SIMULATION OF TYRE/ROAD NOISE AS A TOOL FOR THE EVALUATION OF THE ACOUSTIC BEHAVIOUR OF ROAD SURFACES

Thomas Beckenbauer[1], Christian Angst[2], Philip Buergisser[2]
[1]Mueller-BBM Schweiz AG, Basel, Switzerland
[2]imp Bautest AG, Oberbuchsiten, Switzerland

ABSTRACT

The surface characteristics of road pavements have a significant impact on the generation of tyre/road noise. Road surface texture as well as sound absorption and elasticity are crucial factors when it comes to mechanical interaction and aerodynamic processes within the tyre/road contact. These road surface characteristics are relevant for the generation of rolling noise. However, the tyre/road noise level cannot be directly related to them. Due to highly non linear relations between road surface characteristics and the excitation of vibrations on the tyre structure being relevant for noise generation the physical modeling of contact forces, tyre vibrations and airflow related processes is a necessity.
A model will be presented which properly reproduces the physics of the tyre/road contact and the tyre vibrations. A statistical model takes care of the absolute matching of input and output quantities. The model is capable to reproduce the absolute coast-by noise levels (7.5m distance, 1.2m height) as a function of road surface characteristics, tyre properties and speed with an accuracy of +/-1 dB. In a current Swiss project concerning the acoustic durability of asphalt pavements the model, called SPERoN, is applied in order to evaluate the acoustic behaviour of road surface specimen in different wearing conditions in a lab testing machine.

Keywords: tyre/road noise, acoustic performance, acoustic durability, modelling

1. INTRODUCTION

The calculation model presented in this paper allows for the prediction of tyre/road noise depending on road surface characteristics. It has been developed by the Müller-BBM Group and Chalmers University, Division of Applied Acoustics, Gothenburg, Sweden and is introduced in research an application projects under the name SPERoN (**S**tatistical **P**hysical **E**xplanation of **Ro**lling **N**oise). It pursues a hybrid approach, thus combining a physical model with a statistical model. Statistical models often are regarded as empirical models. The main difference between an empirical model and the hybrid apporach is the fact that pre-processed input data are used, which are of the same quality as one would apply in a deterministic model simulating the rolling process in detail. This means that starting from the description of the road surface (i.e. texture, acoustic and mechanical impedance) and of the tyre (material data for the tyre model, tread stiffness and tread pattern) dynamic contact forces in the tyre/road contact patch are calculated for a certain speed and load case. In doing so several advantages compared to pure statistical models can be achieved. Firstly one can rely on a linearised relation between input (contact force) and output (radiated sound pressure). Secondly only the acoustically relevant roughness is taken into account. This is similar to the so-called envelope technique as it is used by others. However, here the dynamic and non linear system “tyre” is taken into account when determining the envelope. Otherwise, the procedure would only be limited to the static contact problem.
The model framework consists of a number of modules that are linked together. The following modules can be distinguished:
- contact (force) module
- tyre vibrations (rolling) module
- airflow mechanisms module
- radiated tyre cavity noise module
- residual noise module

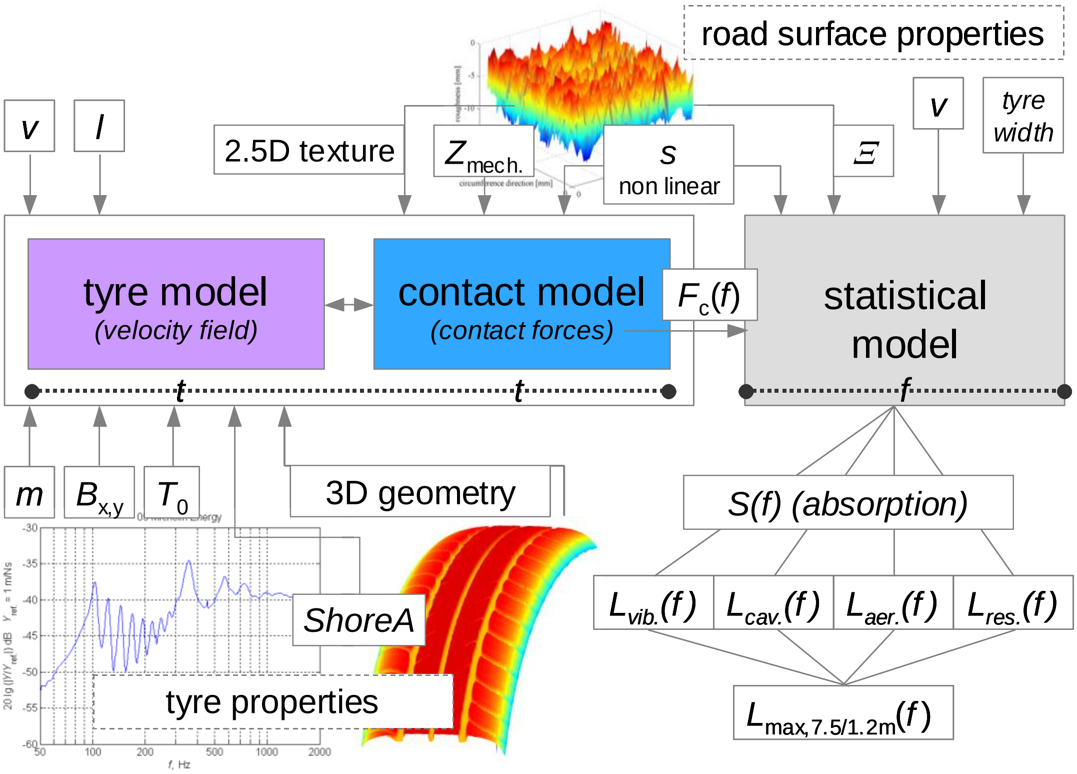

Figure 1: Main structure of the model. Quantities: *m*: mass (inertia), $B_{x,y}$: bending stiffness in longitudinal and cross direction, T_0: tension, *l*: load, v: speed, Z_{mech}: mechanical impedance, *s*: total stiffness, Ξ: texture induced airflow resistance, *f*: frequency, $F_c(f)$: contact force, $S(f)$: transfer coefficient due to sound absorption of the road surface, $L_{vib.}$: mechanically induced noise level, $L_{cav.}$: tyre cavity noise level, $L_{aer.}$: aerodynamically induced noise level, $L_{res.}$: reisudal noise level, $L_{max,7.5/1.2m}$: coast-by level.

The contact module describes the contact interaction between tyre and road surface in terms of local contact forces which are calculated in the time domain. In order to be able to properly describe the tyre/road contact, information on tyre vibrations is needed. However, the tyre vibrations themselves are caused by the dynamic contact forces. Thus a

feedback system exists and has to be taken into account. The airflow module predicts the sound energy generated by airflow related mechanisms in the tyre/road contact patch, often described as air pumping. The cavity module represents the process where interior tyre cavity modes are excited by the tyre pattern variation on smooth surfaces. The residual noise module predicts the noise coming from the airflow around the car body. Strictly, this is not tyre/road noise, but it cannot be avoided during coast-by measurements. The contact and tyre vibration modules are pure deterministic physical models, whereas the other three ones are of the empirical type.
By means of these five modules the input variables are generated for a linear regression model that statistically describes the sound intensity of four incoherent noise sources and their relationship between the sound pressure at a particular receiver point. These noise sources are mechanically induced noise, airflow related noise, tyre cavity noise and the residual source. As target quantity of the model the sound pressure level at the measurement location of coast-by noise mesaurements (7.5 m from the driving lane center, at a height of 1.2 m above the road surface) is chosen. Figure 1 shows the main structure of the model.
The statistical model as linear regression model is a system of linear equations being composed of coefficient/variable products. The variables are generated using the five modules described above. The coefficients are the unknowns in this system. Speed, surface texture and tyre variations demand a multitude of calculation cases in order to be able to determine these coefficients by means of the least square method. About 3,200 cases of different tyre/road surface/speed combinations and a complete set of measurement data for the tyre and road surface characteristics as well as the coast-by level spectra in the speed range from 50 kmh up to 120 kmh for all of the tyre/road combinations have been used. These data are available from the so called ‘Sperenberg project’ [1].

2. MODULES

2.1 Contact module

There are certainly different ways to design prediction models for tyre/road interaction forces. However, the task here differs in several aspects from tasks such as optimising tyre design or basic research of noise generation mechanisms. As main differences one can name:

- The tool is supposed to be an engineering prediction tool capable of answering questions about the influence of road surface properties on the generated noise for different tyres as a function of the rolling speed.
- The model has the main task to deliver contact forces as a function of the road texture in order to supply a statistical model with a variable that is linearly linked to the sound pressure.
- The contact forces have to be predicted for single tyres. Material data are not available from the tyre manufacturer for these tyres. This means that the tyre model used in the approach has to have sufficient accuracy. The required input data can be extracted from vibroacoustic measurements on these tyres.
- The required description of road texture profiles has to be a compromise between required information and what is feasible to measure.

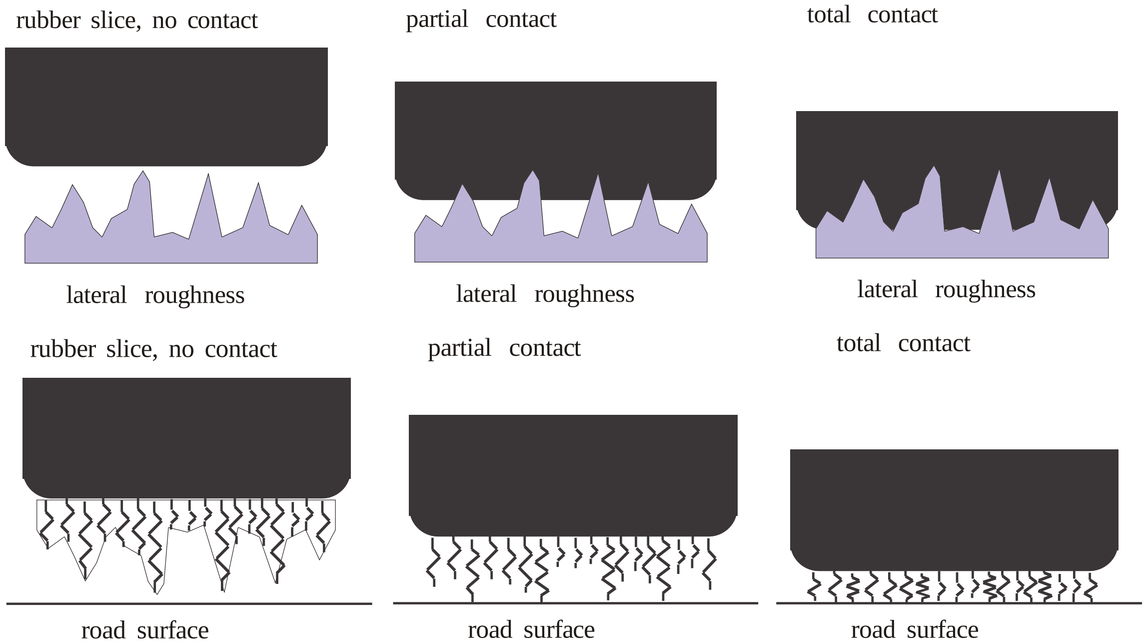

Figure 2: Schematic presentation of a lateral rubber slice in no, partial, and total contact with the road surface (upper figure) and its realization as a Winkler bedding (lower figure)

Based on these facts it has been decided to design a contact force model which has the following properties:

- Application of simplified tyre models for the pre-calculation of the impulse response functions.
- Consideration of a full three dimensional contact in a simplified way based on non linear stiffness functions representing the lateral roughness distribution of the road texture.
- Decoupling of the local radial contact forces.

A Winkler bedding model is used (i.e. a layer of uncoupled springs) as contact model which represents the local stiffness of the rubber layer of the tyre. The contact forces at any point in the contact are consequently given by the stiffness of the bedding and its compression. The compression of the springs is a function of the centre of the rim, the curvature of the tyre, the vibration of the tyre belt, and the roughness of the road. A non linear equation system has to be solved for each time step in order to obtain the contact forces. In the model only contact forces normal to the surface are considered.

The contact model for the hybrid approach can be considered as a quasi-three dimensional model. The main idea is that when a piece of rubber is pressed on a rough surface, the resulting contact force will be proportional to the rubber area in contact with the rough surface. This will lead to a non linear stiffness depending on the lateral roughness distribution of the road surface. Figure 2 shows a schematic presentation of a lateral rubber slice being in no, partial, and total contact with the road surface. In this way the lateral roughness pattern of the road is translated into a variation of the characteristic function of the non linear bedding stiffness. This will lead to a non linear stiffness depending on the lateral roughness distribution of the road surface. The resulting radial contact force $F(\varphi_e,t)$ is then

$$F(\varphi_e,t) = \int_0^{\Delta y_e(\varphi_e)} s_e(\eta)\,\mathrm{d}\eta \tag{1}$$

where Δy_e is the indention depth and s_e is the stiffness function. In this way the lateral roughness pattern of the road is translated into a variation of the characteristic function of the non linear bedding stiffness *K*. For each slice of the tyre tread such a characteristic function is calculated. This is no severe complication since the values of the integral can be pre-calculated and interpolation routines can be used to read values in between pre-calculated ones. Figure 3 (left) shows a typical road surface roughness distribution over the width of the tyre tread and as a function of the 'slice' number (in this case the circumference is divided in 512 slices corresponding to 3.4 mm width of each slice). On the right hand side of the figure the corresponding stiffness functions are displayed. The roughness is measured in six parallel tracks, which turned out to be a sufficient statistical description of the road texture as long as the texture does not show strong anisotropy. However, in this case the number of measured tracks can be increased to ensure a good description of the lateral roughness distribution.

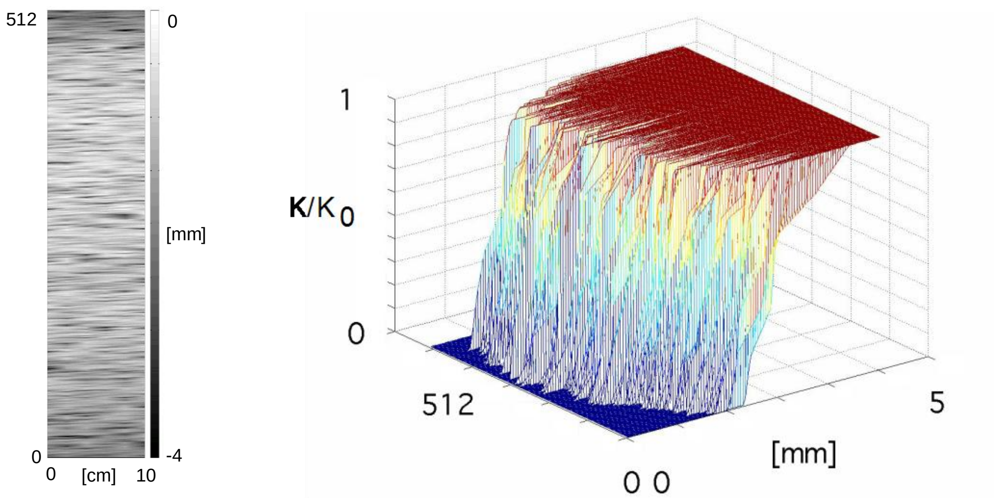

Figure 3: Example of a 3D road surface roughness pattern (left) and the corresponding stiffness of the bedding *K* of a smooth tyre (right), normalised by the stiffness for the complete contact over the width of the tyre

In this way a three dimensional roughness is taken into account, although the calculation effort is reduced to two dimensions. The reason is that the contact force occurring across the slice is summed up and applied as constant load on the belt cross section being in contact. Wullens showed in his PhD thesis [2] that this approach is reasonable. He studied

the influence of different discretisation on the tyre belt and in the tread. While his tread was always discretised in 15 parallel tracks (see Figure 4, right) the tyre structure was discretised differently coarsed.
The diagram on the left in Figure 4 shows five different cases. In case 1 a two dimensional roughness, i.e. a single texture profile in longitudinal direction (this would correspond to a tyre rolling over lateral roughness grooves) is considered. There is only one patch over the tread of the tyre and one patch over the width of the belt. In cases 2 to 5 the roughness is a three-dimensional roughness, i.e. 15 patches over the tread width (see Figure 4 right bottom, blue layer) and the tyre discretisation in the contact is varied between 1 (p_b=1)and 15 (p_b=15) patches.
From this study one can conclude that there is very little variation in the contact force for different resolution over the width of the tyre belt as soon as a three-dimensional roughness is used. For the two dimensional roughness, there is an overestimation of the contact force in the mid and high frequency range. At very low frequencies, the roughness is strongly correlated over the width, and therefore there is less difference between 2D and 3D roughness at frequencies below 100 Hz.

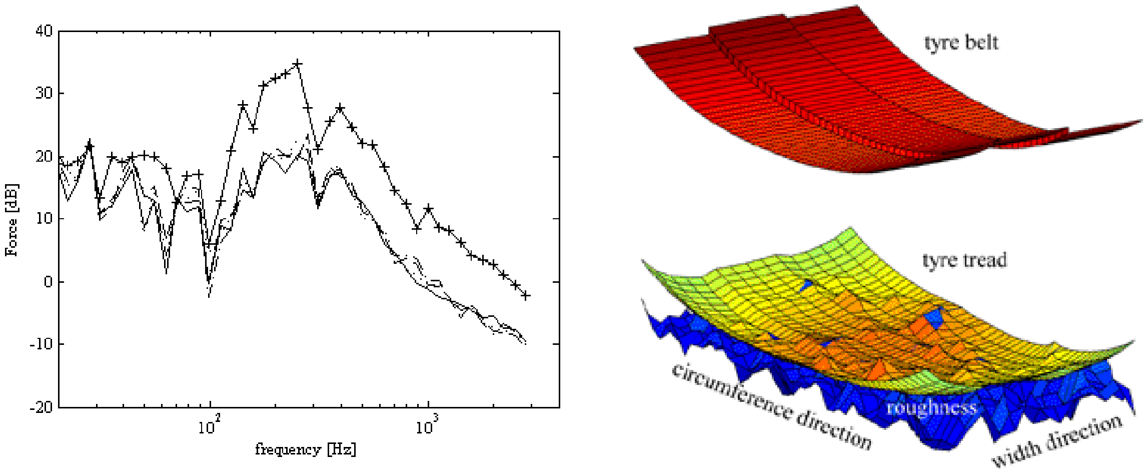

Figure 4: Left: Contact force spectrum as a function of the discretisation for the cases: smooth tyre/rough road; + : case 1, − : case 2, p_b = 1, ··· : case 3, p_b = 3, −· : case 4, p_b = 5, −− : case 5, p_b = 15. Driving speed 80 km/h, rough road.

The tyre profile is taken into account in terms of a stiffness modulation of the smooth tyre depending on the position in circumferential direction. For each strip i with the length Δx and the width b there is a modulated stiffness K_i. This is based on the portion α_i of the cross-section area $A = b\,\Delta x$, which due to the tyre tread profile could be in contact with the road surface and the stiffness K_0 which is due for the slick tyre (see Figure 5). The stiffness K_0 is derived from measurements of the Shore hardness A of tread profile blocks of the tyre. Area α_i is the result of evaluations of the 3D measurement of the tyre tread profile. It is:

$$K_i = \alpha_i\, K_0 \text{ with } \alpha_i = \frac{A_i}{A} \text{ and } A = b\,\Delta x \qquad (2)$$

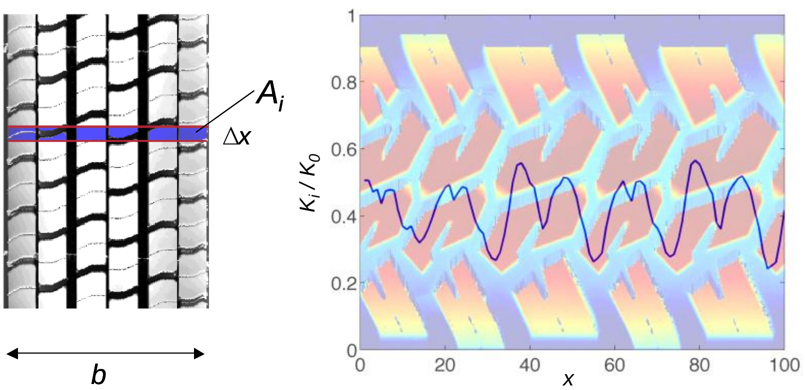

Figure 5: Area A_i per circumference section (left) and stiffness function K_i(x) (right) showing the corresponding tyre tread profile in the background.

By means of a time position transformation depending on speed according to Equation (3) a time function of the stiffness $g_{pattern}(t)$ can be derived for each speed v.

$$dt = \frac{dx}{v} \tag{3}$$

2.2 Tyre vibrations module

Tyre vibrations are caused by time varying forces in the contact between tyre and road. The vibrational energy (i.e. the integral of the velocity squared over the whole surface) is proportional to the squared force in the contact. Parameter studies by Wullens showed that the total contact force is a good estimator for the excitation of tyre vibrations [2] [3]. In the interaction model the tyre vibrations term is mainly based on the pre-calculated contact forces F_c that lead to an excitation of the tyre structure and to radiation of sound.

The model used for the calculation of the tyre vibrations consists of an orthotropic plate on an elastic foundation. It has both the advantages of being handy and of being sufficiently accurate in the frequency range up to 4 kHz. The main idea behind the orthotropic plate model is that the belt and the two sidewalls of the tyre form a flat plate with different bending stiffness in longitudinal and lateral direction. The geometry is shown in Figure 6.

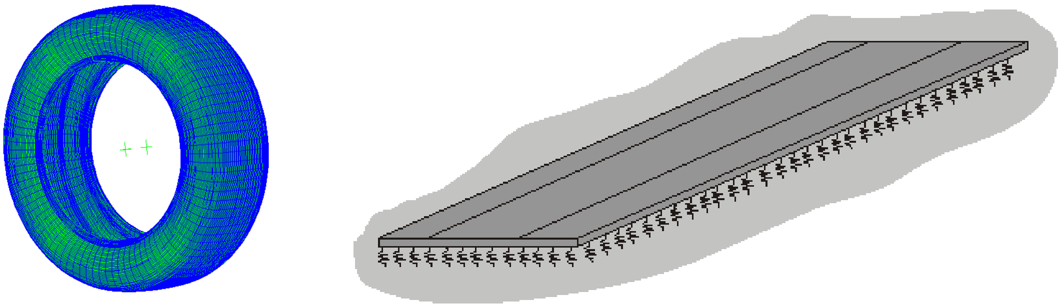

Figure 6: Simplified geometry of the orthotropic plate model. Sidewalls and tread build one flat plate. The support by inflation pressure and sidewalls is simulated by an elastic bedding.

The differential equation for the vertical motion of the plate is:

$$T_0\left(\frac{\partial^2 \xi}{\partial x^2}+\frac{\partial^2 \xi}{\partial y^2}\right)+B_x\frac{\partial^4 \xi}{\partial x^4}+B_{xy}\frac{\partial^4 \xi}{\partial x^2 \partial y^2}+B_y\frac{\partial^4 \xi}{\partial y^4}+m''\frac{\partial^2 \xi}{\partial t^2}+K\xi = F_0'' \tag{4}$$

The plate being under the tension T_0 caused by the interior air pressure (inflation pressure) of the tyre has the bending stiffness B_x in circumferential direction and the bending stiffnes B_y in lateral direction. B_{xy} is the cross stiffness and can be well approximated by $B_{xy} \approx \sqrt{B_x B_y}$. ξ is the vertical displacement respectively the radial displacement in the tyre related co-ordinate system. The elastic foundation of the belt is represented by the spring stiffness K. m' is the mass per cross section and F_0" is the acting force per cross section. A modal approach is used to solve the equation. Comparisons of the model with measurements show a surprisingly good agreement as long as

- the excitation area is not to small; otherwise, the local stiffness becomes involved which is not included in the model
- an accurate set of material parameters for the tyre is available reproducing the tyre properties as exact as possible in this model

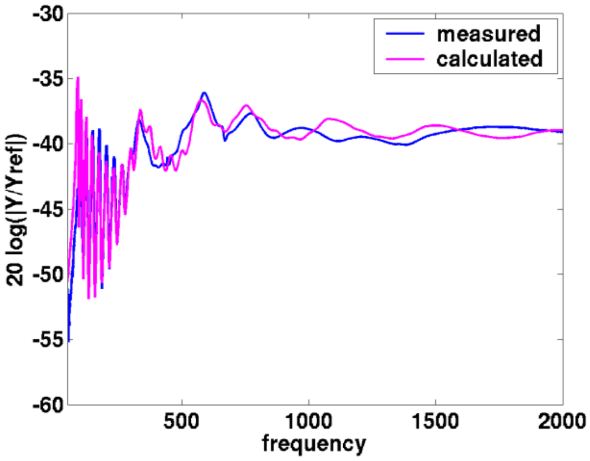

Figure 7: Comparison between calculated and measured radial frequency response to a unit force acting in the middle of the tread. *Y*: point mobility, i.e. input admittance of the tyre structure.

Of course the model has shortcomings too. There is a shift of the resonance frequencies for the frequency range below the ring frequency. The shift is caused by neglecting the circumferential curvature of the real life structure. However, the shift can be compensated by frequency dependent material parameters. Similar problems occur due to neglecting the lateral curvature but can be cured in the same way. In addition to this fact the model can only be used for a frequency range up to about 4,000 Hz. At this frequency the thickness h of the plate is comparable to the wavelength λ_B of the bending waves. Despite these restrictions the model of the orthotropic plate is a simple and useful tool to describe the structure-borne sound properties of a tyre with a low numerical effort. A big advantage of the model is the limited number of input data required to run the model. These data are:

- mass per unit area of the tyre structure, m'
- bedding stiffness (radial) depending on the inflation pressure and the sidewall stiffness, K
- tension depending on the inflation pressure, T_0
- bending stiffness (circumferential), B_x
- bending stiffness (lateral), B_y
- additionally the damping η has to be determined as complex modulus for the different stiffness terms.

All these data can be obtained by vibroacoustic measurements on tyres and by model updating as demonstrated in the German project “Leiser Verkehr” [4] for the tyres used in the Sperenberg project [1]. Based on such data a very good performance of the model can be achieved. Figure 7 shows the comparison of measured and calculated frequency response functions for a typical commercial tyre.

2.3 Airflow mechanisms module

From literature one can conclude that there are many attempts made to describe the airflow related processes in the tyre/road contact but with little success. This might be mainly due to the fact that up to now none of the models took into account the surface properties of the road with respect to its flow resistance. The space between tyre and road is very difficult to define and the approach used in the model as explained in the following might be the first time that the air flow resistance is included in a source model for the “air-pumping” or better “flow related” source mechanisms. In the current stage of the model only one dynamic quantity, the local deformation, is included and it is described rather based on intuition than on a thoroughly derived description of physics.

The deformation ξ in the tread is assumed to be proportional to the ratio between contact force F_c and the tread stiffness S in the form $\xi(f) \sim F_c(f)/S$, the acceleration a is then for a steady state situation $a(f) \sim f^2 F_c(f)/S$. For the acceleration of a fluid we know that the pressure is proportional to the acceleration. However, there are two main uncertainties: Firstly, we do not know how much of the displaced air is able to escape from the contact area. This is taken care of by weighting the expression for the acceleration with the flow resistance measured for the surface (the measurement procedure is adapted to characterise the flow resistance R_s from an area inside the contact patch to the outside). This flow resistance is not the intrinsic flow resistivity for the road surface. The flow resistance used here is the resistance that moving air in the contact patch will experience in a realistic tyre/road contact. This flow resistance Ξ is measured with a proprietary method developed by Müller-BBM [5] and is used in the model. Secondly, the relation between acceleration and deformation is dependent on the driving speed v. To take this into account a speed coefficient is introduced as well. Finally, we obtain the following empirical expression for the noise created due to local deformation

$$p^2{}_{airflow} = b\left(F_c^2\, \Xi^{-1.5} S^{-2}\right)^{\beta_1} B^{\alpha_2} v^4 \qquad (5)$$

where b is the scaling factor, B is the tyre width and β_1, α_2 are exponents. Both are determined by the least square fit of the statistical model.

2.4 Radiated tyre cavity noise module

Measurement results show that for low speeds and low noise road surfaces the noise levels in some third octave bands are rather high and cannot be explained by road texture induced noise only. This is especially true for the 500 Hz band. While slick tyres do not show this special behaviour, patterned tyres do. Taking into account speed and number of tread blocks on the circumference calculating the excitation frequency caused by the impact of individual tread blocks is possible. For example for speeds around 50 kmh excitation frequency values between 450 Hz and 500 Hz will be obtained. At the same time, in this range the second circumferential interior resonance in the cavity between tyre and rim takes place. Although the radiation of cavity resonances do not contribute significantly to the overall level at high speeds it can be an important mechanism for low driving speeds. Therefore, a model was designed empirically taking into account the power spectrum G of the tread pattern variation:

$$p^2{}_{cavity}(f) = c(f) \cdot G_{pattern}^{\gamma_1}(f, v) \qquad (6)$$

where c is the scaling factor and γ_1 is an exponent. Both are determined by the statistical model. The time sequence of the stiffness function $g_{\mathrm{pattern}}(t)$ (see chapter 2.1) is used to calculate the power spectrum $G_{\mathrm{pattern}}(f)$ in terms of third octave bands. This power spectrum is hence implicitly dependent on vehicle speed as the time scale of the time sequence of the stiffness function depends on the rolling speed v.

2.5 Residual noise module

This module represents the aerodynamic noise from the vehicle's body when rolling and is based on measurements carried out in an acoustic wind tunnel for the vehicles used in the measurements. This means that the coefficient d and the exponent δ_1 are actually given and only smaller adjustments are allowed. The formulation is as follows:

$$p^2{}_{vehicle}(f) = d(f) \cdot v^{\delta_1} \qquad (7)$$

2.6 Sound absorbing road surfaces

The sound absorption of void containing road surfaces is taken into account as well. Sound absorption affects both the sound radiation and the sound propagation of tyre/road noise. However, sound absorption is an additional effect which is linearly related to the sound pressure which is caused by the tyre/road interaction. This gives opportunity to superimpose the excess attenuation which is given by the frequency dependent sound absorption coefficient on the calculated spectrum of the coast-by noise as is shown in Figure 1.

3 THE STATISTICAL SUBMODEL

Starting point of the statistical model is the assumption that tyre/road noise is the consequence of the superposition of sound intensities I which are related to noncoherent sound sources. Each sound source is related to a particular sound generation mechanism. Physical noncoherence is in full accordance with the requirement of statistical independence of variables which are part of a linear regression model as is shown in Figure 8.

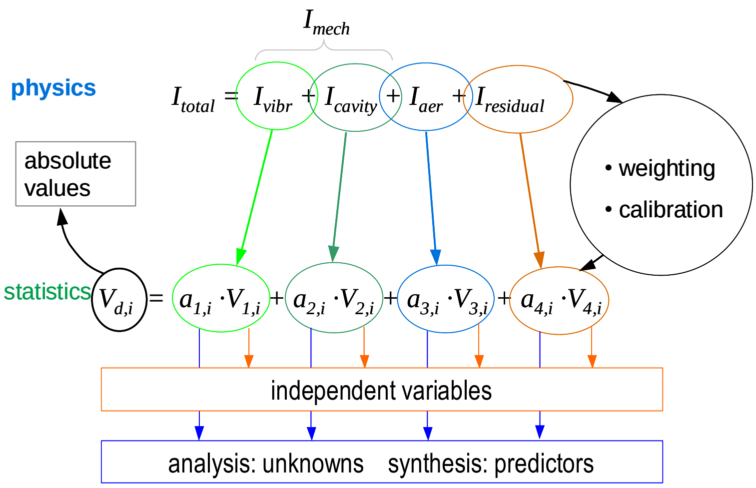

Figure 8: Schematic overview of the statistical model and its relation to physical conditions

The total sound intensity I_{total} of the coast-by noise of a vehicle is combined of the part intensities I_{vibr} which is caused by tyre vibrations, I_{cavity} describing the tyre cavity noise, I_{aer} which is related to noise produced by air flow within the tyre/road contact patch, and $I_{residual}$ which is due to interfering air flow noise around the car body. Each part intensity is represented by a single term in the multiple linear regression equation, each term consisting of a frequency dependent coefficient $a_{\mathrm{i}} = a_{\mathrm{i}}(f)$, and an independent variable $V_{\mathrm{i}} = V_{\mathrm{i}}(f)$. $I_{total} = I_{total}(f)$ represents the antilog of the tenth of the maximum coast-by noise level L_{max}. The unknowns a_i are determined per third octave band by solving the linear equation system for a large number of measured variables using a least square algorithm with $V_{\mathrm{d,i}}$ as dependent variable. The number of physical useful solutions could be significantly reduced by defining reasonable criteria: the coefficients a_i must be positive regarding the superposition of sound intensities and one set of coefficients must be true for all tyre/road/speed combinations; exponents used in empirical variables must be independent of frequency because they contain $F_c(f)$ which represents the dependence on frequency itself. At the moment, the hybrid approach does not contain a model for sound radiation. Thus, the coefficients implicitly take over the “equaliziation” of the noise emission in order to meet the coast-by spectra taken at 7.5 m distance. Once the coefficients are determined the model can be fed with arbitrary road surface data and calculates absolute values of the coast-by level per third octave band in the frequency range from 315 Hz up to 2 kHz depending on these data and on speed.

3 APPLICATION

3.1 General analysis of road surfaces

In Figure 9 results of calculated coast-by noise level spectra are shown for one tyre, two different road surfaces and two speeds. The spectra are split up into the contributions of the mechanical sound source (variable I_{mech}), the air flow related source (I_{aer}) and the residual component ($I_{residual}$). The measured spectra of the total coast-by noise level are shown as well. It can be seen that the rough surface yields considerable higher levels of the mechanical sound source at low frequencies. The smooth hot rolled pavement causes a reduction by 10 dB of this noise component but brings up the aerodynamic component in the mid frequency range by about 5 dB. The air flow related component of the tyre/road noise affects the high frequency range above 1 kHz in any case. Higher speed balances the importance of the different components.

The model results are in good agreement with measured data. The average deviation between measured and calculated third octave band levels amounts to ± 2 dB at the most, regarding all tyres and all road pavements investigated in this work. There is some potential for improvements with regard to the component I_{aer}. In the model, this component also takes over other noise generating mechanisms which are not taken into account so far – especially at low speeds. These missing mechanisms are stick-slip and stick-snap effects which are due to tangential forces and adhesion within the tyre/road contact patch. Implementing a good model for these mechanisms would help to improve the prediction quality of the model especially in the mid frequency range.

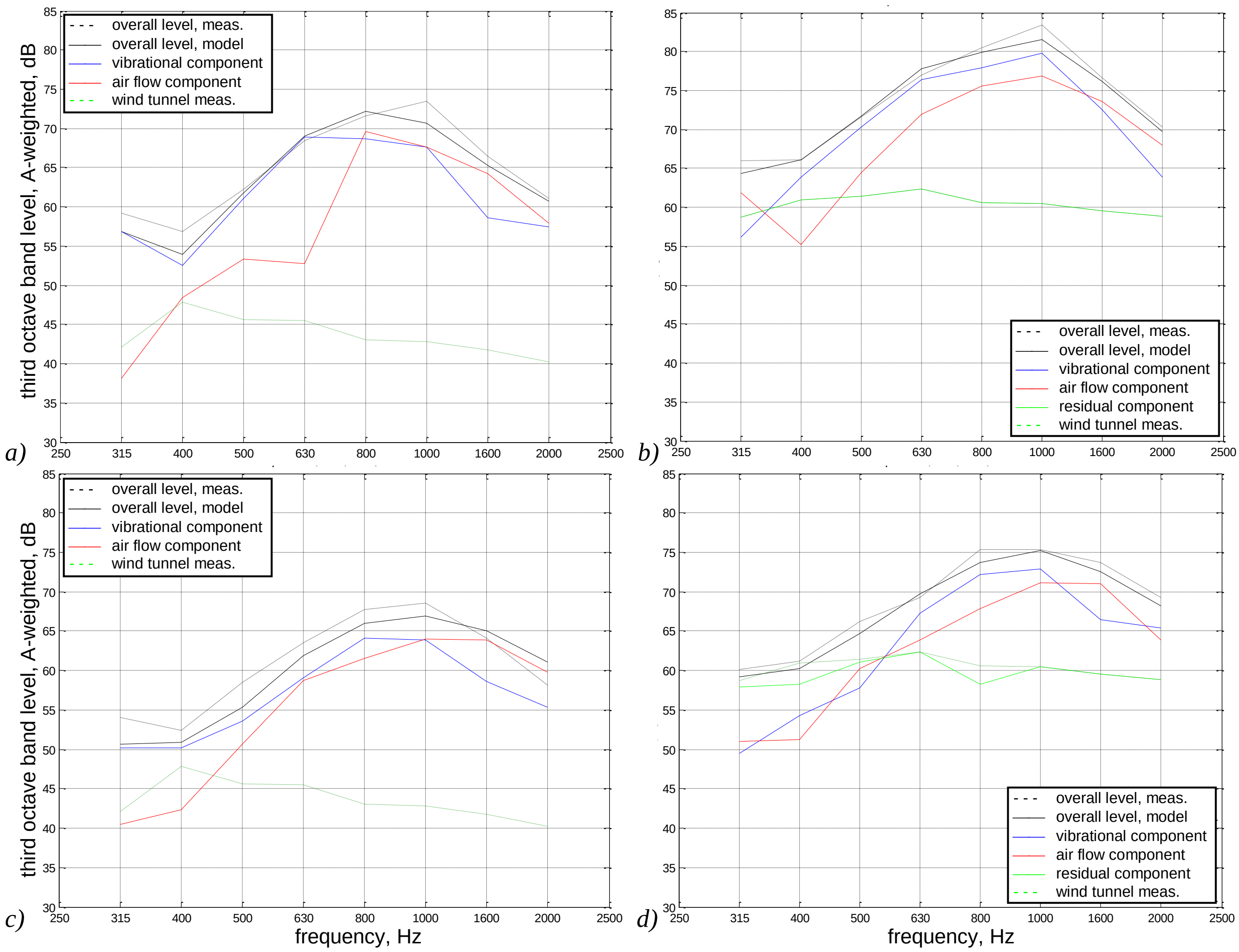

Figure 9. Coast-by level spectra for one type of tyre on different road pavements. Surface dressing 5/8 on stone mastic asphalt, a) 60 km/h, b) 110 km/h; Stone mastic asphalt 0/8, c) 60 km/h, d) 110 km/h.

3.2 Prediction of the acoustical durability

The model is ready to use for the prediction of coast-by levels for any road surface parameters either they are investigated resp. measured on real road pavements or experimentally 'designed'. It is a well suited tool for the

application in lab scaled experiments on the acoustic durability of road surfaces as well. Such experiments are due in a recently started project in the Swiss research framework called "Lärmarme Beläge innerorts" (Low noise road surfaces for urban use). In this project a test stand for testing the acoustical durability of road surface specimen will be developed and specified. The project runs under the acronym IMPACT (**I**nvestigation **M**achine for **P**avement **ACo**us**T**ic Durability). Specimens are produced by means of a roller sector compactor according to EN 12697-33. Two specimens are installed in a row, giving a total test surface length of 1 m and a width of 0.2 m. In order to yield information about the deterioration of the acoustical properties of the road surface depending on mechanical stress the specimens are treated by numerous roll-overs of a specific tyre under well defined temperature conditions. The performance of the SPERoN model is important in order to get a good resolution of the calculated coast-by levels depending on the varying acoustic road surface properties. The acoustic properties, i.e. surface texture, airflow resistance and sound absorption coefficient are measured during testing and are used to feed the model with appropriate data. Due to the fact that the model delivers coast-by levels such as could be measured next to the road the acoustical performance of the road surface under investigation can be evaluated at any time during the test. The following example should demonstrate in which way the model is involved in the testing procedure.
In Figure 10 the 3D texture of a road surface under wearing conditions is shown (left). Six parallel single profiles (right) are taken out of the 3D texture which are used to run the model calculations.

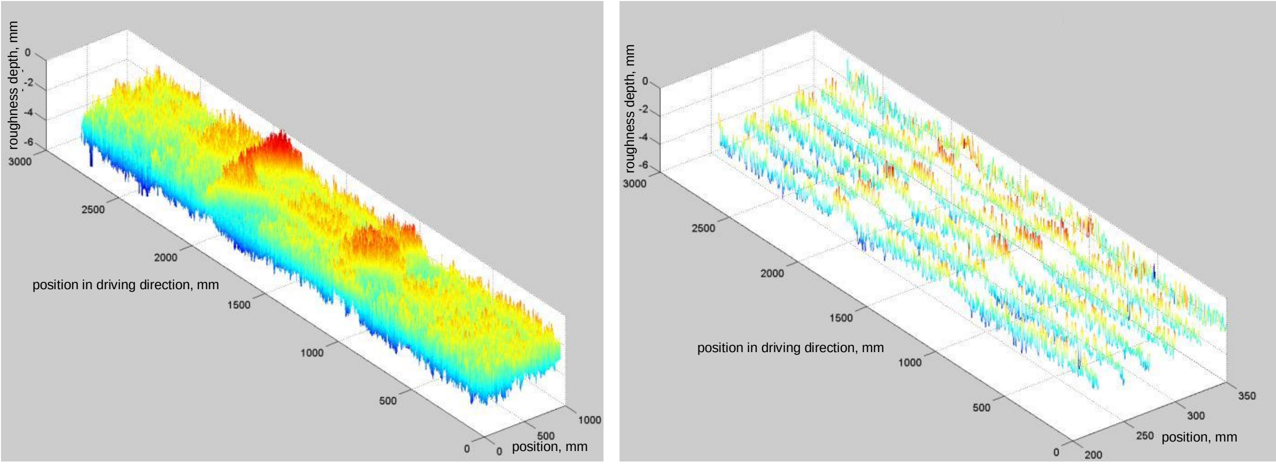

Figure 10: 3D texture (left) and texture profiles (right) of a worn road surface

Figure 11 shows conceivable single texture profiles of a worn road surface and a road surface of the same type in new and good condition. From the diagrams can be concluded that wearing and mechanical stress of the surface has led to a lost of the macro texture with short wavelenghts.

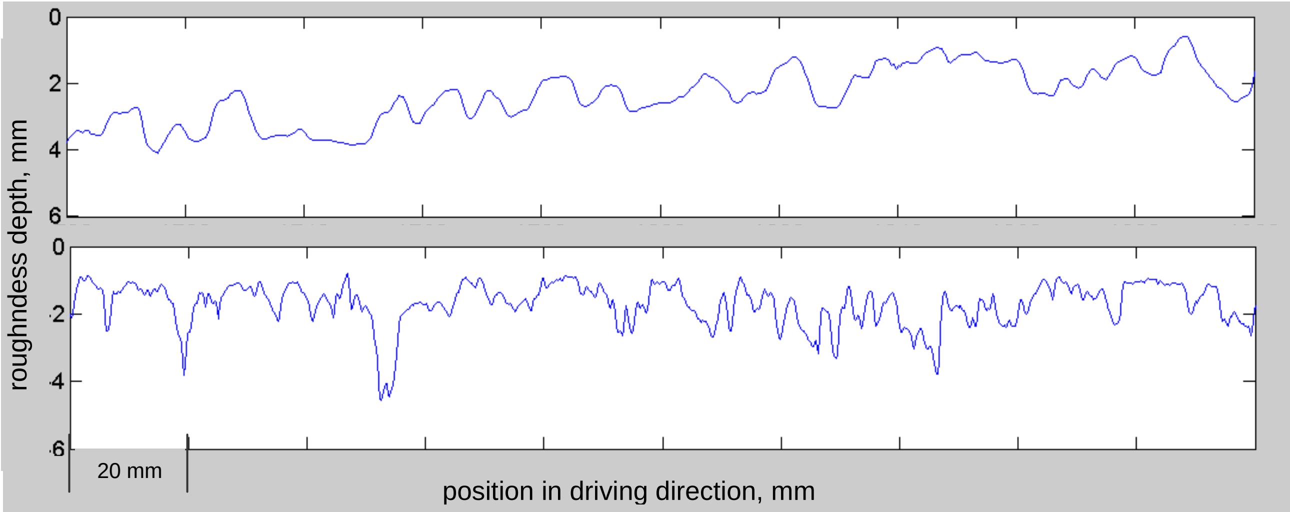

Figure 11: Single texture profiles of the worn (upper) and the road surface in new condition (lower)

During lifetime of a road surface the deterioration develops gradually. The wearing course of the road pavement will change its macrostructure due to changes and loss of material. This has been acoustically simulated by means of the SPERoN model. In Figure 12 eight cases of possible changes of the texture of an idealized road surface are shown. On

the left only the distance of single grains sticking out of the mixture is varyied. The stone size is 8 mm. Each roughness element has a height of 1 mm above the planar mixture. On the right the same distance variation is shown including an additional modulation of the height of the roughness elements. The height changes in a range from 0.5 mm to 3 mm. Between the two columns of diagrams the stone/gap ratio of the different cases is specified.
Figure 13 shows the results of the model calculations. On the left, the results of the total noise levels, containing all three noise source components (mechanical, aerodynamical and residual) are plotted against the stone/gap ratio. On the right, the noise levels caused by the mechanical component only are given. The results (orange curves) for the uniform height of the roughness elements (stones sticking out of the mixture) clearly show the sensitivity of the model. All stone/gap ratios yield a certain noise level difference and can be clearly distinguished. The narrower the grains are positioned next to each other the lower the noise levels are. Especially the mechanically induced noise component clearly shows the advantage of narrowly arranged roughness elements. On the contrary, the more single stones are missing in the surface structure due to wear the higher the noise levels are. This effect gets even worse if an additional process is taken into account: loss of material. This means that not only the amount of mineral aggregate decreases but also the amount of binder material. This leads to an increase of inhomogenity of the surface structure as simulated by the varying grain height. The impact on tyre/road noise is dramatic. The blue curves in Figure 13 correspond to this case. The mechanically induced noise increases by 3 dB to 7 dB and raises the total noise level by 2 dB up to 3 dB concerning the cases under investigation. If similar effects of road surface wear will be retrieved in the IMPACT test stand they can be easily evaluated in an acoustical sense by means of the model.

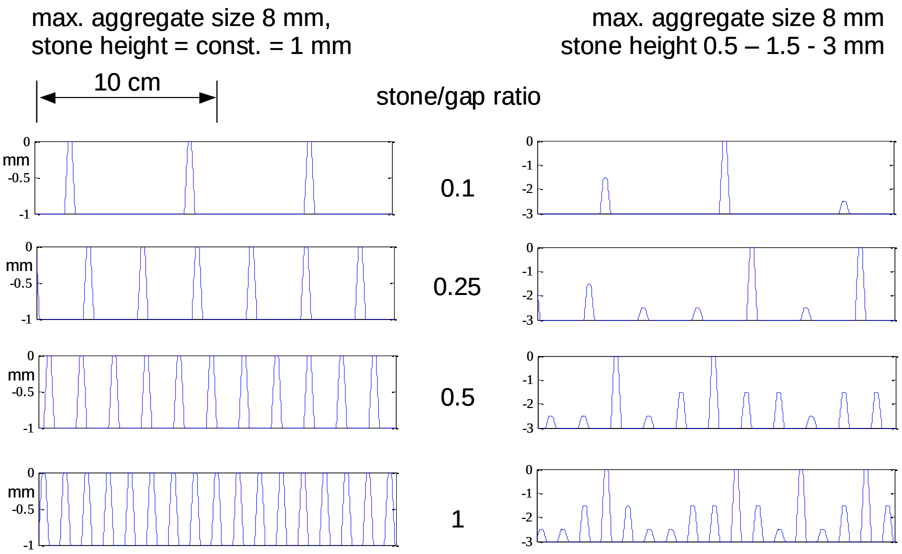

Figure 12: Sections of texture profiles taken for the calculations with SPERoN. Left: alle stones at the same height of 1 mm above the planar mixture, right: variation of the stone height.

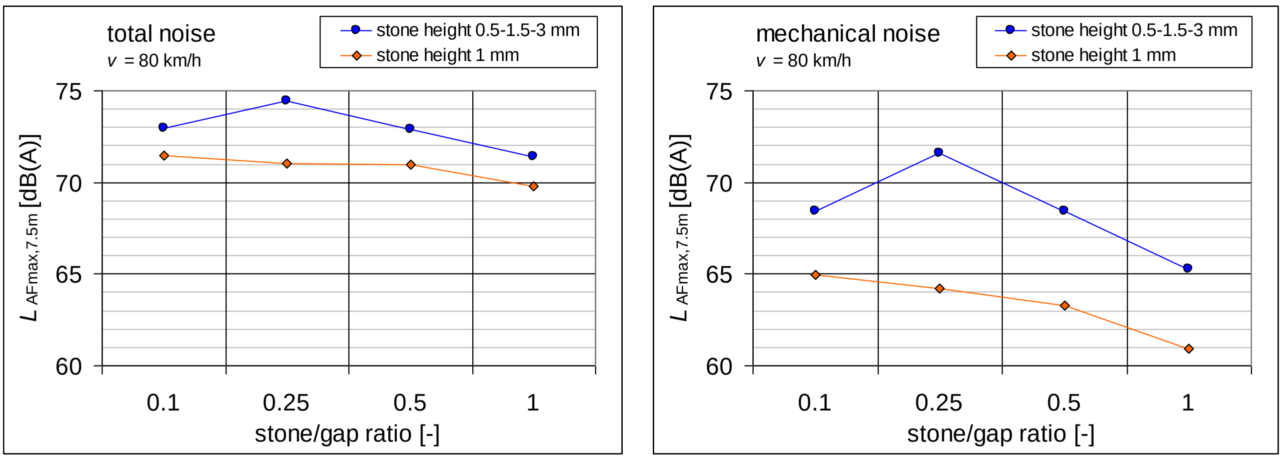

Figure 13: Maximum coast-by levels as they are calculated by the SPERoN model.

4 CONCLUSIONS

The model described in this paper is a useful tool for the evaluation of the acoustical performance of road surfaces. The non linear dynamic tyre/road contact problem is handled by a pure physical model and aerodynamic noise generation mechanisms are taken into account as well. Based on road and tyre data the model predicts the coast-by noise levels in a speed range from 50 kmh up to 120 kmh in terms of third octave band levels from 315 Hz to 2 kHz. Measured road surface data of real wearing courses as well as pavement specimen built in the laboratory can be processed. Actually, the model allows for the prediction of tyre/road noise levels of texture patterns designed on the computer. The quality of the results of +/- 1 dB(A) for the overall level of the tyre/road noise makes it possible to apply the model to the prediction of noise levels of road surface specimen which are worn in a specific testing machine (IMPACT) which is used to investigate the acoustic durability of asphalt mixtures.

REFERENCES

[1] Effect of the road surface texture on tyre/road noise (Einfluss der Fahrbahntextur auf das Reifen-Fahrbahn-Geräusch), T. Beckenbauer et al., scientific report no. 847, German Federal Ministry of Transport, Buildings and Dwellings, Bonn, August 2002

[2] Excitation of tyre vibrations due to tyre/road interaction, F. Wullens, PhD thesis report no. F04-03, Chalmers University, Division of Applied Acoustics, Sweden, 2004.

[3] The modelling of tyre/road noise - a quasi three-dimensional model. W. Kropp, K. Larsson, F. Wullens, P. Andersson, F.-X. Becot, T. Beckenbauer, Proceedings of InterNoise 2001, The Hague, The Netherlands, 2001

[4] Joint research project Quiet Road Traffic – Reduced tyre/road noise (Verbundprojekt Leiser Straßenverkehr - Reduzierte Reifen-Fahrbahn-Geräusche), project partners, scientific report no. S37, German Federal Highway Research Institute (BASt), Bergisch Gladbach, 2005

[5] Dynamic measurement of air flow resistance, B. Altreuther and T. Beckenbauer, Proc. Euronoise 2006 Tampere, Finland, paper no. 227, 2006