inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 1.1

TRIAS - TYRE ROAD INTERACTION ACOUSTIC SIMULATION MODEL

F. De Roo, E. Gerretsen

TNO Institute of Applied Physics, P.O. Box 155, 2600 AD, Delft, Netherlands

Tel.: + 31 15 269 24 67 / Fax: + 31 15 269 21 11 / Email: deroo@tpd.tno.nl

Keywords:
TYRE-ROAD NOISE, PAVEMENT, SOUND ABSORPTION, TEXTURE PROFILE

ABSTRACT
The reduction of tyre-road noise will be greatly enhanced by a well-developed understanding and description of the mechanical interaction in the tyre-road contact patch and of the sound emission that arises from this interaction. For this purpose the mathematical simulation model TRIAS has been developed, which is currently subject to a validation study. As part of TRIAS the module RODAS (**RO**ad **D**esign **A**coustical **S**imulation) has been developed, which predicts the acoustical characteristics of the road surface from the basic material properties, like chipping size and porosity. This module may also be applied separately. The validation of this module has shown that the acoustical characteristics of road surfaces may be predicted with acceptable accuracy and that simulated data can be used as sufficiently reliable input for the TRIAS model.

1 - INTRODUCTION
Since 1996 work has been in progress concerning the development of a comprehensive mathematical simulation model for the excitation and radiation of tyre-road noise. This model is called TRIAS (**T**yre **R**oad **I**nteraction **A**coustic **S**imulation) and comprises two partially independent noise excitation mechanisms, a fully elaborated radiation and propagation modelling and a large number of influential parameters. In Figure 1 a schematic diagram of the set-up of this model is given.
As can be seen the model comprises modules for:

- the description of the mechanical interaction between tyre tread and road surface texture;
- the response of the tyre to the mechanical excitations;
- the radiation of sound originating from the vibrations of tyre tread and carcass;
- the air movements in the contact patch caused by the movements of the tyre relative to the road surface;
- the radiated air pumping noise caused by these air movements;
- the propagation of the sound of the various sources to the environment.

Noise prediction computation with TRIAS will be based on input data concerning the tyre design parameters and the fundamental physical road surface characteristics like texture depth, porosity, flow resistance and / or sound absorption. The input data may be acquired from measurements of these quantities on an existing road surface or on a laboratory test sample. If no measurement results are available or the surface is not yet existing but still in the design stage, input data can be generated by the supporting simulation model RODAS (**RO**ad **D**esign **A**coustic **S**imulation) which generates the physical road surface characteristics from the material composition of the surface mixture (chipping size, binder content, layer thickness).
A full description of the TRIAS model may be found in several Inter-Noise papers [1], [2], [3]. Basically, the approach of the TRIAS model is a two-dimensional extension of the computation method developed by Kropp [4]. The goal of the model is twofold:

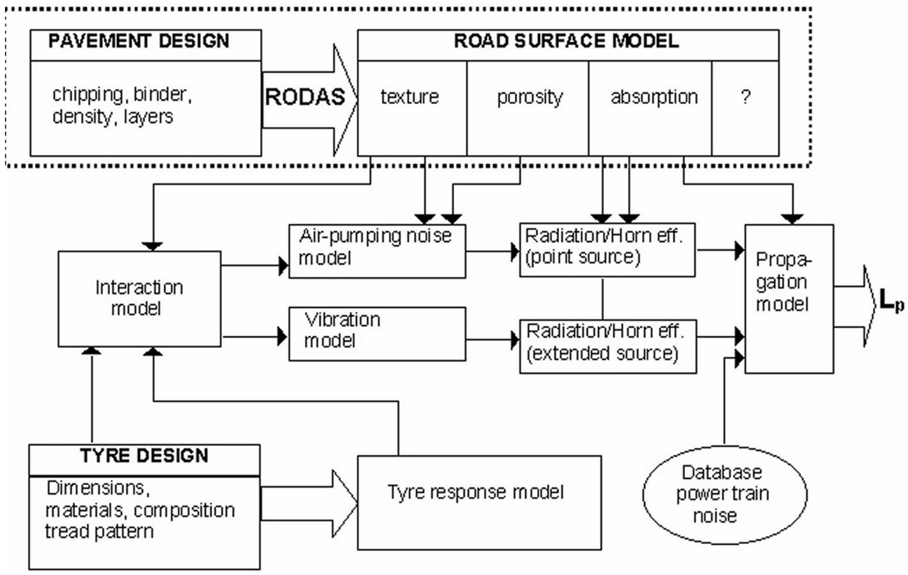

Figure 1: Schematic diagram of the mathematical simulation model TRIAS (**T**yre **R**oad **I**nteraction **A**coustic **S**imulation); the supporting model RODAS (**RO**ad **D**esign **A**coustic **S**imulation) is indicated in the upper part of the scheme.

- Description and prediction of the influence of road surface characteristics on tyre-road noise emission;
- Study of the influence of tyre parameters on tyre-road noise emission and development of design concepts for low-noise tyres.

At present the development process is in the validation stage, which has started with the validation of the RODAS model, the results of which will be discussed in this paper. The validation of the complete TRIAS model is in progress now and will be completed in the course of this year.

2 - DESIGN AND VALIDATION OF RODAS

The RODAS model consists of two separate simulation modules:

- A module comprising a set of analytical formulae for the computation of the sound absorption of porous surface layers and its underlying parameters like: porosity, flow resistance and structure factor, from the basic dimensions of the composing aggregates;
- A module capable of simulating a surface texture profile and analysing its wavelength spectrum.

The predictions from these two modules have been validated against results of sound absorption measurements and texture profile measurements. The pavement types involved were: dense asphalt concrete (DAC; 12 samples), high porosity asphalt concrete (HPAC; 10 samples), stone mastic asphalt (SMA; 6 samples) and brushed cement concrete (BCC; 1 sample).
In the following sections the basic set-up of these modules and the validation results will be discussed.

2.1 - Modelling of sound absorption and its underlying parameters

The sound absorption of porous structures like porous asphalt concrete may be predicted from the classical theory for sound absorbing materials with a rigid skeleton [5]. Recently elaborations and additions [6], [7] to this theory have been suggested. When comparing theory and measurements for porous road surfaces it appears that the theory does not agree satisfactorily with measurements. This is caused by the fact that the theory is based on the dissipation of energy by viscous friction of the air movements in the pores of the material and does not include the thermal dissipative effects due to the thermal conductivity of air. This effect appears to be rather significant for materials with a low flow resistance like porous asphalt layers. By adding the thermal effects Hamet [8] has improved the modelling for the acoustic impedance of porous layers; RODAS is based on this extended theory.

Sound absorption
In this model the acoustic impedance $Z'(\phi_0)$ at an angle of incidence ϕ_0 is considered to be a function of the layer thickness h, the porosity of the layer Ω, the specific flow resistance σ of the material and the structure factor s_f, which is a measure for the tortuosity of the pores. If the pavement consists of several porous layers the impedance may be computed in a similar way from the material parameters of each layer. While the acoustic impedance is the main input parameter for the TRIAS model, the sound absorption coefficient may be more adequate for characterisation of the pavement surface. This sound absorption coefficient $\alpha(\phi_0)$ at an angle of incidence ϕ_0 may be derived from the impedance Z' by the following equation:

$$\alpha(\phi_0) = 1 - \left| \frac{Z'(\phi_0)\cos\phi_0 - 1}{Z'(\phi_0)\cos\phi_0 + 1} \right|^2 \quad (1)$$

Measurement of the sound absorption coefficient of road surfaces will normally be carried out under normal incidence of the sound. The validity of the model will be discussed later in this paper.
Of the above mentioned parameters determining the acoustic impedance the effective thickness, the porosity and the specific flow resistance may be measured directly on road surface test samples. The structure factor is rather difficult to determine by measurement. For pavements still in the design stage or pavements from which no test samples can be taken the values of the parameters cannot be measured and have to be assessed from other data. For each of these parameters formulae have been found that predict the parameter values from the dimensions and characteristics of the composing materials, as will be discussed in the next sections.
Porosity
If the average densities of the pavement ρ_p and of the aggregate ρ_a are known the porosity Ω could be derived by the following formula:

$$\Omega = 1 - \frac{\rho_p}{\rho_a} \quad (2)$$

In most cases the empirical expression below will be more practical:

$$\Omega\,(in\%) = 0,26\,(100 - s_{\%} - f_{\%}) + 2,5\frac{\Delta d_{st}}{d_{average}} - 9\left(1 - e^{-0,00001 b_{\%}^5}\right) \quad (3)$$

where

- $s_{\%}$ = percentage of sand;
- $f_{\%}$ = percentage of filler;
- $b_{\%}$ = percentage of binder;
- Δd_{st} = difference between maximum and minimum grain size of the aggregate;
- $d_{average}$ = average grain size of the aggregate.

This expression has been validated against porosity values measured on 8 different specimen of HPAC. The deviations between predicted and measured values raged from − 9 % to + 13 %, which was considered to be acceptably accurate.
Flow resistance
As a synthesis of the approaches of different authors the specific flow resistance of a granular material may be expressed as:

$$\sigma = \frac{C}{\langle d^2 \rangle}\left(\frac{1}{\Omega} - 1\right)^2 \quad (4)$$

where d = the effective diameter of the aggregate granules (in mm) and C = a constant. The value of C was adapted to fit the measurement data best, which yielded a value of 2,8*10^4. Nevertheless the correspondence between predicted and measured values remains fairly poor; the predictions will be on average correct, but may show considerable deviations. Luckily, the determination of the flow resistance is not a critical step in the assessment of the sound absorption. Variations up to a factor 2 may be acceptable.

Structure factor
The structure factor, which expresses the tortuosity of the pores, can only be assessed theoretically for idealised geometries. For perpendicular uniform channels a value of 1 would apply and for diffusely oriented uniform channels a value of 3 would be valid. In granular materials the structure factor appears to be an approximate function of the porosity:

$$s_f \simeq \Omega^{-1} \tag{5}$$

No validation data were available for this quantity.
Validity of the sound absorption model
As was shown before the model used for the acoustical impedance and the sound absorption is well in line with measurements. Figure 2 shows an example of comparison between prediction and measurement, where the input values for porosity, flow resistance and structure factor have been derived from the formulae (3), (4) and (5).

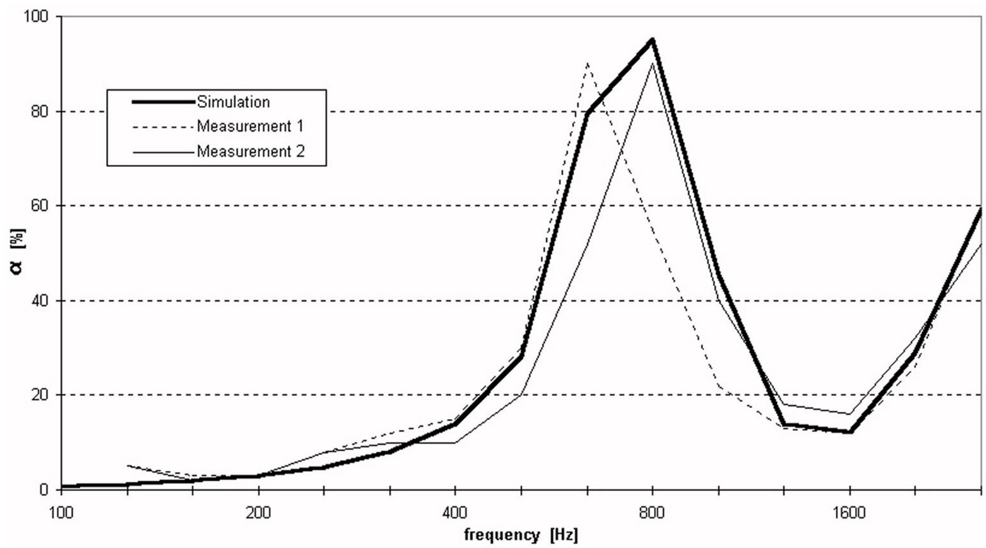

Figure 2: Comparison of measured and simulated absorption curves for a two layer high porosity asphalt concrete (HPAC).

The deviations between measured and simulated absorption curves are reasonably small, especially in the frequency range where the first maximum occurs. The deviations are mostly of the same order of magnitude as the deviations between different pavement samples of similar composition. In general the simulation puts the absorption maximum in the right 1/3 octave band and in that frequency range predicts an absorption coefficient that deviates no more than 10 % from the measured values.

2.2 - Simulation of surface texture profiles and wavelength spectra

The pavement surface texture will be determined by the size and shape of the aggregate granules, the variation of this size, the properties of the binder and the finishing of the surface. As no simulation methods could be found in literature a new simulation model was developed to predict the surface texture profile from the above mentioned parameters.
In the model the production process of pavement surface layers is simulated by means of a random process in which granules of different size (=length) are positioned one after another, according to the distribution function of the sizes, while the height of the texture varies randomly up to the value of the maximum grain size. The peaks of the granules are positioned randomly with respect to the horizontal plane up to a certain maximum height. For dense asphalt concrete (DAC) this maximum is fixed and determined by the compacting process (the granules are oriented with a flat side upwards by the compacting roller), for stone mastic asphalt (SMA) the maximum height depends on the average grain size (compacting is limited by stone-on-stone contact). The gaps between the stones are chosen in accordance with the density of the mixture and the porosity. For DAC and SMA the gaps are filled up to a fixed distance from the highest peaks. For porous asphalt the gaps caused by the porosity are randomly deepened to the maximum grain size.

This simulation process results in a texture profile that is primarily determined by the following parameters: grain size distribution, percentage of stone aggregate in the mixture and porosity.
After the first simulation step the texture of DAC and SMA are modified by simulation of the scattering of grit on a newly laid surface, which leaves small holes of a certain depth in the surface on locations where no stones are present in the surface level.
This second simulation step finalises the shape of the texture profile, which is then digitally scanned and thus yields a sampled texture profile. From this sampled profile a texture wavelength spectrum may be derived by means of Fourier analysis.
Simulation results from this module have been generated and compared with measured results. Figure 3 shows an example of the comparison between measurement and simulation for HPAC.
Generally the correspondence between the measured and simulated texture profiles is acceptable; the visual similarity between measurement and simulation results is good, while the characteristic differences between the profiles of different pavement types appear in the simulations as well. When comparing the simulated and measured wavelength spectra the agreement is not completely satisfactory, because of differences in spectrum shape and level. A difficulty in these cases is, however, that the consistency of the measured data is small. Pavements of the same composition give strongly differing results on different locations and in different measurement series. This indicates that the texture of a pavement shows fairly large variations and is not fully determined by the pavement type and composition. Moreover there is doubt whether the texture profile measurement methods used up to now produce sufficiently reproducible results.

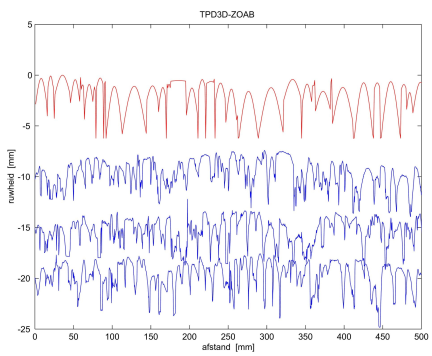

Figure 3(a): High porosity asphalt concrete; comparison of simulated (upper curve) and 3 measured texture profiles (lower curves).

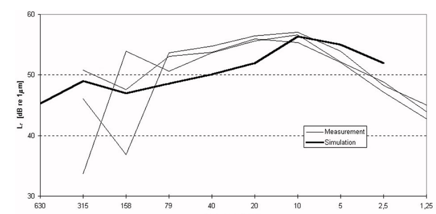

Figure 3(b): High porosity asphalt concrete; wavelength spectra corresponding to fig. 3-a.

3 - CONCLUSIONS

From the validation it has been shown that the acoustical characteristics of road surfaces may be predicted with the RODAS simulation model with acceptable accuracy.
The absorption module has been readjusted and delivers a prediction inaccuracy, which is of the same order of magnitude as the spread between different specimen of a specific pavement.
The texture simulation module delivers only moderate prediction accuracy. Improvements are advisable but can only be implemented on the basis of more reliable measurement data than are currently available. Monitoring of future developments will be useful.
A user friendly runtime software version of the RODAS model will be developed and will be made available to users working in pavement research and design.
The validity of the complete model TRIAS is under investigation; results will be published soon.

ACKNOWLEDGEMENTS

The development and the validation of the models TRIAS and RODAS have been made possible by a joint funding from the Directorate-General of the Environment and the Netherlands Foundation for Research and Standardisation in Road Construction and Civil Engineering (CROW) and was guided and supervised by its Working Group "Road Surface Characteristics".

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