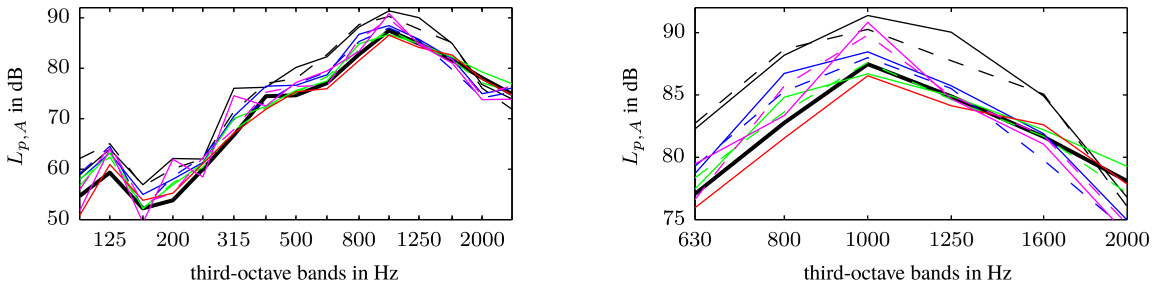
losses on these surfaces are mostly depending on the large-scale running deflections of the tyre while entering and leaving the contact zone. Details of the road surface profile and lateral variations are of lesser importance as long as the surface is sufficiently smooth. For rougher surfaces the influence of the individual road asperities grows, accordingly profile details and lateral variations are of concern. In this case, the results for surfaces B and E suggest that around five or six tracks (i.e. half of the number of actual contact tracks in the model) are necessary.

For rolling noise, the small-scale, high-frequency tyre excitation by the time varying contact forces due to the road texture is of great importance. Accordingly, surface details already have to be considered even for smoother surfaces. This is shown by the fact that at least three tracks seem to be necessary even for rather smooth surfaces if overall tyre/road noise levels shall be predicted with an accuracy of $1\,\mathrm{dB}$. For rough surfaces the number rises again to five or six tracks. This finding agrees with the minimum number of parallel road texture profiles required by the SPERoN tyre/road noise prediction modelling framework [20].

The strong dependance of rolling noise on the road texture is additionally exemplified by the fact that for the majority of cases where the overall reference sound pressure level is sufficiently well approximated, still significant deviations in individual third-octave bands exist.

Interestingly, in the majority of cases sound pressure levels are overestimated; underestimations occur only in approximately $10\,\%$ of the simulations and generally with rather small deviations. The overestimations might be caused by a more coherent excitation of the tyre over the contact width: a particular road asperity comes into contact with the tyre simultaneously in all copies of the initial lateral track it belongs to, i.e. the tyre is excited by the same asperity at different positions over the tyre width, which is beneficial for the excitation of tyre vibrations.

If the number of scanned lines is very limited it seems favourable to assure that the tracks are parallelised in way that ascertains lateral variation, cf. the results for schemes I.a/b and VI.a/b. If only one profile line exists, the obtained results are not necessarily better if the scan is very long and can divided



(a) full frequency range

(b) 630 Hz to 2 kHz

Figure 7 – Third-octave band sound pressure levels for the 205/55 tyre and road surface D. Reference case (—), I (—), II (—), III (—), V (—), and VI (—). Solid lines configurations a, dashed lines configurations b.

into several segments which are then used as parallel tracks, see VI.a/b and VII.a/b. This might be due to larger variations in later longitudinal segments which are not representative for the potential area of contact.

7 FINAL REMARKS

The influence of the number of parallel road surface scans on simulations of car tyre rolling losses and rolling noise are evaluated. It is shown that large variations exist between parallel lateral scans of the same road surface. This implies that it is very difficult to assure representativeness of the profiles if only one or very few lateral scans exist.

Simulation results suggest that around five unique road profile scans are necessary for reasonable predictions, unless rolling resistance on very smooth surfaces is considered. In the latter case one surface line suffices, which might indicate that small-scale surface roughness is of no importance under these conditions. The results also suggest that the lateral variation is of special importance for the rolling noise. An increase in lateral variation might be the main argument why prediction quality increases with increasing number of unique scans.

It is recognised that the presented schemes for extending limited lateral data are rather elementary. Possible future work will investigate possibilities for more advanced procedures, e.g. randomised profile modifications based on road surface spectrum content, MPD, R_{ms}, etc.

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