ODSURF project: modelling and experimental optimization of low noise pavements

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ABSTRACT
ODSURF project, funded by ADEME in France and BASt in Germany, was dedicated to the development and implementation of new low-noise road pavement technologies and new materials adapted to the urban environment. Original solutions including porous and dense structures have been conceived, implemented and tested on-site. Meanwhile, new predicting models for vibration mechanisms, air-pumping and horn effect have been developed to better characterize various physical phenomena during the rolling of a tyre on a textured pavement. Besides the modelling approach, this project had a strong experimental component, necessary for model validation and acoustic classification of road surfaces. Measurements were carried out on test tracks and on sites, in France and Germany, where optimized industrially designed or conventional coatings were implemented. Finally, the common database “DEUFRABASE” already developed during a previous project has been improved. It includes noise emissions produced by passenger cars and heavy vehicles traveling on a large panel of French and German road pavements for various propagation and traffic configurations. Updated at the end of the project, this database will be soon available for free on a website hosted by Ifsttar.

Keywords: Low noise pavements, Tyre-road noise, Optimization, Database
I-INCE Classification of Subjects Number(s): 11.7.1, 52.3

1. INTRODUCTION

In recent years, various documents were published in Europe to establish for the coming years a noise reduction strategy (at least 30%) related to road transport. To this end, many European cities have shown interest in the use of low noise road pavements to comply with the requirements of the European Directive 2002/49/EC. Noise reduction at the source is the first step in the reducing noise process perceived by city residents. In urban areas also, a significant part of the noise emission is due to rolling noise. Two solutions can be considered: reducing the part due to the tyre or that due to the pavement. In this project, we will only discuss on the road impact.

In the past, porous coatings have been tested in urban areas. Even if their effects were substantial at the beginning of their life, the gradual clogging of the porous structure significantly reduced their noise absorption characteristics after several years of service. In fact, at low speed, vehicles do not provide enough self-cleaning of the porous layer to maintain their acoustic performances. In the urban environment, it was becoming urgent to do research on low noise dense pavement structures. Some interesting projects have shown the feasibility of this type of surface. However, acoustic performances comparable to porous structures have not been actually achieved.

Following the results obtained during the previous project DEUFRAKO-P2RN "Prediction and Propagation of Rolling Noise” (1), a theoretical dense surface texture, providing a minimal rolling noise comparable to a single-layer porous asphalt was designed. The resulting surface texture being very different from the conventional ones, the in-situ realization of this texture with conventional techniques and materials has not produced the expected results.

To ensure constant quality of the surface layer, prefabrication techniques have been favored in the ODSURF project. Such solutions allow on one hand, a better maintenance and on the other hand, an
easier repairing after works. Existing solutions need to be optimized. The design and manufacturing issues were mainly supported by German partners while French partners have been more involved on the modelling aspect, the experimental validation after implementation and comparison with respect to more conventional optimized techniques.

Finally, the updating of the DEUFRABASE database, developed during the previous P2RN project was completed.

2. PRODUCTION OF OPTIMIZED ROAD PAVEMENTS (2)

2.1 German Contribution

From a theoretical point of view, and according to the results obtained during the P2RN project (1), it is possible to create a dense pavement with an optimized texture able to produce sound levels of the same magnitude, or even lower than a porous pavement. Conventional techniques used during P2RN project have shown their limits. New concepts have been developed in order to approach the characteristics predicted by the calculation.

These new concepts are based on innovative pavement surfaces, prefabricated, that reach several acoustic, safety and durability criteria. To achieve these objectives, a tender was launched by the German financer (the German Federal Highway Research Institute - BASt with support of the German Ministry for Transportation). Various manufacturers, consulting companies and universities applied for this call. Three projects were selected:

- a low noise surfacing using prefabricated structures made of high performance cement concrete with a texture similar to that determined in the P2RN project;
- a road surface made of porous cement concrete pavers;
- a surface layer using synthetic materials.

The three processes were implemented and tested on experimental sites. However, the first two techniques have been measured for traffic conditions close to actual urban and suburban environments. In addition to acoustic characteristics, surface texture and skid resistance measurements were carried out to check the security criteria.

Some of the main results are presented in (3).

2.2 French Contribution

During this project, the French works were distributed into three main parts: a large experimental contribution, an improvement of the theoretical models used for the rolling noise prediction and the improvement and the updating of the common German-French database (DEUFRABASE) previously developed and implemented during the former P2RN project (1). In the current section, we will develop our experimental contribution.

2.2.1 Experimentation on Real Road Sites

In recent years, French companies have been widely involved in research programs related to the improvement of the acoustical characteristics of wearing courses with respect to tyre-road noise. The partner companies have provided to the project consortium various sites on which were implemented innovative low noise pavement structures in order to test and compare their characteristics to the French reference coatings and innovative German structures briefly presented in the previous section.

The coatings used in this project are Very Thin Asphalt Concrete (VTAC) made of small-sized aggregates (0/4 mm and 0/6 mm).

A first test track in VTAC 0/4 is located on a 2x2 lane suburban boulevard: RD 670 located in Northern France (Mouvaux) (Figure 1). The speed limit on this site is 70 km/h. This 500 m long test track was built in 2009. It was about 5 years old when the experimental campaign was held in July 2014. This VTAC 0/4 is an acoustically optimized pavement because of its small aggregate size (0/4 mm) and its regular shaped communicating pores network. On this site were carried out 3D texture measurements, absorption by the standard method ISO 13472-1 and rolling noise simultaneously by Coast-By (CB) and Close-Proximity (CPX) methods.

The second test track in VTAC 0/6 is located on the RD 911. It was built in 2013 in West-Southern France in the vicinity of Villeneuve-sur-Lot (Figure 2). It is a 2-lane road on which the speed limit is 90 km/h. This 800 m long experimental track, built in fall 2013, was 1 year old when the measurement campaign began in September 2014. Due to its small particle size 0/6 mm and its optimized sound absorption, this road pavement was specifically designed and optimized for a sustainable noise reduction. All noise measurements, texture and acoustic absorption were performed on the same
location and 3D texture measurements were carried out in the rolling path corresponding to the CPX measurements. The various experimental methods and equipments used during the whole experimental campaigns are presented in (4) in the same time of the texture, sound absorption and tyre-road noise first result analysis.

![Figure 1](image1.png)

Figure 1 – Test site with indication of the measurement direction by an arrow (left side) and 10 cm by 20 cm VTAC 0/4 close-up photo (right side)

![Figure 2](image2.png)

Figure 2 – Test site with indication of the measurement direction by an arrow (left side) and 10 cm by 20 cm VTAC 0/6 close-up photo (right side)

In complement to results detailed in (4), Tables 1, 2 and 3 respectively provide Coast-By values in terms of LAmax and Close-Proximity values in terms of LrAeq for both surface coatings on the whole measured speed range. Bold numbers in these tables represent values relative to the speed limitation on each test site.

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100*</th>
<th>110*</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAmax (dBA)</td>
<td>64.6</td>
<td>67.3</td>
<td><strong>69.6</strong></td>
<td>71.5</td>
<td>73.2</td>
<td>74.8</td>
<td>76.1</td>
</tr>
<tr>
<td>LrAeq (dBA)</td>
<td>87.6</td>
<td>90.9</td>
<td><strong>93.6</strong></td>
<td>96.0</td>
<td>98.1</td>
<td>99.9</td>
<td>101.6</td>
</tr>
</tbody>
</table>

Table 1 – Overall noise levels at various speeds for the VTAC 0/4 surface (*extrapolated values from the regression analysis*)
Table 2 – Overall noise levels at various speeds for the VTAC 0/6 surface

<table>
<thead>
<tr>
<th>Speed (km/h)</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAmx (dBA)</td>
<td>64.2</td>
<td>66.8</td>
<td>69.0</td>
<td>70.8</td>
<td><strong>72.5</strong></td>
<td>74.0</td>
<td>75.3</td>
</tr>
<tr>
<td>LrAeq (dBA)</td>
<td>87.4</td>
<td>90.0</td>
<td>92.2</td>
<td>94.1</td>
<td><strong>95.8</strong></td>
<td>97.3</td>
<td>98.6</td>
</tr>
</tbody>
</table>

Finally, on Table 3, we compare at a speed of 70 km/h, noise values and their respective standard deviations for these two low-noise surface coatings and two surfaces implemented on the Ifsttar reference test track in Nantes-Bouguenais (France): a VTAC 0/6 and an old DAC 0/10 (French national reference).

Table 3 – Comparison of the overall noise levels at 70 km/h

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>LAmx (dBA)</th>
<th>LrAeq (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTAC 0/4</td>
<td>69.6 ± 0.7</td>
<td>93.6 ± 1.3</td>
</tr>
<tr>
<td>VTAC 0/6</td>
<td>69.0 ± 1.0</td>
<td>92.2 ± 1.5</td>
</tr>
<tr>
<td>VTAC 0/6 (Ref)</td>
<td>70.6 ± 1.0</td>
<td>93.5 ± 1.0</td>
</tr>
<tr>
<td>DAC 0/10 (Ref)</td>
<td>74.6 ± 1.0</td>
<td>95.7 ± 0.9</td>
</tr>
</tbody>
</table>

From these results, first conclusions can be drafted. Regarding the two VTAC, results presented in the previous tables show that whatever the measuring method, noise levels for each mix are near and slightly below the average value of their family which is around 73 dBA in LAmx at 90 km/h (5). Compared to the reference DAC 0/10, we observe an abatement of about 5 dBA corresponding to a traffic reduction by a factor 3. If we look at the VTAC 0/4 more in detail, despite its 5 years of age, we note that its characteristics in terms of rolling noise are still very acceptable. So, it would be interesting to repeat the same measurements on the VTAC 0/6 after five years of life in order to evaluate the sustainability of its performances over time.

2.2.2 Experimentation on Reference Test Tracks

In order to complement our pavement database including texture, absorption (if available) and rolling noise characteristics, additional measurements have been carried out on both the Ifsttar reference test track in Nantes-Bouguenais (France) and the BAS test track located in Geilenkirchen (Germany). Figure 3 gives close-up pictures of the 17 tested road surfaces; each denominated with the local nomenclature of the test tracks. In France, eleven test sections have been tested: a porous asphalt concrete 0/6 (A), two surface dressings 8/10 (A') and 1.5/3 (F), two dense asphalt concretes 0/10 (E1 and E2), a flexible dense asphalt concrete (G0), a surface conforming to ISO 10844 (ISO), a smooth epoxy resin (L1), a sand asphalt 0/4 (L2) and two very thin asphalt concretes 0/10 (M1) and 0/6 (M2). In Germany, six test sections have been tested: an asphalt concrete optimized for noise reduction (LOA), a stone mastic asphalt 0/8 (LS1), a polished cement concrete with periodic cylindrical cavities (LS2) and another with longitudinal grinding (LS5) and two porous mastic asphalts (PMA and PMAG). Road surfaces A', E1, E2, F, G0, ISO, L1, L2, LS1, LS2, LS5 and M1 are impervious, while A, LOA, M2, PMA and PMAG are porous road surfaces.
The texture of the road surfaces has been measured by Ifsttar using a 3D texture measurement system. This device is fully described in (4). It is based on a 2D laser sensor that is moved over the road surface by a motorized linear axis in the longitudinal direction. A positioning table allows fixing the position of the sensor in the transverse direction. For a given location of the chassis, a unitary texture map is 1.5 m long by 0.35 m wide with a spatial resolution of 0.1 mm and a vertical repeatability of 0.03 mm. During the measurement campaign, between 2 and 4 aligned unitary texture maps have been recorded successively in the wheel track, leading to a full length between 3 and 6 m. Figure 4 gives close-up samples (10 cm by 10 cm) of the 3D texture measured on 15 of the test tracks. The maximum aggregate size and the roughness of each road surface can be assessed qualitatively.

According to ISO 13473, several quantities related to texture have been evaluated from the measurements. The Mean Profile Depth (MPD) was calculated from 7 to 8 longitudinal profiles extracted from the 3D texture map with a lateral sampling of 4 cm. MPD was ranging between 0.31 mm (ISO surface) and 3.28 mm (A'). The height probability density has also been assessed from 3D texture samples of 200 mm by 200 mm, as well as the standard deviation, the skewness and the kurtosis of the surface. It has been found that most of the surfaces have negative texture, except A' with a highly positive texture. Texture spectra have been calculated using the same profiles as MPD, subdivided in 1.50 m long profiles with 50% overlap. One-third octave band texture spectra are plotted in Figure 5.
for random road surfaces only and for spatial wavelengths ranging between 1 mm and 250 mm. A wide range of texture levels is observed, the smallest being found for the ISO surface. Above a wavelength of 12.5 mm, texture levels can be very different and the gap can reach up to 20 dB between ISO and A’. Below a wavelength of 12.5 mm, the gaps between road surfaces are smaller and decrease from 10 dB for 8 mm to less than 5 dB for 1 mm. In this range, A and M2 have the highest texture levels due to narrow negative peaks of high intensity in the profiles for these porous road surfaces.

Sound absorption has been measured by Ifsttar according to ISO 13472-1. The equipment was a stationary system described in (4). The tests have only been performed on porous road surfaces which have potential acoustical absorption properties, i.e. A, LOA, M2, PMA and PMAG. The sound absorption coefficient $\alpha$ in 1/3 octave band is given for each porous road surfaces in Figure 6. An absorption peak of magnitude 0.8 between 1250 Hz and 1600 Hz is observed for road surface A while for road surface M2 a peak of magnitude 0.4 is found between 800 Hz and 1000 Hz. On the contrary, road surfaces LOA, PMA and PMAG have a very weak absorption coefficient of magnitude less than 0.2 within the frequency range between 315 Hz and 2000 Hz. These surfaces are very few absorbing and therefore will be considered as impervious road surfaces in the following.

Close-Proximity (CPX) and Coast-by (CB) rolling noise measurements have been performed simultaneously by Ifsttar over a distance of 20 metres around the pass-by microphone. CPX measurements have been carried out according to ISO 11819-2 and CB measurements according to European directive 2001/43/EC. The test procedure is further described in (4). The test vehicle was a Renault Scénic. Two kinds of tyres have been tested: patterned tyres (Michelin Energy E3A 195/60...
R15) and slick tyres (Avon 16” radial slick 210/60 R16). Only the results for the patterned tyres are reported in this study. For each road surface, several runs were performed at different vehicle speeds ranging between 50 km/h and 110 km/h. Then the relation between noise levels and the logarithm of the vehicle speed was evaluated using a classical regression method.

The estimated noise levels at the reference speed of 90 km/h enable to obtain an acoustical classification of the road surfaces (Figure 7) in the case of the patterned tyres. Both CPX and CB noise measurement methods give similar ranking of the road surfaces. A large range of noise levels is observed with up to 10 dBA between the quietest and the noisiest road surfaces.

![Figure 7: Noise levels at 90 km/h measured by the CPX method (top) and the CB method (bottom)](image)

Figure 7 gives the statistical correlation between CPX and CB overall noise levels (left) and 1/3 octave band spectral noise levels between 400 Hz and 4000 Hz (right). All road surfaces are included in the calculation. The correlation coefficient and the regression slope are close to 1 in both cases, indicating a very good correlation between both measurement methods.

![Figure 8: Statistical correlation between CPX and CB overall noise levels (left) and 1/3 octave band spectral noise levels (right), including the 17 road surfaces involved in the study](image)

The analysis of noise spectra has led to the identification of four categories of road surfaces: porous surfaces (A and M2), dense asphalt concretes (E1, E2, G0, L2, LOA, LS1, M1, PMA, PMAG), smooth (or quasi-smooth) surfaces (ISO, L1, LS2 and LS5) and surface dressings (A’ and F). The CPX noise spectra are given separately for the four categories in Figure 9. For the porous surfaces, the maximum noise level is located at 800 Hz and a high noise reduction is observed after 1000 Hz due to acoustical absorption of these road surfaces (Figure 6). Dense asphalt concretes have completely different spectral shapes with a high peak at 1000 Hz due to the impact frequency of the tyre tread blocks at 90 km/h. A similar shape is observed for the smooth surfaces, but with a second harmonic peak around 1500 Hz.
2000 Hz. Finally, the acoustical energy for surface dressings is located at low frequencies between 400 Hz and 1600 Hz due to vibrational excitation of the tyre when rolling on these very rough surfaces.

Figure 9: CPX noise spectra at 90 km/h for the four categories of road surfaces

3. IMPROVEMENT OF THEORETICAL MODELS

To understand the sound phenomena in the contact area when a tyre is rolling on a pavement surface, it is essential to be able to control several suitable models to simulate the vibration and noise emission mechanisms on and around the tyre. Hybrid approaches (6, 7) simulate the result in its entirety while the physical approaches (8) represent each phenomenon individually.

The validation of these models still requires using experimental texture and noise databases regrouping a large range of conventional coatings but also some specific surfaces to highlight particular phenomena. Such a database is detailed in section 2.2.2.

During the ODSURF project, a special effort has been focused on the modelling of air-pumping phenomenon and the influence of tyre and pavement textures on the horn effect.

3.1 Air-pumping mechanism

The air-pumping phenomenon is a major part in the tyre-road noise emission. This mechanism is related to the succession of air compression and depression and air flow occurring in the contact zone. Two main noise generation mechanisms due to air pumping are now identified without knowing their relative importance on a real dense road surface. On one hand, we observe the volume variation of the cavities inside the contact area: tyre grooves modification due to the load supported by the tyre and the indentation of the tyre rubber by the superficial pavement roughness and on the other hand, the air compression due to a boundary layer effect. The various analytical and numerical approaches developed during the project have been already described in (9, 10).

3.2 Horn effect

The noise generated in the contact area between the tyre and the pavement can be amplified inside
cones constituted by the tyre and the pavement surfaces in front and behind the contact zone. This amplification effect due to the multiple reflections between the tyre and the road surface is commonly called “horn effect”. First studies devoted to this particular phenomenon assumed that both surfaces were flat (11). In the project, we assumed that tyre treads and pavement texture in the contact zone can be considered as acoustic resonator networks as shown on Figure 10. Since the network resonators in the contact zone have large influences on the acoustic field around their resonant frequencies, the acoustic behaviors inside the networks and the resonant frequencies should be investigated.

![Figure 10 – Pipe resonators in the contact zone between a tyre and a road](image)

The predicting model extensively detailed in (2, 12) is based on the coupling of two domains (cf. Figure 11). The exterior one corresponds to an arbitrary flange and the network extremities and the interior one corresponds to the inside network constituted of pipes.

![Figure 11 – An arbitrary flange (a) with the interior network (b)](image)

To obtain the acoustic pressure $p$ and its derivative $\partial p/\partial n$ on the surface $\Gamma$ of a complex network with flange, the computational domain should be divided into an exterior subdomain and an interior subdomain by creating imaginary ends for the network. The exterior subdomain is solved by BEM to get BEM system matrices and an excitation vector. The interior subdomain can be solved by analytical methods (transfer matrix) or numerical methods (FEM or BEM) to get the relation between $p$ and $\partial p/\partial n$ at these ends. Then the exterior and interior subdomains are coupled at the interfaces. Finally, by solving the overall equations system we obtain $p$ and $\partial p/\partial n$ on the surface $\Gamma$. For easier calculation, the interior pipe network is assumed to be rectilinear and parallel. The network can be optimized using genetic algorithms. An example of a resulting network is shown on Figure 12.

![Figure 12 – An example of a network generated randomly in the first generation of the Genetic Algorithm procedure](image)
Experimental validation of the predicting approach has been carried out. The amplification due to the horn effect is calculated by the equation (1).

$$A = 10 \log_{10} \left( \frac{P}{P_{\text{ref}}} \right)^2$$ (1)

where $P$ is obtained with the tyre on the road and $P_{\text{ref}}$ with the tyre positioned in free field. For sake of convenience, in a first approach, the tyre is simulated by a hard wooden cylindrical structure and the network between a cylinder and a plane surface is calculated and measured to validate the multi-domain coupling methods. When we measure the case without network, we close the pipe ends with wood. Thanks to the reciprocity principle, the source and receiver locations are exchanged for the measurements. An example of results for an optimized network is shown on Figure 13.

Figure 13 – (a) Optimized network; (b) Wooden optimized network between a cylinder and a plane surface; (c) Predicted results; (d) Measured results

We can note a rather good agreement between prediction and measurement for this optimized theoretical case. The resonance frequency positions and magnitudes are relatively well predicted. To go further in the experimental validation, the same measurement has been performed with a real tyre artificially loaded (not inflated). The first results are encouraging but need to be improved in order to better take into account the actual load applied to a real inflated tyre to generate a more realistic contact area.

4. DEUFRABASE DATABASE

When a low noise road pavement is developed, its characteristics in terms of noise emission are measured in the road vicinity (7.50 m from the road axis and 1.20 m above the road surface) or in close proximity of the tyre. To test its environmental qualities, it is necessary to know their impact for different road environment configurations and for distances more representative of actual situations, i.e. several hundred metres. The aim of this database is to be able to estimate from a number of predefined situations the effects of various mixes for realistic situations in terms of geometrical configurations, traffic composition and propagation characteristics, taking into account ground impedance and meteorological variations.
At the end of P2RN project (1), a first version was designed and put online. During ODSURF, the basic structure was completely upgraded using a new development philosophy (Django tool) to give it in the future, at a lower cost, extensible possibilities allowing to add easily new geometric configurations and traffic compositions, possibly including some urban constraints, new indicators and new mixes in the same time they are available on the market.

After choosing the input parameters of the problem: geometry, type of mixes and traffic composition, the overall and spectral hourly L\text{Aeq} and L\text{den} indicators are calculated and displayed for each case and for all selected mixes. Examples of hourly L\text{Aeq} distributions and L\text{Aeq}(1\text{ hour}) spectra for different mixes (0/10 Porous Asphalt, 0/10 Very Thin Asphalt Concrete – Type 1 and 0/10 Ultra-Thin Asphalt Concrete) are presented in Figure 14.

After complete validation, the updated DEUFRABASE will be freely available on a website hosted by Ifsttar.

\begin{figure}[h]
\begin{center}
\includegraphics[width=\textwidth]{figure14.png}
\end{center}
\caption{Figure 14 – (a) Representation of the hourly L\text{Aeq} distribution and global L\text{den} \hspace{1cm} (b) L\text{Aeq}(1\text{ hour}) spectrum for different mixes}
\end{figure}

5. CONCLUSION

Following the DEUFRAKO-P2RN project, ODSURF allowed working on a complete approach regarding the design, the realization and the validation of low noise pavements for urban use.

In the years 1990-2000, the porous low-noise road surfaces combining drainage and sound absorption abilities had been implemented. Problems related to the sustainability of their acoustic
performances due to the clogging of pores led road companies to study and produce thin-layer asphalt concretes (VTAC). Researches in this field having shown that the aggregate size had a strong impact on noise emission, mixes incorporating small aggregates (0/6 or even 0/4 mm) were considered. Two of these mixes were tested during the project and one of them showed that even after 5 years of use in peri-urban areas, interesting acoustic performances were maintained.

To avoid further clogging problems, we also investigated low-noise dense surfaces. A suitable texture geometry has been designed from a theoretical approach. Benefiting from the experience of our German partners on the hydraulic cement concrete techniques, solutions have been experimented and tested. Although it is still possible to improve their implementation, first significant results have been achieved. However, we note that more conventional coatings such as VTAC are still more efficient. Thus, according to multiple conditions of use, a wider range of solutions to make our roads and streets less noisy is available to planners.

This project also showed that from a theoretical modelling, even if improvements have still to be done, it was possible to design new low-noise wearing courses. Further study on tyre-road noise generation mechanisms, important contribution to road traffic noise seems essential to better control these phenomena and thus develop comprehensive numerical tools grouping tyre vibration mechanisms, air pumping, horn effect and absorption. Validation by adapted experimental techniques will allow us to better optimize our road pavements to further reduce the noise produced by vehicles on these surfaces while maintaining excellent skid resistance characteristics essential to ensure the road user’s safety.

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