Experimental review on interior tire-road noise models

D.A.Bekke[1], Y.H.Wijnant[2], A.de.Boer[2]
[1] Apollo Vredestein B.V., Technical Centre Enschede, Research Department
P.O. Box 27, 7500 AE Enschede, Netherlands
email: **dirk.bekke@apollovredestein.com**

[2] University of Twente, Department Mechanical Engineering, Section of Applied Mechanics, Chair: Structural Dynamics & Acoustics, P.O. Box 217, 7500 AE Enschede, Netherlands

Abstract

Exterior and interior tire-road noise is a common problem for car and tire manufactures. Exterior tire-road noise is bounded by UN-ECE R117 and EC R661/2009. Interior tire-road noise on the other hand is determined by market requirements. Since the beginning of the last century different model approaches on exterior and interior tire-road noise have been reported. A brief review of these model approaches is given in order to distinguish which approach to model interior tire-road noise is most promising. Some experimental considerations are given as a guide line for this evaluation. The paper concludes that the most efficient model approach is a full interior tire-road noise consisting of a FEM/BEM exterior tire-road noise model combined with measured structure and air-borne transfer paths.

1 Introduction

Tire-road noise is experienced by the driver in the car (interior tire-road noise) and by pedestrians (exterior tire-road noise). Exterior tire-road noise measured during a free rolling passage of a vehicle at 7.5 meters distance is bounded by UN-ECE Regulation 117 and the upcoming EC-Regulation 661/2009. Interior tire-road noise on the other hand is determined by market- and OE-requirements.

The origin of both noise sources is the dynamic tire-road interface which is present when a tire rolls over a road-surface. The transfer paths from this interface towards the ears of the driver and the ears of the pedestrian are different. In Figure 1 these transfer paths are schematically shown.

Sandberg and Ejsmont [1] give an overview of the literature until 2002. They grouped the different tire-road noise mechanisms into aerodynamic mechanisms (air pumping, air turbulence, Helmholtz and pipe resonances) and structure borne mechanisms (tread and road excitation, rolling deflection, stick/slip, stick/snap). The aerodynamic mechanisms directly produce noise which then transfers through the air. Structure borne mechanisms excite tire-wheel vibrations which can result through radiation into the second origin of exterior noise. As can be seen both noise sources also contribute via the air borne path to interior noise.

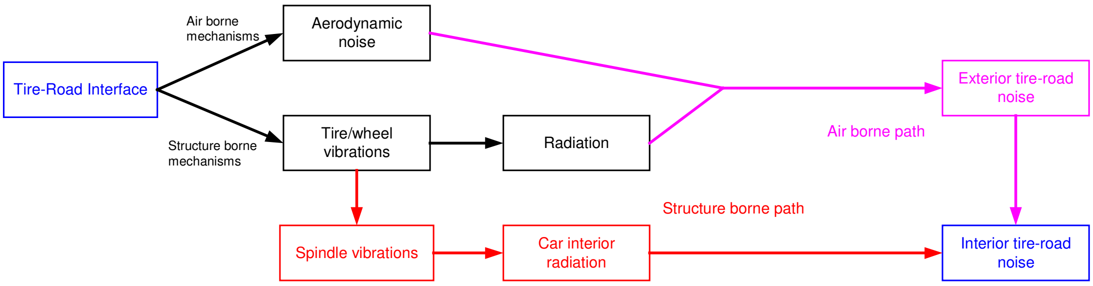

Figure 1: Schematic overview of interior and exterior tire-road noise.

Looking at interior tire-road noise one can distinguish two different transfer paths:

- Air borne path: exterior tire-road noise coming into the car interior (purple)
- Structure borne path: hub vibrations excite the car panels which radiate noise inside the car (red)

In this paper we will first investigate which modeling approaches are present on exterior and interior tire-road noise (chapter 2). We give some experimental guide lines for tire-road noise modeling (chapter 3). We conclude, as already can be seen from Figure 1, that the most efficient way to develop a full interior tire-road noise model is to combine an exterior tire-road noise model with possibly measured air- and structure borne transfer paths (chapter 4).

2 Literature survey on tire-road noise modeling

2.1 Exterior tire-road noise

A lot of models have already been developed for exterior tire-road noise and also reviewed [1], [2], [3]. The exterior tire-road noise models can roughly be grouped as:

- **Statistical models** (goal is to optimize road design.)
- **Hybrid models** (goal is to optimize tire-road design by extrapolation.)
- **Physical models** (goal is to optimize tire-road design by physical modeling.)
  - **Ring & Shell models** (2D & 3D, 0 - 300 Hz)
  - **Plate** (3D, 600 - 2000 Hz)
  - **FEM/BEM/WaveguideFEM** (3D, 0 - 3000 Hz)
  - **Submodels** (describe one physical phenomena only)

Statistical models relate measured data from road (roughness, absorption) to the measured SPL. As explained by Kuijpers [2] often these models treat the tire as “black box” because of lack of detailed information.

Hybrid models try to combine measured data from the tire and the road with some physical models to obtain a fast model that can be used for tire-road design purpose by extrapolating measurement data via physical modeling. The acoustic optimization tool is a good example of this approach [4].

Physical models often include more tire details. The majority of the physical models describe the vibrational behavior of the tire. An example of this vibration behavior is shown in Figure 2 where one can distinguish three different regions: Circumferential modes (red), lateral or cross sectional modes (green) and plate behavior. (blue)

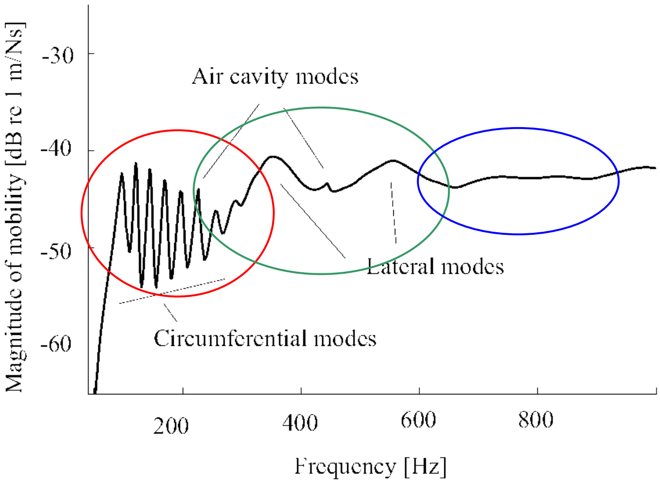

Figure 2: Radial driving point mobility for a smooth tyre excited in the middle of the tread [5].

A subsection of four different physical models can be made:

- Ring & Shell (2D or 3D) models describe the tire behavior until it's first cross sectional mode which is around 300 Hz for tire size 205/55R16 (red region). Kim and Bolton [6] describe a shell model and the models from Molisani [7] describe the acoustical-structural coupled resonances.
- Plate models are only valid above this frequency range and hence only describe the plate-like behavior of the tire at high frequency. (blue region). The TRIAS model from TNO [8] and the plate model form Larsson and Kropp [9] are two examples of this approach.
- FEM/BEM/Waveguide-FEM models can be valid for the whole frequency range, but their limitation is mainly determined by calculation times. Structural born mechanisms are often used as input to describe the tire-wheel vibrations. Boundary Element Methods are then used to describe the radiation characteristics of the vibrating tire-wheel combination. Biermann et al [10] have developed a complete FEM/BEM model whereas Nilsson investigated a faster Waveguide-FEM method [11].
- Different submodels exist which investigate only specific phenomena for example air pumping, pipe resonance, etc. These submodels can be included in the above mentioned BEM-model to complement the structure-borne mechanisms with aerodynamical mechanisms to obtain a complete description of the exterior tire-road noise for example air pumping submodel [12].

2.2 Interior tire-road noise

Less review work has been done on interior tire-road noise models. The intention of the survey is not to be complete but to distinguish, as for the exterior case, which kind of interior tire-road noise model approaches have been developed. One can distinguish four major groups:

- **Pitch sequence models** (goal is to optimize tread pattern)
- **NVH-simulators** (goal is define SoundQuality targets from jury-testing)
- **Hub vibrations / vibrational modal analysis** (goal is to describe the vibrational transmissibility of the tire-wheel combination.)
- **Full interior tire-road noise models**. (goal is to physically describe the interior tire-road noise)

A lot of different **pitch sequence models** have been developed, starting with Ewart in 1934. From that period on, pitch sequence modeling was mainly reported in the public domain by universities and with patents by tire companies. Although there are a lot of different approaches they all have the same goal of tread pattern optimization. The most simple pitch sequence model is a spatial Fourier transform of one tire circumference. This reveals the tread orders, as can be seen from Figure 3. A similar order spectrum can be obtained when averaging the experimental results of Figure 5 (bottom) along the order axis. It can be seen that the order spectrum between 30-47th orders is similar, but that this model is not capable of prediction other phenomena present in the measurement as road excitation transferring through the tire-wheel in the car (visible as low orders due to the averaging process) and the damping characteristics of the transferpath towards the car interior. It can thus be seen that pitch sequence tools have their limitations depending on the model approach and can not be used for a full prediction of the total interior or exterior tire-road noise. Varterasian [14] and Ejsmont [15] are examples of pure pitch sequence models.

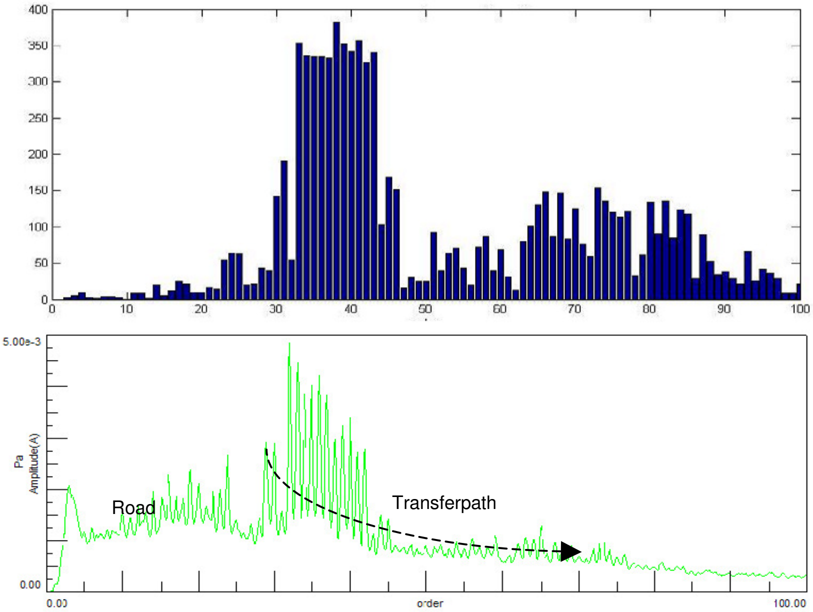

Figure 3: Modeling result from spatial Fourier transform (above) compared to measured interior order spectrum on road (below).

A second major group is from a more recent period and can be defined as **NVH-simulators**. These simulators are mainly based on operational (transfer path) measurements. Combined with some physical modeling they provide a sometimes full NVH-feeling of interior car noises. The main goal of this tooling is not to get a precise physical understanding of the phenomena, but to provide SoundQualityEngineers an engineering tool by which they can easily perform jury-evaluations and define SoundQuality-targets for developing cars and it's components. The method of jury-evaluation and SoundQuality-targets is useful to obtain objective market requirements for interior noise. Unless one would like to define very consumer specific tire-markets these SoundQualityMetrics can also be obtained by using measurement data from a free rolling situation. Frank [17] shows a model from which tire-road noise SoundQuality-targets can be defined.

The third group of **hub vibrational models** is less clearly distinguishable but they have the mutual goal to get physical understanding of how the tire-wheel combination plays a role in the structure borne interior tire-road noise. The tire-wheel models start from simple ring models up to fully coupled structural-acoustical FEM/BEM models. This group has some relationship with the ring/shell models mentioned earlier in the exterior case. It is a first step towards understanding interior tire-road noise, but two major draw backs can be drawn. One is that only structure-borne noise is considered which for winter tires and higher driving speeds is not so evident. The second is that hub vibrations are not the drivers evaluation points in the car. Some examples of this approach are Kindt [3], Molisani [7] and Kung [18].

Full interior tire-road noise models can be considered the most complete models where transfer path measurements have been combined with a full exterior tire road noise model as explained in Figure 1. In earlier days the computing power was limited, but nowadays a complete FEM/BEM tire models up to 1.000.000 DOF can be calculated within reasonable time. Saguchi [19] and Rustighi [13] are an example of this approach.

3 Experimental discussion on tire-road noise models

To determine which tire-road noise model approach is most promising we take a look at some experimental investigations performed by Apollo Vredestein B.V. A CPX set-up mounted on a car and capable of measuring exterior tire-road noise has been developed together with University of Twente and TNO [20].

Interior and exterior tire-road noise is measured simultaneously with the CPX-set up mounted on a car and two microphones at the headrest of the passenger seat, as shown in Figure 4.

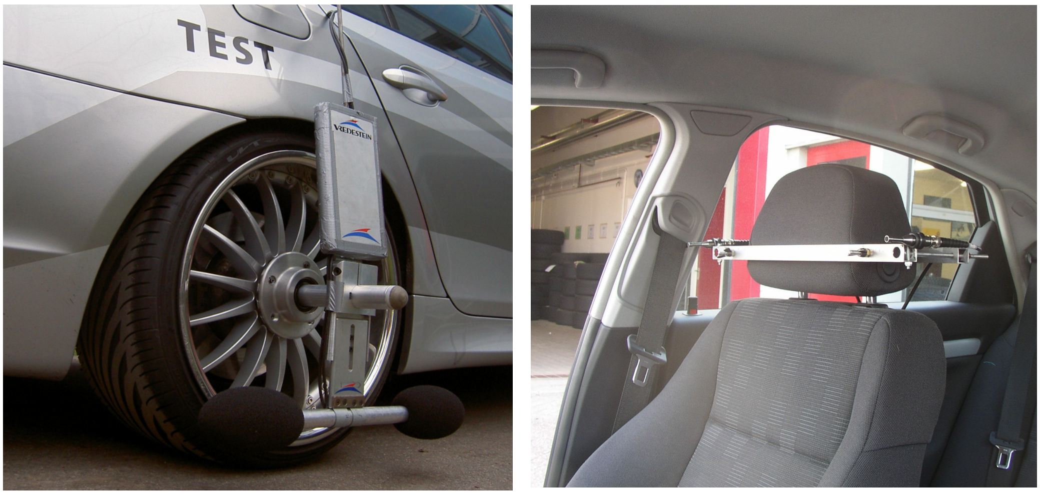

Figure 4: CPX-set-up and interior microphones in the same car for measuring interior and exterior tire-road noise simultaneously.

A, so-called, coast down can be performed by letting the car roll out from 90 km/h to 40 km/h with the engine shut down. In this way the no engine is present and due to the low speed wind noise is reduced. Figure 5 shows a result of the leading CPX-location (above) and right interior microphone (bottom) for one tire-road combination. This figure shows the A-weighted frequency spectrum of the sound pressure level during each tire revolution (vertical axis).

Noise-sources whose frequency-content is linearly related to the tire-revolution are thus shown by skew lines. The tread impact frequency is such an example and is easily calculated by

$$f = n\left[v / O\right] = n\omega \tag{1}$$

where f denotes the frequency [Hz], n is the tread order or the total number of tread blocks, v is the driving speed [m/s] and O is the tire circumference [m]. The term between brackets is simple the tire rotation frequency ω [Hz].

Resonances are not dependent on the tire rotation frequency and hence appear as vertical lines. For example the tire-cavity resonance is:

$$f = v / L \tag{1}$$

where L is the circumferential length in middle [m], v is the speed of sound [m/s].

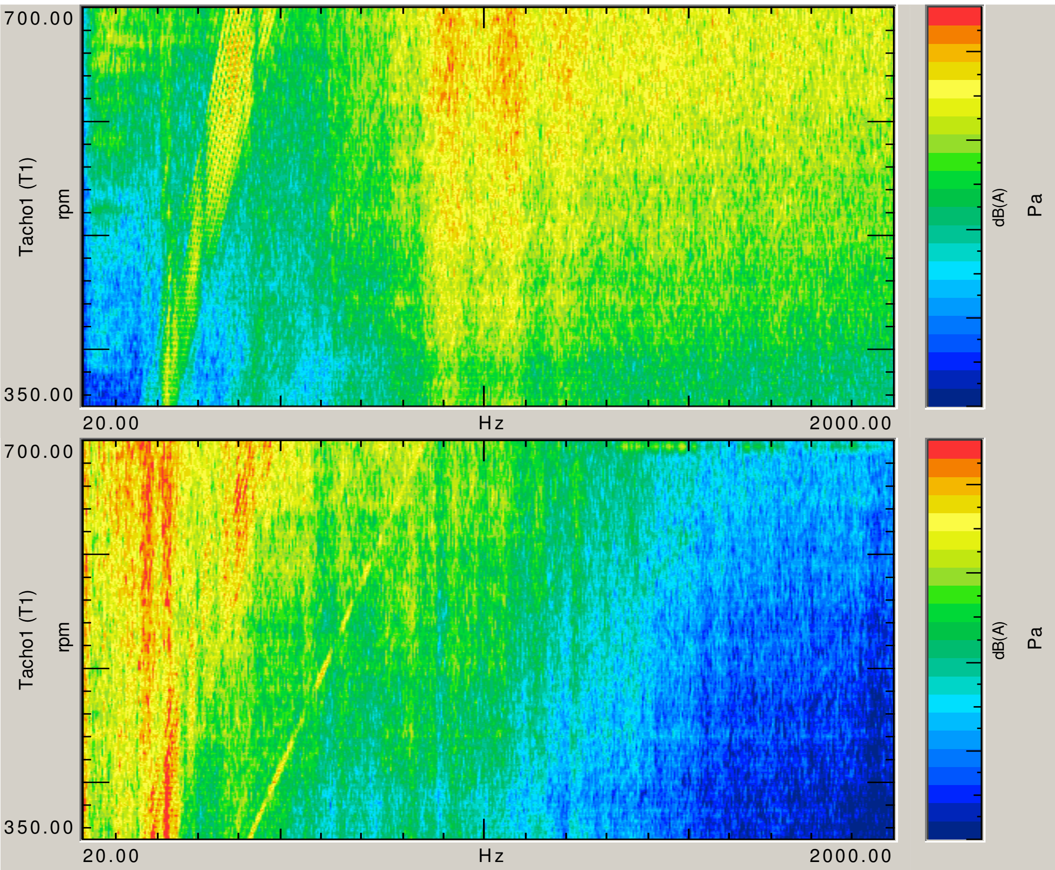

Figure 5: Coast down measurement of exterior noise at the leading CPX (above) and interior noise at right-ear passenger seat (below).

From Figure 5, one can clearly distinguish the tread orders in both the exterior and interior images. At the same time the exterior plot shows a peak around 1 kHz, referred to as the horn-effect [2], and a lot of speed-dependent high frequency noise above this peak, according to [2],[3] being the transient non-linear phenomena air pumping, stick/slip and stick/snap. Also the tire-wheel cavity resonance around 220 Hz can be distinguished. Predicting exterior tire-road noise thus means modeling the tread orders, the horn-effect and high frequency noise correctly,

In the interior plot next to the tread orders, low frequency structural resonances of the tire-wheel have high amplitudes and the acoustical tire-cavity resonance play an important role. Low frequency noise due to road roughness excitation is the major initiator of the tire-road noise. So for interior noise modeling one has to model tread and road excitation, structural (and acoustical) resonances of tire-wheel combination and the transfer paths into the car correctly.

From this experimental investigation one may conclude that interior and exterior tire-road noise are very different and can be modeled with two different approaches for example a ring/shell approach for interior and plate-approach for exterior tire-road noise. This model approach is of course correct, but from a tire-design point of view this is not an efficient combination to develop and use.

It is preferred to extend a full FEM/BEM exterior tire-road noise model with measured structure- and air-borne transfer path to obtain a full interior tire-road noise model because:

- Tire design is evidently put into both models
- Interior and Exterior noise can be optimized simultaneously
- Improvements for one model is automatically applied to the other (aerodynamic sources for example, structural-acoustical coupling, tread/road excitation)
- SoundQualityMetrics can be used to tune for market-requirements (for the measured cars)
- The interior tire-road noise model can in this way be used to tune for OE-specifications
- The FEM-model can also be used for other performances like rolling resistance, wear, etc.
- When applying a transient approach also non-lineair effects, cleat/puthole impacts, transient handling characteristics, etc can also be modeled.

4 Conclusions

With these considerations in mind we finalize the discussion. In this paper we distinguished three different groups of exterior tire-road noise models: (a) statistical models, (b) hybrid models and (c) physical models where the last one could be subcategorized as Ring/Shell models below 300 Hz, Plate models above 500 Hz, FEM/BEM-models for the whole frequency rang and submodels for specific (aerodynamic) phenomena.

At the same time four different groups of interior tire-road noise models have been distinguished: (1) Pitch sequence models (goal tread pattern optimization), (2) NVH-simulators (goal SQM-research), (3) Hub vibrations / Vibrational modal analysis (goal physical understanding tire-wheel contribution), (4) Full interior tire-road noise models. (goal physical understanding and prediction of interior tire-road noise).

Experimental results from a coast down measuring simultaneously interior and exterior noise shows that for exterior noise the tread orders, horn effect and high frequency noise has to be modeled correctly. For interior noise the tread and road excitation, structural (and acoustical) resonances of tire-wheel combination and the transfer paths into the car has to be modeled correctly. From a tire-design point of view a full interior tire-road noise model should be based on a FEM/BEM exterior tire-road noise model and measured transfer paths.

Acknowledgements

The authors want to thank Apollo Ltd and Apollo Vredestein B.V. for granting permission to publish and the University of Twente for their cooperation.

References

[1] U.Sandberg, J.A.Ejsmont, *Tyre/road noise reference book,* Informex, Harg, Sweden (2002).

[2] A.H.W.M..Kuijpers, G.J.van Blokland, *Tyre/road noise models in the last two decades: a critical evaluation, Proceedings of The 2001 International Congress and Exhibition on Noise Control Engineering, the Hague, The Netherlands, 2001 August 27-30,* The Hague (2001).

[3] P. Kindt, *Structure-brone tyre/road noise due to road surface discontinuities*, Katholieke Universiteit Leuven, Departement Werktuigkunde, Leuven (1997).

[4] A.H.W.M.Kuijpers, H.M.Peeters, W.Kropp, T.Beckenbaurer, *Acoustic Optimization Tool, RE4 modeling refinements in the SPERoN framework*, M+P consulting engineers, 2007.

[5] P.Andersson, K.Larsson, F.Wullens, W.Kropp, *High frequency dynamic behavior of smooth and patterned passenger car tyres,* Acta Acustica united with Acustica, Vol 90, S. Hirzel Verlag (2004), pp 445-456.

[6] Y.J.Kim and J.S.Bolton, *Effects or rotation on the dynamics of a circular cylindrical shell with the application to tire vibration, Journal of Sound and Vibration*, 275:605-621, 2004.

[7] L.R.Molisani, A coupled tire structure-acoustic cavity model, Virginia Polytec Institute and State University, Blacksburg, Virginia, The united States of America, 2004

[8] K.Larsson and W.Kropp, *A High frequency three-dimensional tyre model based on two coupled elastic layers, Journal of Sound and Vibration*, 253 4):889-908, 2002.

[9] F.de.Roo, E.Gerretsen, H.Mulder, *Predictive performance of the tyre-road noise model TRIAS, Proceedings of The 2001 International Congress and Exhibition on Noise Control Engineering, the Hague, The Netherlands, 2001 August 27-30,* The Hague (2001).

[10] J.Biermann, O.von.Estorff, S.Petersen, H.Schmidt, *Computational model to investigate the sound radiation from rolling tires*, Tire Science and Technology, Vol. 35, No 3, July-September 2007, pp 209-225.

[11] C.M.Nilsson, *Waveguide finite elements applied on a car tyre,* Royal institute of Technology, Department of Aeronautical and Vehicle Technology, Stockholm, Sweden (2004).

[12] M.J.Gagen, *Novel acoustic sources from squeezed cavities in car tires, Journal of Acoustical Society of America,* Vol 106, No 2, August 1999 pp 794-801.

[13] E.Rustighi, S.J.Elliott and S.Finnveden et al, *Linear stochastic evaluation of tyre vibration due to tyre/road excitation,* Journal of Sound and Vibration, 310:1112-1127, 2008.

[14] Varterasian, *Quieting noise mathematically – its application to snow tires*, Society of Automotive Engineers, Mid-Year meeting, Chicago, May 19-23 1969

[15] J.Ejsmont, *Tire/road noise simulation for optimization of the tread pattern, Proceedings of The 2000 International Congress and Exhibition on Noise Control Engineering, Nice, France, 2001 August 27-30,* The Hague (2000).

[16] Bridgestone, *Method for designing tire noise pitch sequence*, European Patent, EP 2135751 A2, 31-October 2003.

[17] E.C.Frank, D.J.Pickering, C.Raglin, *In-vehicle tire sound quality prediction from tire noise data*, SAE International, 2007-1-2253, 2007

[18] L.E.Kung, *On the vibration transmission of a rolling tire on a suspension system due to periodic tread excitation,* Journal of Sound and Vibration, Vol. 115, No 1, 1987, pp.37-63.

[19] T.Saguchi, T.Tomida, S.Urata, K.Kato, *Tire radiation-noise prediction using FEM, Proceedings of Inter-Noise 2006, Honolulu, Hawaii, USA, 2006, December 3-6.*

[20] D.A.Bekke, *The development of a CPX-measurement set-up capable of measuring tire-road noise effectively, Proceedings of NAG-DAGA 2008, the Hague, The Netherlands, 2009 March 23-2.*