Silent and Safe Roadtraffic-project: An optimization of the tyre-road interaction on noise and wet grip.

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Summary
The tyre-road interaction is responsible for many tyre and road 'characteristics' like rolling resistance, noise, hydroplaning and wet grip. In the EC legislation R1222 the 'tyre characteristics' are measured using 'standard roads'. Whearas 'road characteristics' like noise in the ISO11819-2 and skid resistance are often measured using 'standard tyres'. As the standards are often old technology, real innovative steps are hard to achieve. Therefore the project 'Stil Veilig Wegverkeer' is started, translated as 'Silent and Safe Roadtraffic', where the tyre-road interaction is studied in more detail regarding noise and wet grip. With new developed simulation and test methodogies the tyre-road combination is optimized. An overview of the project and the first results will be given.

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1. Introduction

The main origin of many tyre-road 'characteristics' (or performances) are the forces interacting at the tyre-road contact. Tyre-road noise originates from the *variation* of these contact forces in both place and time. Two geometrical origins are responsible for this contact force variation: tread pattern and road texture. Making these geometries more smooth, i.e. more smooth tread pattern and more smooth road, will reduce the noise.

On the other hand those geometrical roughnesses are required to remove water from the contact patch and establish tyre-road contact during rain. Therefore silence and safety are in balance and trade off with each other. Figure 1 illustrates how the different tyre-road performances are related to the tyre-road roughness at different length scales. Red coloured performances indicate a decrease of desired performane for higher texture amplitudes, whereas green performances shows an increase of the desired performance.

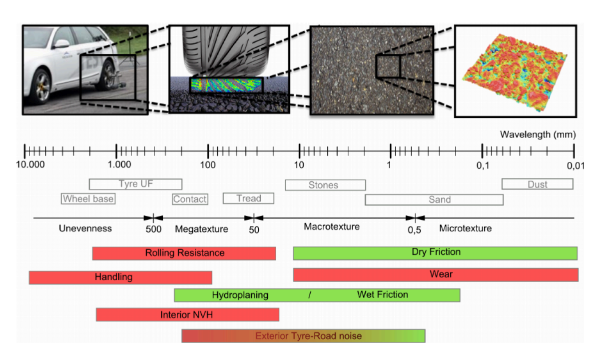

Figure 1. Wavelengths of tyre-road-vehicle system[1].

The need of knowledge on these tyre-road performances is required by both the tyre and the road in-

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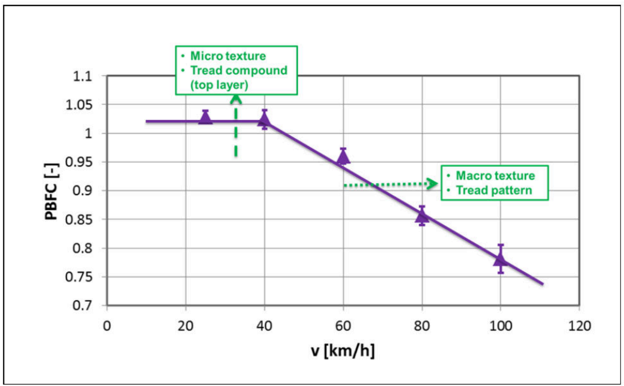

Figure 2. Measured stribeck curve of a regular tyre-road system.

dustry. The development of this knowledge is the primary focus of the tyre-road consortium of the University of Twente. The project 'Stil Veilig Wegverkeer', translated as 'Silent and Safe Roadtraffic', is started by Apollo Tyres Global R&D B.V., Reef Infra B.V., University of Twente, Province Gelderland and Stemmer Imaging. The project is sponsored by the partners and subsidized by the Regio Twente, Province Overijssel and European Regional Development Fund. The project goals are:

- Fundamental research on noise & wet grip (*knowledge*)
- Development of silent & safe tyre, roads and tyre-road combination (*valorisation*)
- By wich the roadtraffic becomes more silent & safe (*sustainable society*)

The fundamental research involves also the development of new measurement equipment to be able to characterize the tyre-road interaction more thoroughly. The project is subdivided in four phases:

- Equipment(2011-2013); Development of new measurement equipment
- Research & Modelling (2011-2015); Development of knowledge, simulation & test tools
- Development (2013-2015); Optimization of tyres & roads using the new insights and tools
- Production & Demonstration (2015); Producing & demonstrating the optimized tyre-road configuration.

2. Scientific goal

The scientic and engineering challenge is best explained by using the tribological Stribeck curve as shown in Figure 2. This stribeck curve is from a wet tyre-road combination as measured at one of the special manufactured roads at the former Military Airport Twenthe in Enschede (The Netherlands). It shows the frictional force for different driving speeds. The frictional force shown here is the maximum peak braking force coefficient (PBFC) during a complete braking slip measurement from free rolling to full braking (100 % slip ratio).

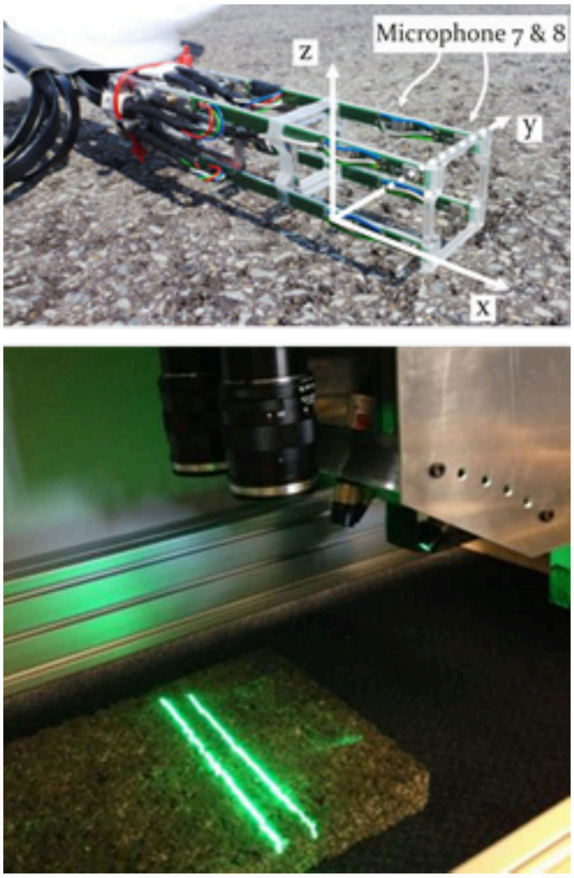

Figure 3. The 8p-probe (top) of University of Twente and the 3D macro scanner (bottom) of Stemmer Imaging B.V..

At lower speeds, the water has sufficient time to flow into the grooves and aside the contact patch. A maximum braking force is obtained being indepent of the speed. In this region the maximum braking force is mainly determined by the tyre tread compound and the road texture amplitudes of the micrometer regime. Both determine namely the friction between the rubber and road. Higher texture amplitudes of more hysteresis of the treac compound increses the friction, moving the stribeck curve towards higher braking forces.

For higher speeds the water has not sufficient time to flow aside an into the grooves and hydroplaning starts to occur at the beginning of the contact patch. Dominant parameters in this regime are the macroscopic road texture, road porosity and the tyre tread pattern. Increasing these macrocopic roughnesses moves the stribeck curve towards higher speeds.

At even higher speeds complete hydroplaning occurs and there is no tyre-road contact anymore.

The example shown here illustrates that the road texture amplitudes and tyre tread pattern design are influencing the both the silence and safety aspects.

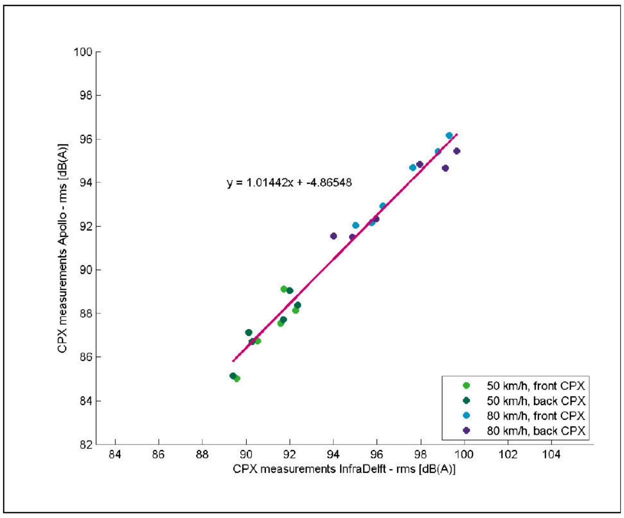

Figure 4. Measured SPL by Apollo open CPX and InfraDelft closed CPX [1].

The scientific goal of this project is therefore to develop the knowledge and tools to reduce the noise while maintaing this hydroplaning / wet grip performance.

3. Equipment

Two new 3D asphalt scanners have been developed by Stemmer Imaging in order to measure the road texture in the micro (20 mm..10 μm) and macro (20 cm..0.1 mm) region. The two scanners are cotained in a rigid housing to minimize the external and dynamical influences of the system. Furthermore an x-y stage moves the scanners over the surface to measure a 3D geometry. An example is shown in Figure 3. Post processing is done using Matlab software. The micro-system is mainly used to investigate and validate the friction models of the rubber-road interface, whereas the macro-system is used to determine and validate the contact models.

Another equipment further developed in this project is the 8p-probe or 3D microphone array shown in Figure 3. Classically the sound absorption characteristics of asphalt pavements are measured by impedance tubes assuming normal incident sound waves. But the vibrating tyre radiates sound in all directions and predominantly as grazing incidence! The angle of incidence and its relation to the real absorption of these waves are investigated using this 8p-probe [2].

To define within the project one test procedure for noise and wet grip an comparison was made between the tyre and road legislative standards. Pass-by noise is measured at 7.5 m at 1.2 (or 5m) height. In the tyre legislation UNECE-R117 this is done without engine between 90-70km/h, whereas in road standard ISO11819-1:2001 this is done in cruising conditions at the local maximum allowed driving speed.

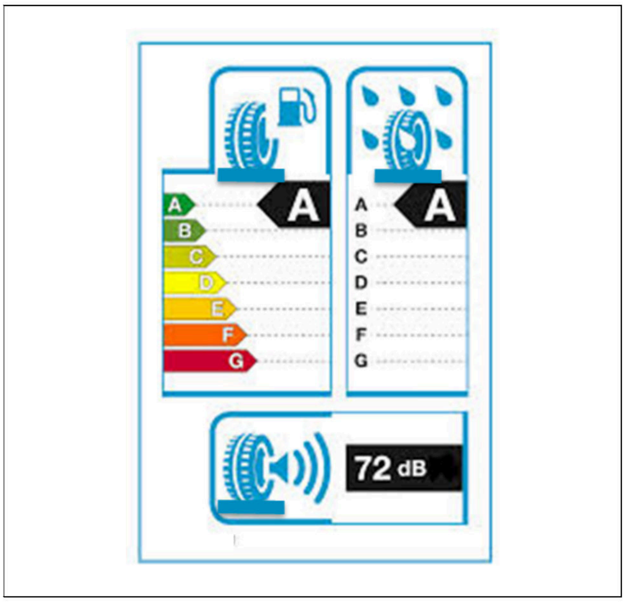

Figure 5. Current proposal of a label describing the **tyre-road interaction**.

The ISO11819-2 specifies Close Proximity locations (CPX) near the tyre-road contact measuring more directly the source. Within the project this CPX set-up is used to characterize the tyre-road configurations. Figure 4 shows the comparison between the open CPX set-up of Apollo Tyres with the closed CPX trailer of InfraDelft. The correlation is clearly seen and the offset is explained by the difference between the used outer respectively inner CPX microphone positions.

In a similar manner the rankings between the Peak Break Force Coefficient (typically achieved around 12-20 % slip ratio) of the tyre legislation R1222 and the Break Force Coefficient at 80% slip ratio of the road standards showed an similar trend, alhough the absolute values differ and depent on the tyre-road properties.

Using these, within the project standardized, test protocols for noise (CPX & Pass-by) and wet grip (PBFC) the tyre-road performance is measured. In order to demonstrate the improvements an *tyre-road interaction* label will be defined. Inspired on the R1222, Figure 5 shows the current proposal for such tyre-road interacion label. In this manner a future outlook for improvement potentials will be given.

Other equipment like the SR-ITD of Ooms, developed in the SKIDsafe project and the LAT100 & DMA of Apollo Tyres for which test protocols have been developed in 'Safe Tyres, Save Energy' project are extensively used to characterize and predict the friction of each rubber-road combination respectively the viscoelastic material behaviour.

4. Research

Using the background knowledge of both companies the first experimental designs were made and evalu-

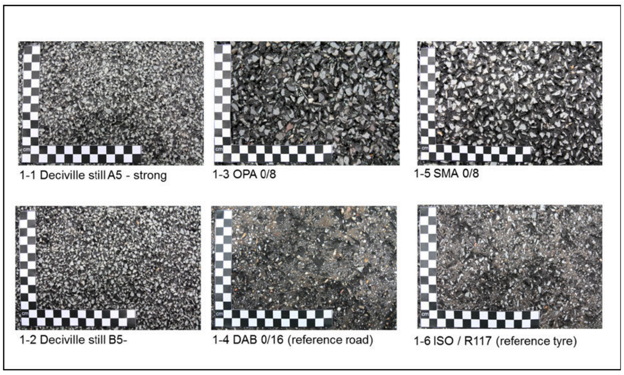

Figure 6. First set of road manufactured by Reef Infra B.V..

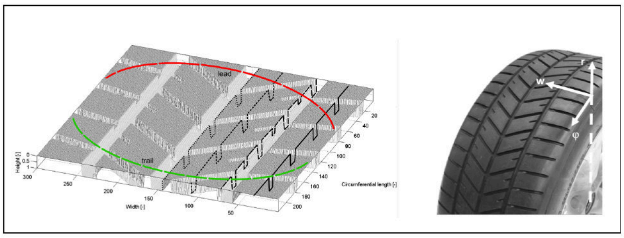

Figure 7. Tyre (right) and source model (left) with leading (red) and trailing edge (green) of tyre-road contact.

ated. Reef Infra B.V. manufactured six different road configurations focussing on smooth toplayered dense apshalts and open porous asphalts. Figure 6 shows the pictures of these six roads, where each block is 1 cm. More than 50 special hand carved tyres are used to investigate the resulting wet grip and noise performances of the different tyre-road combinations of which Figure 2 was an example. Road 1-4 is the reference road for the road industrial legislation, whereas road 1-6 is the reference road for the tyre industrial legislation.

The open CPX set-up attached to an Audi A6 measured the exterior noise, while the interior noise is measured simultaneously. The road texture and absorption characteristics were separatedly measured. These experiments gave input to the different research investigations:

- Friction contribution of tread toplayer [3]
- Friction contribution of tread hysteresis [4]
- Interior noise & human sound perception [1]
- Structural tyre vibrations & exterior noise [5]
- Sound radiation & road absorption [6]

For more details on the last two noise simulation models the reader is referred to the other two Eurnoise papers.

A brief overview of the noise models will be given here.

4.1. Interior noise & human sound perception

For the first optimization of tyre tread pattern and road texture an interior noise model is developed.

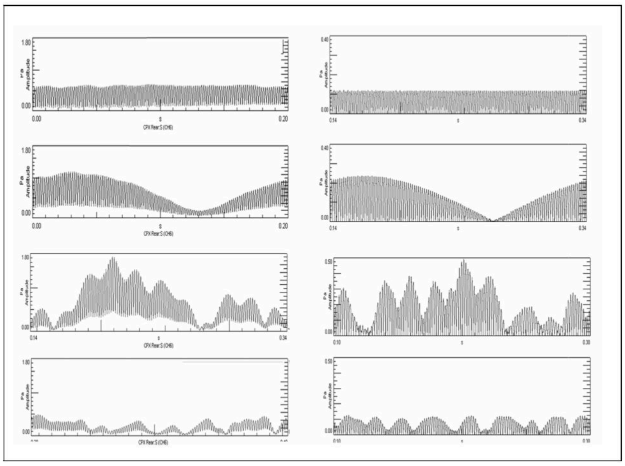

Figure 8. Comparison between the measurements (left) and predictions (right) for four different tyre-road combinations.

The interior noise model consist of a source model and a human perception model. The source model predicts, using the combined tyre-road geometrical roughness the sound pressure level. The combined tyre-road roughness H_{tr} can be described by:

$$H_{tr}(\varphi, w) = H_0 H(\varphi, w) \tag{1}$$

where $H_0[mm]$ is a scaling factor for the maximum tread-road height and $H(\varphi, w)[-]$ is the (normalized) tyre-road roughness, describing an (statistical averaged) tyre-road roughness for one tyre circumference $\varphi[rad]$ and axial width $w[mm]$. Figure 7 illustrates this for a smooth surface. Upon rolling, this geometry passes the contact patch, resulting into the contact pressure variations in both time and space. It is assumed that the complete contact patch contributes to the noise and all contact points (φ, w) contribute coherently. The averaged geometry in contact:

$$\widetilde{h}(\varphi) = \frac{1}{A} \iint_{contact} \widetilde{H}(\varphi, w) dS \tag{2}$$

for all $\varphi = 0 \ldots 2\pi$, and with A the contact area is validated to follow the same trend as the measured sound pressure p. Figure 8 shows also a comparison in between the experiments (left) and simulations (right) in time domain of four different tyre-road combinations. The results are clearly seen to match quite well.

The human sound perception model uses dedicated Sound Quality Metrics STD, OP, MOM describing respectively the sound level, the tonality and the modulation. A jury evaluation of different sound fragments results into a rating of these sounds. A linear regression of the calculated Sound Quality Metrics on this rating resulted in the human perception model, called the Sound Quality Preference Index (SQPI):

$$SQPI = Y_0 - \alpha STD - \beta OP - \gamma MOM \tag{3}$$

where α, β, γ are coefficients and Y_0 an off-set value.

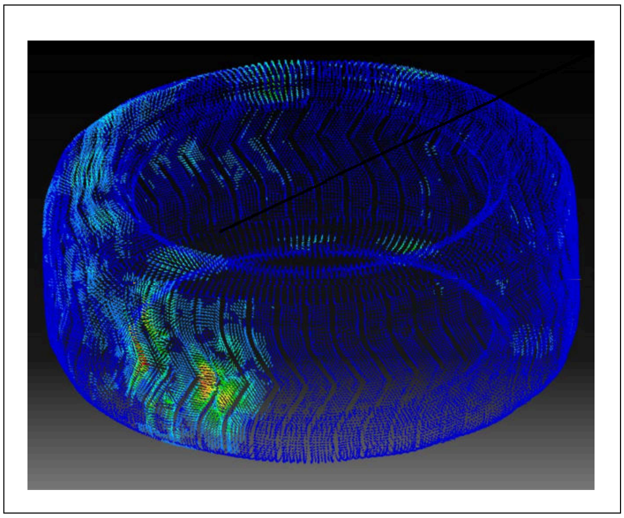

Figure 9. Predicted sound intensity for a treaded rolling tyre on a smooth drum.

4.2. Structural tyre vibrations & exterior noise

To optimize the tyre construction and road construction in more detail a numerical model by which the structural tyre vibrations and the sound radiation of a rolling tyre can be predicted, [7]. The predictions of the structural tyre vibrations are based upon on a complete finite element model of the tyre and road texture. A transient rolling simulation of this tyre over the road texture predicts the vibrations of the tyre.

These timed domain vibrations of the tyre are mapped onto fixed acoustic mesh to predict the sound radiation in frequency domain using eigther the finite elements or boundary elements methods [5]. An example is shown in Figure 9. The radiation near the leading edge of the contact patch and the vibrational modes are clearly seen.

4.3. Sound radiation & road absorption

To optimize the sound absorption of porous asphalt pavements, an hybrid impedance model is developed which can predict the sound field in and above non-locally reacting porous materials. The modelling approach combines an analytical and a finite element approach, as shown in Figure 10, and includes the viscothermal effects within the pores of the porous asphalt pavement as well as the scattering at the stones in the pavement.

With this hybrid modelling approach the sound absorption for oblique incidence can be optimised, based on the stone size and stone matrix within the porous asphalt pavement. The predicted total pressure is obtained by adding the analytical solution of the incident and reflected pressure field to the numerical solution of the scattered pressure field.

The results can be used to predict the absorption coefficient for oblique incidence of which an example is shown in Figure 11. The developed model will be validated by measurements of the absorption coefficient for oblique incident sound waves using a small 8p-microphone array. The validated model will be used to optimise the sound absorption of porous asphalt pavements. Together with the structural vibration model to predict the sound radiation of a rolling tyre, the tyre and road can be optimised in an integral manner to reduce traffic noise.

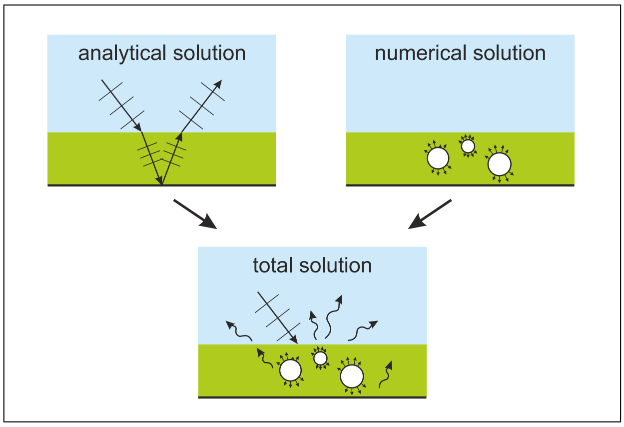

Figure 10. Hybdrid modelling approach of road absorption.

5. Outlook

The different analytical and FEM simulation models have nearly all been validated. At the same time the development phase has been started. The final tyre and road variants have been finalized and manufactured while currently the testing and evaluation is going on. By the end of 2015 the final results will be ready.

6. Conclusions & Recommendations

The project showed that the tyre and road industry are independently trying to optimize the tyre-road performance within their limitation of the legislation. In order to achieve innovative steps a close cooperation is required.

The results of this project already shows the benefit of close coopertions. At the same time it is also only the first step on the path of an holistic research and development route to optimize the tyre-road interaction for a more durable society.

Acknowledgement

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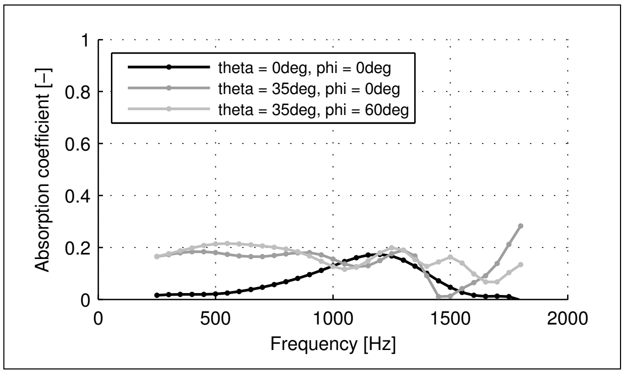

Figure 11. Predicted absorption coefficient for oblique incidence.

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