2013

Influence of changes in surface layer properties on tire/pavement noise

Mingliang Li
Iowa State University

Wim van Keulen
Iowa State University

Halil Ceylan
Iowa State University, hceylan@iastate.edu

See next page for additional authors

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Abstract
This paper investigates changes in tire/pavement noise caused by variations in the road surface characteristics. This research is based on the analysis of noise and surface characteristics collected from sections with 25 mm thickness thin layer surfacings in the Netherlands. Investigations are first performed on the measured noise levels in 1/3rd octave bands, texture levels and the sound-absorption curves. The one-way analysis of variance is employed to test the changes of noise caused by variations of the pavement surface characteristics. It is found that the significant differences in the noise levels between road surfaces mainly appear at frequencies higher than 1000 Hz, and they are considered to be related to surface layer properties. Multivariate linear regression analysis is performed for describing the relationship between the noise level changes and the variations of surface characteristics. By using the partial least square (PLS) regression, the combined effect of texture and sound absorption coefficients on different spectral bands is displayed. From the regression results, it can be inferred that the sound absorption variations at 1000 and 1250 Hz are important factors influencing noise reduction of thin layer surfacings. The founding provides information for designing the noise reducing thin layer surfacings.

Keywords
combined effect, multivariate linear regression analysis, partial least-square regression, pavement surface, sound absorption, surface characteristics, tire/pavement noise, noise abatement, roads and streets

Disciplines
Civil and Environmental Engineering | Construction Engineering and Management

Comments
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Reference to this paper should be made as follows: Li, M., Van Keulen, W., Ceylan, H., van de Ven, M., & Molenaar, A. (2013). "*Influence of changes in surface layer properties on tire/pavement noise*," Noise Control Engineering Journal, Vol. 61, No.4, pp. 417-424.

Influence of Changes in Surface Layer Properties on Tire/Pavement Noise

Mingliang Li, Wim van Keulen, Halil Ceylan, Martin van de Ven, and André Molenaar

Abstract: This paper investigates changes in tire/pavement noise caused by variations in the road surface characteristics. This research is based on the analysis of noise and surface characteristics collected from sections with 25 mm thickness thin layer surfacings in the Netherlands. Investigations are first performed on the measured noise levels on 1/3rd octave band, texture levels and the sound-absorption curves. The one-way analysis of variance is employed to test the changes of noise caused by variations of the pavement surface characteristics. It is found that the significant differences in the noise levels between road surfaces mainly appear at frequencies higher than 1000 Hz, and they are considered to be related to surface layer properties. Multivariate linear regression analysis is performed for describing the relationship between the noise level changes and the variations of surface characteristics. By using the partial least square (PLS) regression, the combined effect of texture and sound absorption coefficients on different spectral bands is displayed. From the regression results, it can be inferred that the sound absorption variations at 1000 Hz and 1250 Hz are important factors influencing noise reduction of thin layer surfacings. The founding provides information for designing the noise reducing thin layer surfacings.

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1 INTRODUCTION

The generation of tire/pavement noise is a complex process which depends on various mechanisms and influencing parameters[1, 2]. From existing research, it is known that the surface texture and sound absorption are two of the road surface characteristics that play important roles in the tire/pavement noise generation. In general, the noise level at frequencies above 1 kHz reduces with increasing texture levels at wavelengths in the range of 0.5 to 10 mm. Below 1 kHz, noise level increases with texture at wavelength between 10 mm and 500 mm[3, 4]. In porous asphalt, the sound wave is partly absorbed due to the porous structure of the surface. The maximum noise reduction caused by road surface absorption generally occurs at frequencies around the maximum absorption coefficient with a small frequency shift[5, 6].

Much work has been carried out on modeling the tire/pavement noise generation. In nearly all the existing models, surface texture and sound absorption are used to describe the properties of the pavement[5-7]. It is now well-known that the tire/pavement noise generation is a complex and sensitive system and many factors influence the noise levels. As a consequence, the existing models are unable to provide an accurate prediction.

In this study, the generation process of tire/pavement noise is treated as a 'black box'. It is assumed that there are only changes of road surface properties, and all the other factors are considered stable. Under such conditions, the change of the noise level is assumed to be caused completely by the variation of road surface properties.

The concept of "changes" has been introduced for investigating the relationship between the tire/pavement noise and the road surface characteristics[8]. "Changes" exist in each process of road design, construction, and application. It can be the result of different designs of the road mixture composition, changes of road surface characteristics during service time, and different surface properties between various sections. However, "changes" of course also occur because of natural variability of the surface characteristics. For tire/pavement noise, the "changes" describe the increase or decrease of the noise level, and can be used directly as an indication of noise reduction.

A new type of model has already been proposed by the authors. This model focuses on the change of the tire/pavement noise caused by changes of the road surface properties[8]. The model is developed using regression analyses on data from measurement on a certain type of pavement, such as dense surface, porous asphalt or thin layer surfacings, etc. It is known that statistical models give good predictions for pavements with similar properties, but it is difficult to provide a universal model for all types of surfacings. Accurate predictions can be obtained by developing specific models for different types of surfacings. Moreover, most of the modeling work concentrates on dense and porous asphalt pavements. There is less research on thin layer surfacings, which are commonly used as noise reducing surface layer in Dutch cities. Therefore, thin surface layers are researched in this study.

The research aims to investigate the changes of tire/pavement noise caused by variations of the road surface characteristics. It is based on the analysis of noise and surface characteristics data from different thin layer trail sections in the Netherlands. This study can be considered as a refined work which focuses on thin layer surfacings. It aims to provide information to the road engineers about noise reduction of thin layer surfacings and will help them to improve the material properties. As the range of changes is small, we can make the assumption that the relationship between the change of noise and the change of surface characteristics is linear. Statistical methods, including the one way analysis of variance (ANOVA) and linear regression analysis are used for investigating the influence of the surface texture and the sound absorption

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on the change of the tire/pavement noise level. From the study, it is found that the large differences of noise levels between the investigated road surfaces mainly appear at frequencies of 1000 Hz and higher. In terms of practice application, the regression model can also be used as a tool for evaluating the change of tire/pavement noise on thin layer surfacings.

2 INVESTIGATION ON THIN LAYER SURFACINGS AND NOISE

2.1 Investigation on Measurement Results

This research focuses on thin layer surfacings, which generally have a thickness of 25 mm and an air voids content varying between 9% and 20%. The noise level is considered to be reduced by the fine texture as well as the sound absorption of the surface layer[9]. The data used for this study were obtained from measurements on the Kloosterzande trial sections in the Netherlands and provided by the Centre for Transport and Navigation (DVS) in the Netherlands. Four thin layer wearing courses were designed and two tracks were constructed for each mix design. Because of the variation in the construction process, the surface characteristics and the sound emission properties are different for tracks with the same nominal design. Therefore, they can be considered as different surfacings[10]. Thus, a total of 8 surfaces are used in the analysis and numbered from 1 to 8. The mixture composition of each surface is given in Table 1. It should be noted that the values given in Table 1 are the design properties of the pavements. The measured properties are not always in consistent with design values. However, in this paper, the influence of the material properties is not the main subject to be discussed, so the measured results of material properties are not shown here.

Table 1. Mixture compositions of different types of surface

Surface	Thin layer 1, 2	Thin layer 3, 4	Thin layer 5, 6	Thin layer 7, 8
Max. aggregate size, mm	4	6	6	8
Coarse aggregate size, mm	2/4*	2/6	2/6	4/8
Air voids, % by volume	12	8	12	12
Thickness, mm	25	25	25	25

*2/4 means the coarse aggregate size is between 2 mm and 4 mm. The explanation is also suitable for other surfaces.

The texture of the road surface was measured by a laser profilometer according to ISO standard 13473[11]. The measurement was performed over a length about 2.95 m. 20 traces were measured in a width of 0.2 m[10]. The texture levels of the 8 thin layer surfacings in an octave band spectrum with wavelengths ranging from 1 till 250 mm are shown in Fig. 1. From the figure, it can be seen that the differences in texture level are small when the wavelengths are below 4 mm. Therefore, texture data at wavelength less than 4 mm are not used for further analysis in this study.

The absorption coefficient is used to measure the sound absorbing ability of the pavement. The measurements were performed by the extended surface method (ESM), according to ISO standard 13472-1[12]. The average sound absorption coefficients for each section are shown in Fig. 2. It can be seen that considerable differences between the absorption curves occur at frequencies $f \geq 1000$Hz. Below 1000 Hz, the sound absorption coefficients are smaller than 0.2, and the differences of absorption coefficients between sections are all within 0.1. These small coefficients are considered to have insignificant influence on the change of noise. In this case, all the sound absorption data at f<1000 Hz are not taken into account.

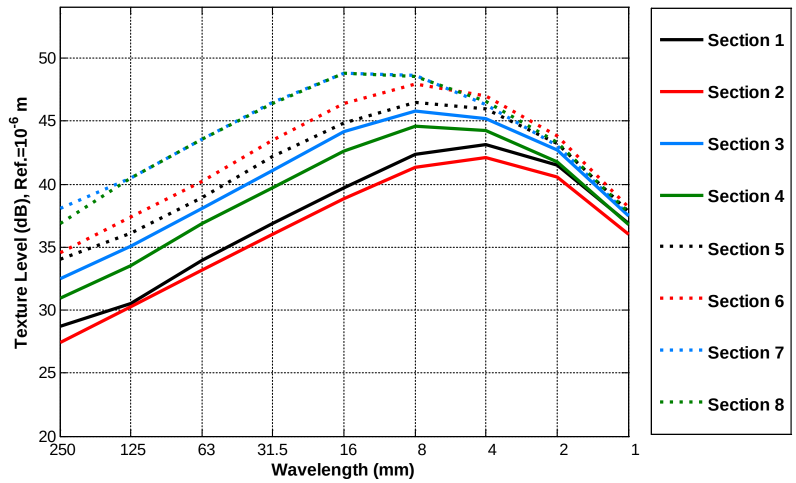

Fig. 1. Surface texture levels for the thin layer surfacing sections

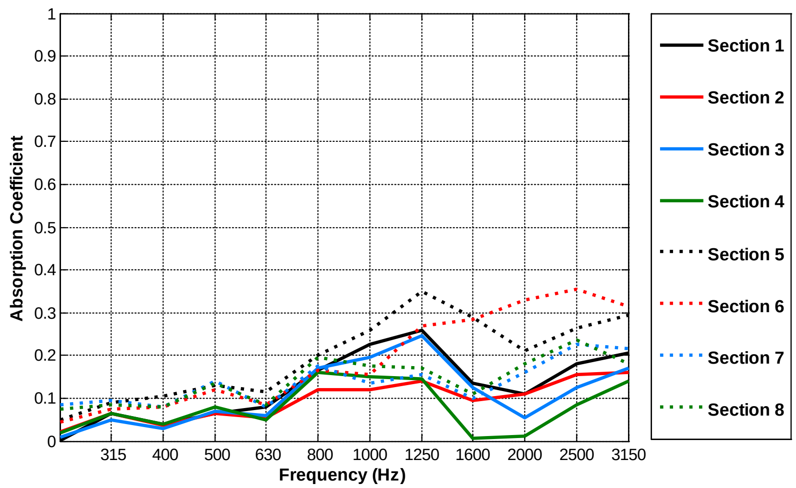

Fig. 2. Sound absorption coefficients for the thin layer surfacing sections

The noise data referred to in this study are the noise levels from Close Proximity (CPX) tests[13]. It is a near field test method, the noise levels are collected by the microphones mounted close to a rolling tire. The measurements were performed for different tire types and at various speeds[10]. In this paper, only the results measured with passenger car tires driving at a speed between 75 – 85 km/h are taken into account. Data used in the analysis are from the central segment of each track, the length of which is 20 m. Eight types of passenger car tire with summer tread pattern and two winter tires were selected for this study. There is one standard tire in the group, namely the passenger tire type A, referring to ISO/CD-11819-2[13]. So the regression result from this work can also give an approximate evaluation of the CPX noise level from standard tire A.

Examples of the noise levels measured on the thin layer surfacing trial sections are shown in Fig. 3 in the form of the overall A-weighted equivalent level L_a and noise levels in 1/3rd octave bands. Fig. 3 (a) and (b) illustrate the noise levels measured by different tires, and Fig. 3 (c) gives the average noise levels from the 10 passenger tires. It can be seen that the distribution of

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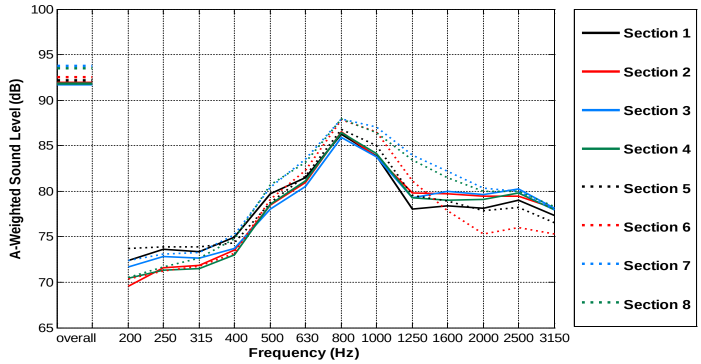
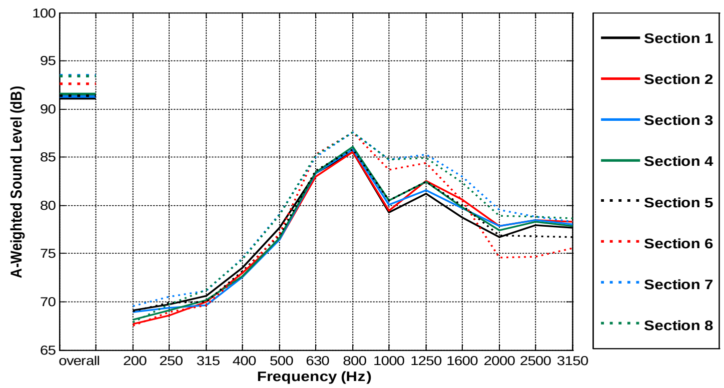
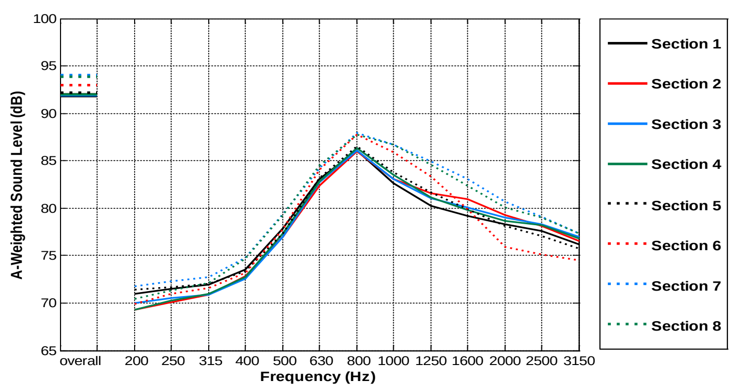
the noise levels from different tires are comparable. The peak values are generally located at a frequency of 800 Hz. The highest noise levels are generated by sections 7 and 8. They are notably caused by the large surface texture of these sections (see Fig. 1). For section 6, a great drop in noise level is observed at frequencies higher than 1250 Hz. This can be regarded as the result of the increase of the sound absorption coefficients in the corresponding frequency range as shown in Fig. 2. Moreover, it is also found that significant differences in noise level between various road surfaces mainly appear in the frequency range $f > 1000$ Hz.



(a) Tire 01: Summer tire 175/65R14*



(b) Tire 07: Summer tire C-2 195/65R15



(c) Average noise level of the 10 passenger car tires

*175=Tire width in mm; 65=Aspect ratio (height is 65% of width); R = Tires with a radial construction; 14=Diameter of rim (in inch).

Fig. 3. Tire/pavement noise level for different sections and tires

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2.2 Study with ANOVA

As shown in Fig. 3, the noise levels are different for various sections, and it is essential to examine whether the noise differences are caused by variations of the surface properties or by random errors in the measurement system. A hypothesis test is conducted to investigate the influence of the pavements with different surface characteristics on noise generation. The measurement results follow a normal distribution which makes the application of ANOVA possible. The null hypothesis is that there is no effect of the difference of the pavements on the tire/pavement noise levels. The noise data for all the tire types are included in the calculation, and the analysis is performed using the SPSS software package. The calculated significances for each noise level are listed in Table 2. The significance level for the judgement is concerned as 0.05 in this study. The null hypothesis is rejected when the obtained significance is less than 0.05, which indicates that the road surface characteristics have a considerable effect on the tire/pavement noise level. When the resulting significance is higher than 0.05, the null hypothesis is accepted and it implies there is no influence of the road surface properties.

Table 2. Significance of different road surfaces on noise level

	L_a	L_{200}	L_{250}	L_{315}	L_{400}	L_{500}	L_{630}	L_{800}	L_{1000}	L_{1250}	L_{1600}	L_{2000}	L_{2500}	L_{3150}
Sig.	0.00	0.23	0.22	0.13	0.10	0.01	0.83	0.10	0.00	0.00	0.00	0.00	0.00	0.00

From the results in Table 2, it is concluded that the road surface variations account for the differences of overall noise level and noise levels at frequencies above 1000 Hz. The influence of road surface on noise level below 1000 Hz is trivial, and only the noise level at 500 Hz is considered to be affected by the road surface characteristics based on the ANOVA.

3 REGRESSION ANALYSIS

3.1 Model Description

For studying the influence of specific parameters of the surface layer properties on the tire/pavement noise level, a regression analysis is performed. The model proposed by the authors[8] is schematically represented in Fig. 4. It does not attempt to relate the global noise level to a certain surface characteristic, but calculates the differences of tire/pavement noise level caused by changing surface characteristics or material properties.

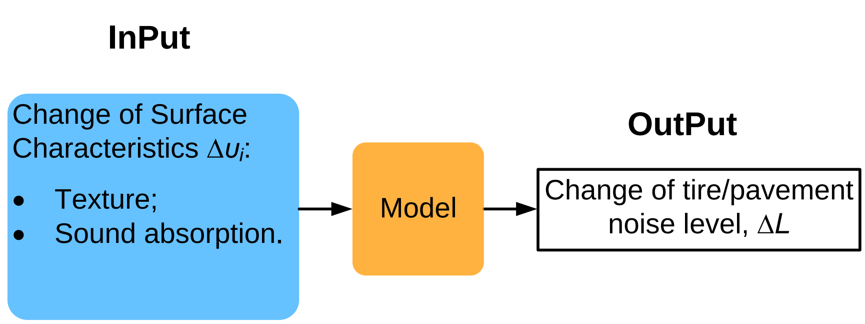

Fig. 4. Model linking the variation of tire/pavement noise to change of surface characteristics

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For a certain type of road surface, such as a thin layer surfacing, it can be assumed that the surface characteristics of different sections vary within a small range. The difference of the noise level caused by the variation of road surface properties is, therefore, in a limited range. Within this small range, the relationship between the input and output variables is considered to be linear. The model can thus be developed by means of linear regression:

$$\Delta L = \sum_{i=1}^{n} \alpha_i \Delta \upsilon_i \qquad (1)$$

where ΔL is the change of the noise level in dB, $\Delta \upsilon_i$ denotes the change of a certain factor representing the surface texture or sound absorption, and α_i are the coefficients to be identified by regression analysis.

3.2 Variable Selection and Data Preparation

As the road surface texture and absorption can be expressed by various indices, there are several possible combinations of the explanatory variables. The explanatory and the response variables selected in this study are listed in Table 3. This selection is aiming to detect the relationship of the noise level differences with the change of texture level and sound absorption on the spectrum band. Texture levels with wavelengths below 4 mm and sound absorption coefficients below 1000 Hz are not involved, as the differences are very small and considered to have no effect on noise emission. The selection of the response variables is mainly based on the ANOVA results. Significant noise level changes are chosen as response variables. In addition, the noise level generally reaches a maximum at 800 Hz as shown in Fig. 3, so the noise level at 800 Hz is also taken into account.

Table 3. Selection of explanatory variables and response variables

Explanatory variables		Number of explanatory variables	Response variable	Number of responsible variables
Sound Absorption	Changes of sound absorption coefficient at frequencies 1000, 1250, 1600, 2000, 2500 and 3150 Hz	13	Change of the overall noise level and changes of noise levels at 500, 800, 1000, 1250, 1600, 2000, 2500 and 3150 Hz	9
Surface Texture	Changes of texture levels at wavelengths 250, 125, 63, 31.5, 16, 8, 4 mm			

For regression, difference values of the noise level, texture level, and sound absorption coefficient are calculated between each two of the eight thin layer surfacing sections. The different values are calculated once between two different road sections. Therefore, total data set of change values is 28. This method is a special trial in this study. Firstly, in this way, the target model is just related to the change of the variables, and no reference surface is involved. This will facilitate the investigation and the application of the model. As the regression is purely based on change values, there is no need to appoint a reference section in the analysis by using the model. Moreover, this measure increases the size of the data set for regression in comparison with using the global data, from 8 to 28. As the differences between the pavements are small, it is assumed that the 28 data sets are achieved from independent tests. So the regression is to be performed with these data sets.

By comparing the noise curves from different tires as shown in Fig. 3, it can be seen that the distribution of the noise level on the frequency axis are comparable for the sections. The averaged noise levels from the 10 passenger car tires are thus considered as representative of the CPX noise levels on thin layer surfacings. The differences of the averaged values from the 10 passenger car tires are used in the regression analysis.

According to the number of selected variables and data set used in the regression, the regression equation which is to be solved is shown as follow:

$$\underset{(9\times 28)}{[\Delta L]} = \underset{(9\times 13)}{[\alpha]} \bullet \underset{(13\times 28)}{[\Delta \upsilon]} \tag{2}$$

where,
9 = number of predicted acoustic variables,
13 = number of explanatory variables (ΔAL and ΔTL), and
28 = number of data sets.

Therefore, there are 117 unknown α coefficients and 28 linear equations.

3.3 Regression method

Multivariate regressions are carried out on these calculated data based on Eqn. (1). It should be noticed that multicollinearity[14] exists between the explanatory variables since they have very similar properties. With normal regression method, the multicollinearity is reflected in the regression coefficients. It does not influence the prediction ability of the model as a whole, but the contribution of the individual predictor $\Delta\upsilon_i$ to the response ΔL cannot be truly presented by these coefficients. In order to eliminate the multicollinearity, the partial least squares (PLS) regression[15] is employed in this study.

According to the algorithm, the PLS method creates orthogonal combinations of explanatory variables by maximizing the covariance between the predictor $\Delta\upsilon_i$ and the response ΔL. These combinations are called latent variables in statistics. The first several latent variables are considered to cover most of the information of the input variables and these latent variables are selected for the regression. The rest of the components are thought to cause multicollinearity and are not included. The regression is performed with the selected latent variables and ended by transforming the regression equations into the general linear formula expressed by the original surface characteristics. The regression process is illustrated in Fig. 5.

Generation of the combinations can be accomplished by the SIMPLS approach[16]. The computing module is embedded in Matlab. The selection of the components is based on investigating the percent of variance which is explained by the PLS components and the mean squared error (MSE) of equations with different input components.

In the regression, only the first several latent variables are selected, and this selection reduces the dimension of the input data. The PLS regression is thus considered an efficient approach for analysis of high dimensional data and widely used in the cases when large amount of input variables are involved[17]. In this study, there are 13 input variables denoting the road surface characteristics. However, only the first two latent variables are finally chosen, and

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regression equations are developed with these two latent variables. This guarantees the degrees of freedom in the regression.

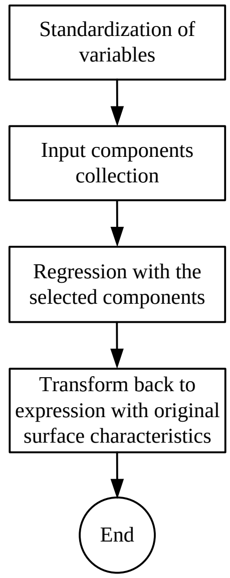

Fig. 5. Regression process with PLS approach

3.4 Investigation on the regression results

The PLS regression is performed on the calculated difference values, and a set of regression equations is achieved. The regression coefficients for all the surface parameters are shown in Table 4. As the units of texture level and absorption coefficient are different, the coefficients for each parameter in the equation are thus normalized. In this way, the influence of parameters with different type can be compared directly. In comparison with the correlation analysis between the noise level and a single parameter[3], results from the PLS regression give an overview of the combined effect of the texture level and sound absorption on spectral band. The equation for the change of overall noise level ΔL_a is given as an example:

$$\begin{aligned}\Delta L_a = {} & 0.15\Delta TL_{250} + 0.15\Delta TL_{125} + 0.16\Delta TL_{63} + 0.15\Delta TL_{32} + 0.14\Delta TL_{16} + 0.10\Delta TL_{8} + 0.06\Delta TL_{4} \\ & - 0.13\Delta AL_{1000} - 0.15\Delta AL_{1250} - 0.08\Delta AL_{1600} + 0.04\Delta AL_{2000} + 0.05\Delta AL_{2500} - 0.03\Delta AL_{3150}\end{aligned} \quad (3)$$

where ΔTL_i presents the change of texture level with wavelength i mm. The unit is dB, with reference 10^{-6} m. ΔAL_j is the change of sound absorption at frequency j.

From the regression results in Table 6, it can be seen that R^2 for the equation of ΔL_{500} is low. Therefore the residual plot is checked and it is concluded that the relation between change of surface characteristics and ΔL_{500} is not completely linear, or the difference in noise level between the sections at 500 Hz is not that significant as judged by the hypothesis testing because only 8 sections are taken into account. Examples of the residual plot for the equation of ΔL_{500} are given in Fig. 6. For the noise level at other frequencies, good linear relationships with the variations of layer properties are found, as the R^2 are all higher than 0.65.

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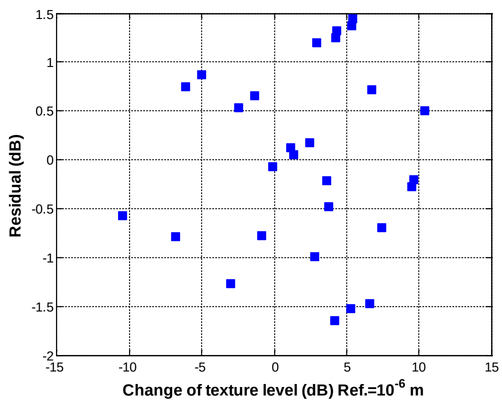
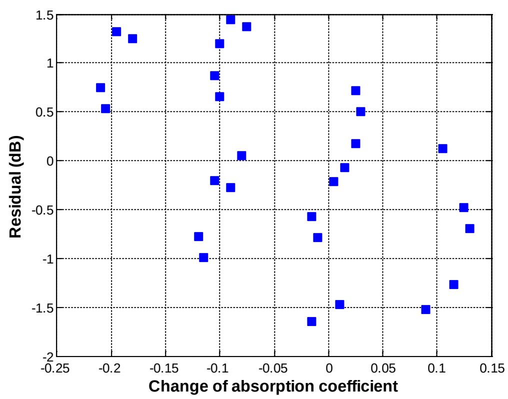
Table 4. Standardized regression coefficients from PLS regression

	ΔL_a	ΔL_{500}	ΔL_{800}	ΔL_{1000}	ΔL_{1250}	ΔL_{1600}	ΔL_{2000}	ΔL_{2500}	ΔL_{3150}
ΔTL_{250}	0.15	0.11	0.14	0.14	0.15	0.14	0.11	0.10	0.09
ΔTL_{125}	0.15	0.11	0.14	0.15	0.16	0.15	0.11	0.10	0.10
ΔTL_{63}	0.16	0.11	0.14	0.15	0.16	0.15	0.12	0.11	0.11
ΔTL_{32}	0.15	0.11	0.14	0.15	0.15	0.14	0.11	0.10	0.10
ΔTL_{16}	0.14	0.10	0.13	0.14	0.14	0.12	0.09	0.09	0.09
ΔTL_{8}	0.10	0.09	0.11	0.12	0.10	0.07	0.04	0.04	0.05
ΔTL_{4}	0.06	0.07	0.08	0.08	0.05	0.00	-0.03	-0.02	-0.01
ΔAL_{1000}	-0.13	-0.01	-0.13	-0.13	-0.17	-0.17	-0.07	-0.04	-0.04
ΔAL_{1250}	-0.15	-0.03	-0.11	-0.12	-0.16	-0.21	-0.19	-0.19	-0.18
ΔAL_{1600}	-0.08	-0.01	-0.03	-0.05	-0.06	-0.12	-0.18	-0.20	-0.21
ΔAL_{2000}	0.04	0.03	0.09	0.07	0.06	-0.02	-0.14	-0.18	-0.19
ΔAL_{2500}	0.05	0.04	0.10	0.07	0.06	-0.02	-0.12	-0.16	-0.18
ΔAL_{3150}	-0.03	0.01	0.03	0.00	-0.02	-0.11	-0.18	-0.21	-0.22
R^2	0.84	0.51	0.89	0.90	0.86	0.68	0.67	0.78	0.84



(a) With input variable ΔTL_{32}



(b) With input variable ΔAL_{1250}

Fig. 6. Residual plots for equation of ΔL_{500} with the variable ΔTL_{32} and ΔAL_{1250}

For the change of overall noise level ΔL_a and noise level from 800 Hz to 1600 Hz, the values and signs of the coefficients of the five equations are similar between each other. It indicates that the influences of surface texture and sound absorption on noise levels at these frequencies and overall noise level are almost the same. On these levels, it can be seen that the difference of the texture level displays a positive influence on the change of noise. In other words, the noise increases when the texture level becomes larger. Major contributions are observed from the texture level with wavelength from 16 mm to 250 mm, as the regression coefficients for these texture levels are relatively larger. The influence of texture at 8 mm or 4 mm is smaller in contrast. In terms of sound absorption, large negative regression coefficients are obtained at 1000 Hz and 1250 Hz. It means increase of sound absorption at 1000 Hz and 1250 Hz leads to reduction of the overall noise levels and noise levels between 800 Hz and 1600 Hz. The sound absorption coefficients around these two frequencies are thus found to be essential factors providing the noise reduction function of thin layer surfacings.

The change of noise level at high frequency (≥2000 Hz) decreases with the increasing sound absorption coefficients, especially with sound absorption above 1250 Hz. According to existing studies, there is a shift of frequency on which the absorption influences the noise levels[5, 18]. For CPX noise level, the horn effect contributes to this shift[5]. So the regression results achieved in this study are expected. It is also found that the influence of sound absorption at 1000 Hz is tiny. Therefore, increasing the sound absorption at frequencies higher than 1250 Hz is an efficient way to eliminate the high frequency noise. The effect of the texture becomes smaller compared with that on medium frequency noise (800 Hz to 1600 Hz). The reason is that the impact mechanism, which is highly related with the surface texture, is lowered at high frequencies, while the air pumping mechanism appears to be dominant. The sign of the coefficient for the short wavelength texture level ΔTL_4 changes from positive to negative at frequency levels higher than 2000 Hz. This is because the texture level with small wavelength results in a lower noise production generated from air pumping. Similar results of the influences of surface texture on high frequency noise were also found by Sandberg[1] on dense and porous asphalt surface.

4 CONCLUSIONS

The influence of variations of road surface properties on the tire/pavement noise is investigated for thin layer surfacings in the Netherlands. It is found that the variation of the surface texture level mainly occurs in the wavelength range higher than 4 mm. Pronounced variations of sound absorption occur at frequencies above 1000 Hz.

Statistical methods, including ANOVA hypothesis tests and linear multiple regression with the PLS approach are conducted for further analysis. They show that the differences of noise levels at frequencies higher than 800 Hz are highly related to the changes of the road surface properties. By investigating the regression coefficients, it can be seen that the surface texture level in the wavelength range higher than 8 mm is in positive relation with the overall noise level and noise level above 800 Hz. The influence of texture level becomes smaller at frequencies above 2000 Hz, and the short wavelength texture level is negatively related with high frequency noise levels. The sound absorption variations at 1000 Hz and 1250 Hz show significant influences on the change of noise in medium frequency range from 800 Hz to 1600 Hz and on the overall level. It can be considered that increase of sound absorption at 1000 Hz and 1250 Hz is critical to reduce the medium frequency noise as well as the overall tire/pavement noise on thin layer surfacings. The absorption coefficients at frequencies higher than 1250 Hz also show effect on attenuation of noise level above 2000 Hz.

In the regression, the multicollinearity between the explanatory variables is effectively removed by using PLS algorithm, and the regression results show the combined effect of surface texture level and sound absorption on different spectral bands. The linear relationships achieved from this study are thus suggested to be used as models to evaluate the change of noise level caused by the variation of surface characteristics with proper validation and improvement using extra data sets in the future. However, for further application of model forwarded in this study, validation needs to be made by considering tests results from other thin layer surfacings. Such validation work has been under going and will be shown in the future work of the authors.

5 ACKNOWLEDGEMENTS

The authors are grateful to Centre for Transport and Navigation (DVS) of the Ministry of Infrastructure and the Environment in the Netherlands for providing the measurement data on the trail sections.

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