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CONTRACT N°	TIP4-CT-2005-516420																																																																																	
PROJECT N°	FP6-516420																																																																																	
ACRONYM	QCITY																																																																																	
TITLE	Quiet City Transport																																																																																	
Subproject	5																																																																																	
Work Package	5.5																																																																																	
	Implementation of measures at validation sites Validation site Göteborg Mechanical Model for Tyre Vibrations including Road Surface Compliance Deliverable D5.19 "Quantify predicted benefits" is merged into this deliverable.																																																																																	
Written by	Odd Sylwan and Nils-Åke Nilsson ACL																																																																																	
Date of issue	2009-01-30																																																																																	
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PROJECT START DATE	February 1, 2005																																																																																	
DURATION	48 months																																																																																	
	Project funded by the European Community under the SIXTH FRAMEWORK PROGRAMME																																																																																	
	PRIORITY 6 Sustainable development, global change & ecosystems																																																																																	

This deliverable has been quality checked and approved by QCITY Coordinator
Nils-Åke Nilsson

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0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

The objective of this deliverable is to better understand how a softer road surface could possibly reduce the external tyre/road noise. By better understanding the active mechanisms for noise reduction will also provide a tool for further optimization of the parameters of compliant road surfaces, such as optimizing the amount of crumb rubber and the type of bitumen binder used etc.

0.2 STRATEGY USED AND/OR A DESCRIPTION OF THE METHODS (TECHNIQUES) USED WITH THE JUSTIFICATION THEREOF

The strategy is to establish a theoretical model in which measured mobilities of the road surface and the tyre will form input data.

0.3 BACKGROUND INFO AVAILABLE AND THE INNOVATIVE ELEMENTS WHICH WERE DEVELOPED

The innovative element in this deliverable is that we start with the existing model for the wheel / rail –system and extending this model to cover also the tyre/road system.

0.4 PROBLEMS ENCOUNTERED

See chapter 4 – A critical review.

0.5 PARTNERS INVOLVED AND THEIR CONTRIBUTION

ACL

0.6 CONCLUSIONS

Even if the here presented contact model could be refined in many ways we believe that we have caught some of the major features that has to be addressed when designing and predicting low noise compliant road surfaces at least for standard car tyres rolling straight forward with constant speed on rough standard roads as well as “rubberized asphalt” surfaces.

0.7 RELATION WITH THE OTHER DELIVERABLES (INPUT/OUTPUT/TIMING)

D5.5 Performance report on applied measures.

1 INTRODUCTION

A mobility based theoretical model has been developed to judge the influence on the sound power radiated from tyre/road-systems due to increased road surface compliance such as “rubberized asphalt”.

This is because there is no direct measurement method available. Another reason is that a simulation tool is needed for minimizing the tyre/road noise generation.

In this document the theoretical model is presented as well as some examples of measured mobilities on tyre and road surfaces for extraction of input data.

2 THEORETICAL MODEL

2.1 REMINGTON'S MODEL FOR ROUGHNESS-INDUCED VIBRATIONS IN THE WHEEL/RAIL-SYSTEM

Remington's model /1/ /2/ is designed for describing the vertical and lateral contact conditions of a wheel-rail system. Matrix formulations are not necessary, as the wheel/rail contact patch can be considered as one single contact point at least up to fairly high frequencies.

For example, a vertical fraction of the relative wheel/rail roughness ($j\omega \Delta x$) will be transferred to the wheel contact patch (u_{wheel}) according to the following equation:

$$u_{wheel} = j\omega \Delta x \cdot Y_{wheel} / (Y_{wheel} + Y_{rail}) = j\omega \Delta x / (1 + Y_{rail} / Y_{wheel}) \quad \dots \dots \dots (1)$$

where

- u_{wheel} = vertical vibration velocity of wheel contact patch, m/s
- Δx = relative roughness of wheel/rail contact patch, m
- Y_{rail} = vertical complex point mobility of rail, m/Ns
- Y_{wheel} = vertical complex point mobility of wheel, m/Ns

The vertical complex point mobilities involved are illustrated in figure 1.

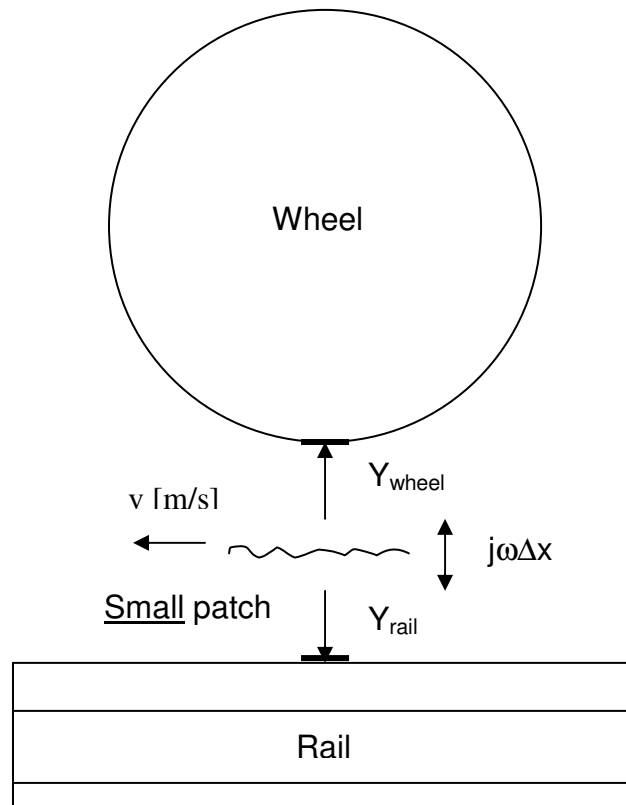


Figure 1 Vertical point mobilities of a wheel/rail system.

2.2 EXTENSION OF REMINGTON'S MODEL TO BE VALID ALSO FOR A TYRE/ROAD SYSTEM

2.2.1 The complete multiple contact model leading to matrix formulation

Remingtons model can not be used directly for describing the vertical contact conditions of a tyre/road-system, as there are many local contact patches (100 – 200 units) within a tyre/road contact surface. Instead, it is necessary to extend equation (1) to corresponding matrix formulation as follows:

$$\{u_{\text{tyre}}\} = [Y_{\text{tyre}}] \cdot [[Y_{\text{tyre}}] + [Y_{\text{road}}]]^{-1} \cdot \{j\omega \Delta x\} \quad \dots \dots \dots (2)$$

where

- $\{u_{\text{tyre}}\}$ = vertical vibration velocity column vector of tyre contact patches, m/s
 $\{\Delta x\}$ = relative roughness column vector of a rough road, m
 $[Y_{\text{road}}]$ = vertical mobility matrix of road contact surface (big stones), m/Ns
 $[Y_{\text{tyre}}]$ = vertical mobility matrix of tyre contact patches, m/Ns

Theoretically, the individual mobility elements of the sub-matrices $[Y_{\text{tyre}}]$ and $[Y_{\text{road}}]$ in (2) can be measured on the free tyre and road surfaces. The combined matrix $[[Y_{\text{tyre}}] + [Y_{\text{road}}]]$ can then be created from these measured individual mobility elements. On the other hand, the corresponding impedance matrix $[[Y_{\text{tyre}}] + [Y_{\text{road}}]]^{-1}$ in (2) can be achieved only by inverting the full mobility matrix $[[Y_{\text{tyre}}] + [Y_{\text{road}}]]$. However, this is not feasible for measured mobility data as the errors of the column vector $\{u_{\text{tyre}}\}$ would be too big (due to that the matrix could be what is called "bad-conditioned").

2.2.2 Simplification of the matrix model to a scalar model.

If all matrix elements of each sub-matrix $[Y_{\text{tyre}}]$ and $[Y_{\text{road}}]$ and column vector $\{j\omega \Delta x\}$ could be considered as equal, then it would be possible to use the simple scalar Remington model (1) to calculate one representative element u_{tyre} **of the column vector** $\{u_{\text{tyre}}\}$ (thus using one single contact point only).

This would be possible if the following conditions are met:

1. The roughness of a rough road is evenly and randomly distributed over the contact surface of the tyre/road system.
2. The contact conditions (mobilities) of the tyre/road surface are equal for each individual contact point (i.e. big stone penetrating rubber surface).
3. The point mobility of the road surface (big stone) is "locally reacting".
4. The point mobility of tyre patch ($\phi=3-5$ mm) is "locally reacting".
5. There are no significant Doppler effects on the tyre patch mobilities (Mach < ca 0.3).
6. There are no significant non-linear effects on the tyre patch mobilities.

If all these 6 assumptions are fulfilled, then each matrix in (2) will contain equal diagonal elements and all off-diagonal elements will be zero. Then (2) will degenerate into the following **scalar** Remington equation:

$$u_{\text{tyre}} = j\omega \Delta x \cdot Y_{\text{tyre}} / (Y_{\text{tyre}} + Y_{\text{road}}) = j\omega \Delta x / (1 + Y_{\text{road}} / Y_{\text{tyre}}) \quad (3)$$

where

- u_{tyre} = vertical vibration velocity of tyre patch ($\phi=3-5$ mm), m/s
- Δx = relative roughness of a rough road, m
- Y_{tyre} = vertical complex mobility of tyre patch ($\phi=3-5$ mm), m/Ns
- Y_{road} = vertical complex point mobility of road surface (big stone), m/Ns

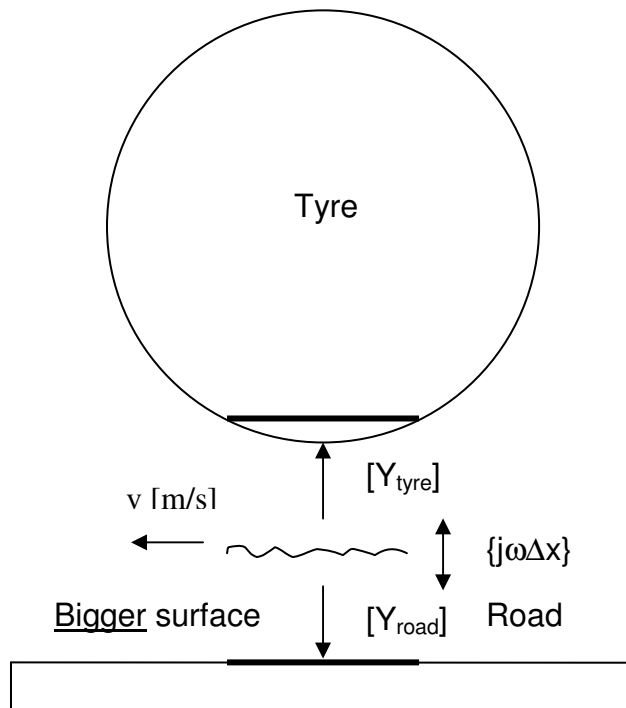


Figure 2 Vertical point mobilities of a tyre/road system.

If the conditions 3 and/or 4 above are not met, then the mobilities in (3) must be corrected before use. For frequencies within about 500 – 2 kHz the corrected tyre and rough road mobilities can be approximated by the following expressions based on measured mobilities:

$$Y_{\text{tyre}} = j\omega/k_{\text{tyre}} + 1/Z_{\text{tyre}} + \text{NLR-tyre correction} \quad \dots \dots \dots (4)$$

$$Y_{\text{road}} = j\omega/k_{\text{road}} + \text{NLR-road correction} \quad \dots \dots \dots (5)$$

$$\text{NLR-tyre correction} = 1/j\omega m_{\text{corr}} \quad \dots \dots \dots (6)$$

$$\text{NLR-road correction} = j\omega/k_{\text{corr}} \quad \dots \dots \dots (7)$$

where

- NLR = Non-Local-Reacting (tyre and road corrections, m/Ns)
- $1/Z_{\text{tyre}}$ = transfer mobility (side-by-side) of tyre contact ($\neq Y_{\text{tyre}}$), m/Ns
- k_{tyre} = local stiffness of tyre contact patch ($\phi = 4$ mm), N/m
- k_{road} = local stiffness of rough road (big stone), N/m
- $1/m_{\text{corr}}^1$ = contributing accelerance of neighbouring contact patches, 1/kg
- $1/k_{\text{corr}}^2$ = contributing compliance of neighbouring bigger stones, m/N
- $j\omega$ = $(-1)^{0.5} \times$ (angular frequency), 1/s

¹ $1/\omega m_{\text{corr}}$ = Σ off-diagonal matrix mobility elements for tyre contact surface. The quantity m_{corr} is identified from measured noise level spectrum shapes of standard car tyres running on rough roads (other quantities are based on mobility measurements). 195/205 std car tyres at 1 kHz: $m_{\text{corr}} = 0,01$ kg, $k_{\text{tyre}} = 3E5(1+j0.15)$ N/m for 69° Shore and $Z_{\text{tyre}} = 110$ Ns/m

² ω/k_{corr} = Σ off-diagonal matrix mobility elements for road contact surface. The quantity k_{corr} (and k_{road}) are identified from measured mobilities for rough road surfaces (big stones). Eklandagatan/Kärraverket 2007 at 1 kHz: $k_{\text{corr}} = k_{\text{road}}/0,6$ N/m where $k_{\text{road}} = 1.5E6(1+j0.8)$ N/m

3 PRACTICAL CONSEQUENCES OF THE ACOUSTICAL TYRE/ROAD CONTACT MODEL

3.1 TYPICAL MOBILITIES FOR CURRENT TYRE AND ROAD DESIGNS

Figure 3 shows an example of a measured patch/point mobility spectrum for a typical 195 standard car tyre (Hydragrip).

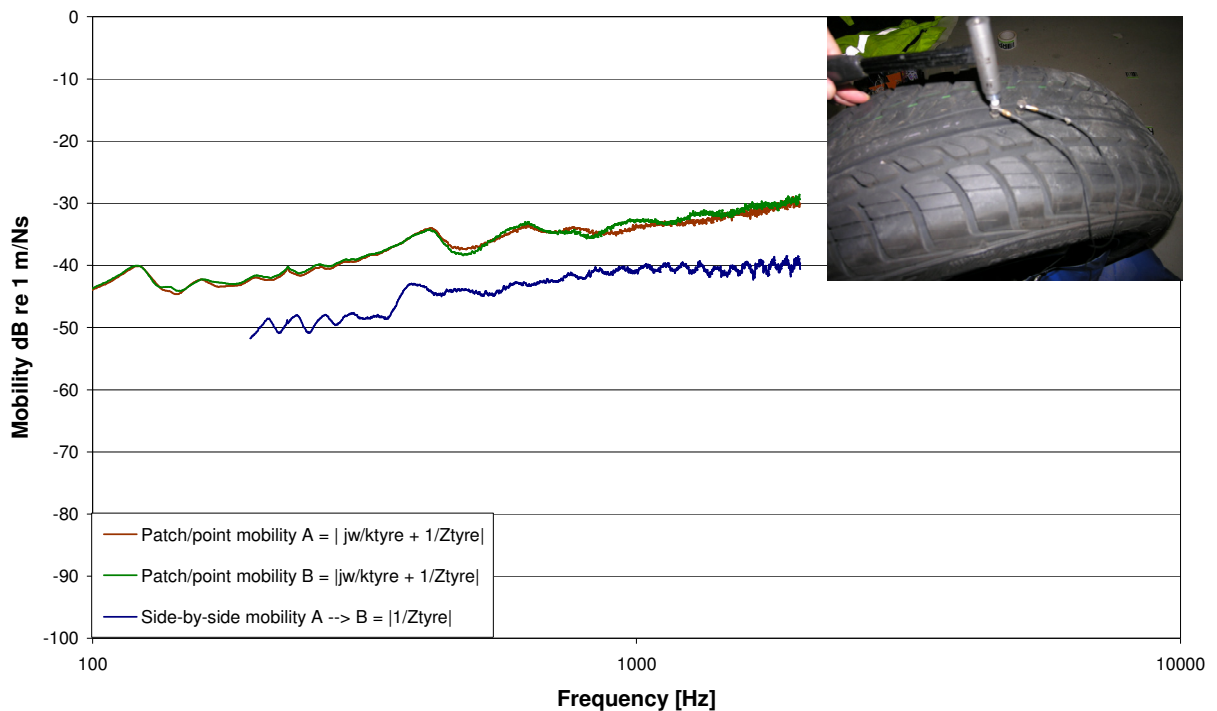


Figure 3 The patch/point (Y_{tyre}) and side-by-side ($1/Z_{tyre} \neq Y_{tyre}$) mobilities of a 195 standard car tyre.

In figure 3 the local stiffness k_{tyre} ($= 3E5$ N/m at 1 kHz) is included in A and B for an unloaded patch diameter of $\phi = 8$ mm, which is estimated to be equivalent to a loaded patch diameter of approximately $\phi = 4$ mm.

Figure 4 shows examples of measured point impedance spectra for big stones ($= 1/\text{point mobility}$) on rough road surfaces including roads with excess compliancy.

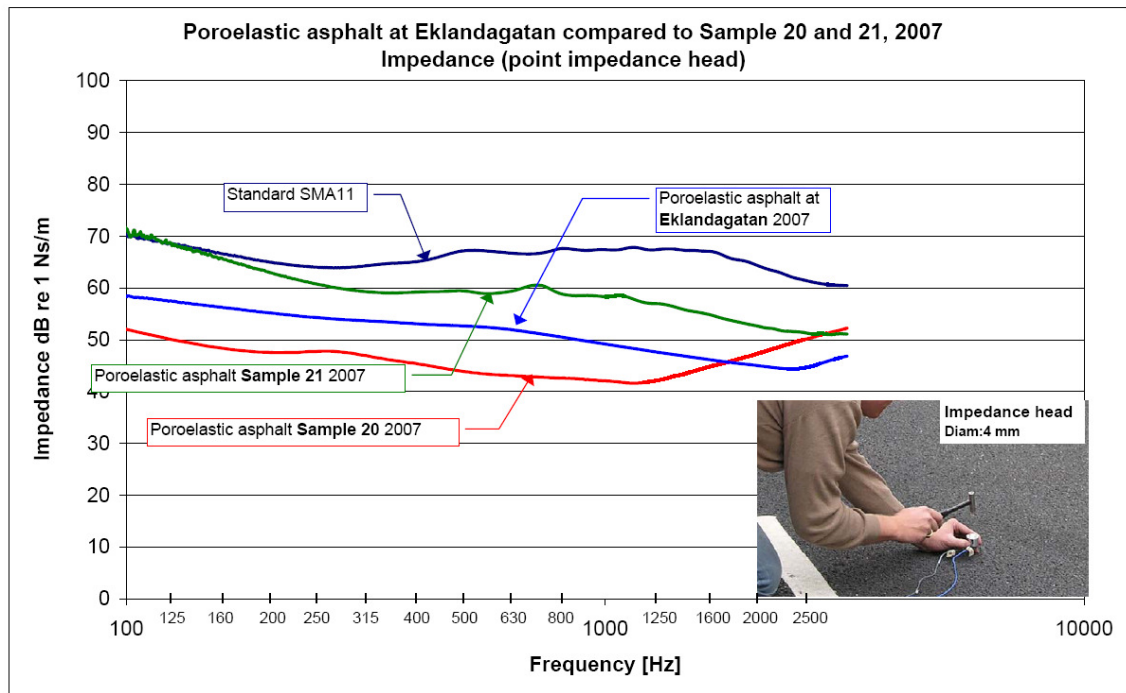


Figure 4 Examples of measured point impedance spectra on one rough road “rubberized asphalt” surface (max stone size 8 mm) and two laboratory “rubberized asphalt” samples.

3.2 WHEN WILL A COMPLIANT ROAD SURFACE REDUCE NOISE

According to (3), the **Gain** of using a compliant rough road surface compared to corresponding non-compliant road can be expressed as follows:

$$\text{Gain} = 20 \cdot \text{LOG} \left| 1 + Y_{\text{road}} / Y_{\text{tyre}} \right| \dots \dots \dots (8)$$

$$\text{Gain} = 20 \cdot \text{LOG} \left| 1 + (1/k_{\text{road}} + 1/k_{\text{corr}}) / (1/k_{\text{tyre}} - j/\omega Z_{\text{tyre}} - 1/\omega^2 m_{\text{corr}}) \right|$$

It can be concluded from (3) and (8) that the point mobility of the rough road surface $|Y_{\text{road}}|$ needs to be comparable to or greater than the mobility of the tyre $|Y_{\text{tyre}}|$ including the local stiffness of the contact patch. If so the compliance of the rough road surface will, to varying degree, result in noise reduction. For the tested durable rough road “rubberized asphalt” surfaces (max stone size 8 mm) and tyres the road compliance effect is though,

according to the model, limited to just about $1 - 2^{1,2,3}$ dB(A) units when compared to a non-compliant road surface and about 0.5 dB(A) less when compared to a standard road surface (ABT11). This is expected for typical 195/205 standard car tyres.

3.3 IMPLICATIONS FOR TYRE DESIGNS

In previous deliverables it has been quite convincingly revealed that decreased transfer or side-by-side mobility to the tyre rubber belt ($1/Z_{\text{tyre}}$ i.e. stiffness of local contact patch not included) leads to decreased noise (shown both by UCAM (for polyurethane filled tyres) and GOOD for standard and spare tyres). However, in most of these cases the rubber stiffness of the contact patches has not been changed (i.e. same rubber quality). Then the tyre contact patch mobility (i.e. Y_{tyre} stiffness of local contact patch included) will be decreased much less³ than the corresponding side-by-side mobility (i.e. $1/Z_{\text{tyre}}$ stiffness of local contact patch not included).

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- 1 According to (8) a noise level reduction of about **0,7** dB(A) is expected for "Tagenevägen 2006" and also for corresponding laboratory "rubberized asphalt" specimen "Prov 21 2007", **1.8** dB(A) for "Eklandagatan/Kärraverket 2007" and **3.7** dB(A) for a softer laboratory "rubberized asphalt" specimen "Prov 20 2007" (all cases with max stone size 8 mm) when compared to a non-compliant road surface. At the resonance frequency ($\approx 1 \text{ kHz} = (1/2\pi)(k_{\text{tyre0}}/m_{\text{corr}})^{0.5}$), the noise level reduction is expected to achieve approximately a two times greater maximum value (in dB) than indicated above for the overall reductions. No reductions are expected below 500 Hz. A noise level reduction of about **0.3** dB(A) is expected for a standard road surface (ABT11) when compared to a non-compliant road surface.
 - 2 However, recent mobility measurements on some poroelastic road samples indicate that the aging process of the Polymer Modified Bitumen (PMB) after some years might result in both increased road roughness (wear effects) and decreased road surface mobilities (increased hardness). This long term aging process of the poroelastic road surface will result in increased rolling noise levels compared to the lower noise levels of a tyre rolling on corresponding new poroelastic road surface. Probably the noise level increase rate will be very low during the first year of operation, as the wear will result in both increased road roughness and increased road mobilities during this early period of time (i.e. the increased road mobilities will reduce or neutralize the noise level increase caused by the road roughness increase). After this early period of time the long term hardening effects of the poroelastic road surface will be gradually more significant, which will result in increased noise levels.
 - 3 Adding an extra rubber layer inside the tyre will increase the **Gain** according to (8) at lower frequencies (i.e. less than 1 kHz) and decrease the **Gain** at higher frequencies (i.e. greater than 1 kHz), by decreasing the NLR-quantity $1/j\omega m_{\text{corr}}$. However, the resulting overall gain in dB(A) by decreasing this NLR-value is very small. Unfortunately, the dominating quantity $j\omega/k_{\text{tyre}}$ in Y_{tyre} is not influenced by this extra rubber layer as k_{tyre} is a function of the Young's modulus and plate diameter only. The quantity $1/Z_{\text{tyre}}$ in Y_{tyre} is significantly decreased by the extra rubber layer, but as $|1/Z_{\text{tyre}}|$ is small compared to $|j\omega/k_{\text{tyre}}|$ at most frequencies (fig 3), $1/Z_{\text{tyre}}$ will almost not influence Y_{tyre} .

However, according to the tyre/road contact model presented in 2.2.2 a significant decrease in the tyre contact patch mobility $j\omega/k_{\text{tyre}}$ (e.g. by increase of rubber shore index thus Young's modulus and/or contact patch diameter) will improve the mobility relationship for the case where the road mobility is near the tyre mobility. Thereby lower tyre contact patch mobility provides a potential for further noise reduction from road surfaces with high compliance^{1,2,3}.

During the last 20 years the shore index for standard car tyres has been increased from typically 60° to 67 – 70° Shore. This hardness trend has contributed to reduce the excitation of tyre noise and vibrations more than earlier expected regarding modern tyres running on compliant road surfaces like "rubberized asphalt" (see footnote¹ on page 12 where 1.8 dB(A) for "Eklandagatan/ Kärraverket 2007" at 69° Shore is only 0,8 dB(A) at 60° Shore in the tyre contact surface).

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- 1 The resulting overall gain in dB(A) can be roughly estimated from **Gain** $\approx 20 \cdot \text{LOG}(1 + 1.6 |k_{\text{tyre}}/k_{\text{road}}|)$, where $|k_{\text{tyre}}| \approx 3E5 \cdot (\text{max stone size [mm]} / 8)$, as long as $|\omega/k_{\text{tyre}}|$ is significantly greater than $|1/Z_{\text{tyre}}|$.
 - 2 Note that this expression doesn't contain any damping quantities of the tyre/road system, although such quantities are included in the theoretical model. This is indicated in the example of footnote 1 stating that the complex point stiffness of the tyre ($\phi = 4$ mm) is $k_{\text{tyre}} = 3E5(1+j0.15)$ [N/m] – thus the loss factor is 0.15 (rubber damping is dominating). However, increasing the loss factor of the tyre stiffness will not influence very much the **Gain** according to (8), as the loss factor contribution to k_{tyre} resulting from Z_{tyre} only (apparent or propagational damping is dominating) is as much as three times greater than the rubber damping (0.15) or just about 0.45 at 1 kHz. Then the total loss factor is about 0.6.
 - 3 In the field studies of poroelastic road surfaces damping is also included since the binder is Polymer Modified Bitumen (PMB). This is indicated in the example of footnote 2 saying that the complex point stiffness (big stone) of the road is $k_{\text{road}} = 1.5E6(1+j0.8)$ [N/m] – thus the loss factor is as much as 0.8. A great portion of 0.8 results from apparent damping and the rest of bitumen damping. Unfortunately, road damping of any kind (apparent or bitumen) is not expected to increase the **Gain** according to (8).

4 THE ACOUSTICAL TYRE/ROAD CONTACT MODEL. A CRITICAL REVIEW

4.1 DIAMETER OF THE CONTACT PLATE USED FOR MOBILITY MEASUREMENTS

During mobility measurement a contact plate with diameter d (mm) is used. The apparent stiffness is grossly determined by the selected diameter of the contact plate. We selected a plate diameter of 4 mm for our measurements thus resembling an estimated average stone-to-tread-block contact diameter for road surfaces (critical assumption) with a maximum stone size of 8 or 11 mm. Greater plate diameter would result in lower tyre mobilities, but lower mobilities partly also in the road surface, and thus a more favourable relationship between the tyre and road mobilities could arise regarding the noise reduction effect from high road surface compliance. So the net noise reduction seen by the mobility measurements could in part be dependent on the selected diameter of the contact plate.

4.2 TANGENTIAL SLIP

The model only includes the excitation and point mobilities in vertical direction. Tangential tread block vibrations or other vibrations in horizontal direction is not included in the model. If e.g., tangential vibrations would be reduced (both by its compliance in vertical and horizontal direction) by a high compliant road surface resulting in lower total sound emission from the tyre/road system, this cannot be handled by the current contact model. However, our investigations indicate that tangential tread block vibrations in horizontal direction must not be added to the modified Remington model, which is aimed for standard car tyres rolling on rough road surfaces.

4.3 CONTACT AIR PRESSURE PULSATIONS

Contact Air Pressure Pulsations mean that noise is generated in the thin gap between the tyre and road contact surfaces caused by contact air pressure and air flow variations in the remaining cavities between the tyre and road surface when the tyre is rolling. Such effects are expected to contribute significantly to the tyre noise contribution for frequencies above about 1.0 kHz. Generated noise by Contact Air Pressure Pulsations is expected to be reduced somewhat less than already indicated by the acoustical tyre/road contact model for any selected compliant road surface.

4.4 STICK-SLIP AND STICK-SNAP EFFECTS

Stick-slip and stick-snap effects mean vibrations generated in the tyre contact surface caused by time dependent horizontal friction and radial adhesive contact forces when the tyre is rolling. Such effects are not expected to contribute significantly to the tyre noise contribution at least when the tyre is rolling straight forward with constant speed on any rough road surface.

4.5 NON-LINEARITY IN THE CONTACT PROCESS

Measurements of tyre mobilities during in-service rolling conditions are very difficult to perform. However measurements at lower frequencies (ride dynamic properties) by shaking the entire tyres indicate that the mobility at lower frequencies goes down with increased speed from 1-20 km/h. (Tests at Birmingham University, Dept of Mech Eng). If this is true also at higher frequencies and in particular more locally in the contact patch then this could mean that the mobility relationship can be more favourable at rolling conditions compared to stationary.

4.6 STATIONARY COMPARED TO ROLLING TYRE MOBILITIES

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5 CONCLUSIONS

Even if the here presented contact model could be refined in many ways we believe that we have caught some of the major features that has to be addressed when designing and predicting low noise compliant road surfaces at least for standard car tyres rolling straight forward with constant speed on rough road standard as well as “rubberized asphalt” surfaces.

6 REFERENCES

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