Statistical Model of Tyre - Road Noise for Thin Layer Surfacing

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ABSTRACT

Noise produced from the tyre – road surface interface is one of the most important contributions to the overall traffic noise, and there is an increasing requirement for predicting the tyre – road noise levels prior to road construction in the Netherlands. In practice, a model with a simple structure as well as a high accuracy is applicable in road engineering. And material properties are preferred to be used as input variables of the prediction model, which will facilitate the pavement design.

Based on these considerations, models are developed for evaluating the tyre – road noise from the asphalt mixture compositions and road surface characteristics. They are statistical models developed from the measurements on thin layer surfacings in the Netherlands. Different regression methods, model types and input variable combinations are taken into account. The selection of the model is due to the fitness of the prediction and validation by using measurement data from in service road sections. Two models are finally selected which evaluate the tyre - road noise level from the surface characteristics and from material properties respectively. By using these models, only a small number of input variables are required and reliable predictions can be provided. The models achieved in this study can be used for predicting the tyre – road noise generation in road engineering and investigating the influence of surface characteristics and material properties on tyre - road noise levels.

Key words: tyre - road noise; statistical model; thin layer surfacing; surface texture; sound absorption

INTRODUCTION

The term tyre - road noise implies the noise generated from the interaction between a rolling tyre and the road surface. It has proved that tyre - road noise is the most important source of the road traffic noise (*1*). Currently, there is an increasing need for prediction models which provide information about noise generation before the road is constructed. Such models play an important role in predicting tyre - road noise, optimizing the pavement design and improving the materials and building technology (*2*).

Tyre - road noise models can be classified into three categories: statistical models, physical models and hybrid models. There are two important considerations for a model being effective for application in road engineering. The considerations and the corresponding modeling strategies are discussed below:

1) In practice, a model with a simple structure, small number of inputs as well as a high accuracy is preferred. Statistical models generally have simple structures and they are developed by regression on data collected from measurements (*3-7*). In this way, the model provides a more practical approach to evaluate of tyre - road noise compared with the theoretically based physical models (*8-10*), which to some extent are based on an idealized situation.

Statistical models however have difficulties in providing a general rule for all types of surfacings. For improving the accuracy of the prediction, this study therefore provides models for a certain type of road surface, but not one general model which is applicable for all types of surfacings. The accuracy of the prediction is expected to be improved in this way. In this paper, tyre - road noise models for thin layer surfacings with thickness between 20 mm and 30 mm are developed. A similar method can also be adopted for other surface types.

2) The road parameters in existing models are normally derived parameters such as a texture spectrum but they are not linked directly to the construction materials (*11*). For road engineers, a model linking the noise level to the mixture composition of the road surface is essential for being able to design and constructing noise reducing surfacings.

In this study, both the surface characteristics and the basic mixture properties are considered as input variables for the model. It means that the evaluation of the tyre - road noise can be made either from the parameters of the surface layer, such as surface texture, absorption coefficient or mixture properties, such as aggregate size, aggregate gradation or air voids content, etc..

Based on these two considerations, a statistical model, using typical material parameters and surface characteristics as input variables are developed for thin layer surfacings in this paper. Framework of the target models and the modeling methods are firstly described. Series of models are developed by using different combinations of input variables and regression methods. An initial selection is then made to collect candidate models with a higher prediction power. After that, validations are performed on the candidate models. The models which give the best prediction results are proposed for application in road engineering.

DESCRIPTION OF THE MODEL

Framework of the Model

FIGURE 1 shows three possibilities to relate tyre - road noise with the mixture composition and the surface characteristics. The figure shows that the noise levels can be predicted from the mixture composition, surface characteristics, or a combination of the two. Three types of models can thus be developed based on the choice linking the tyre - road noise to material properties. They are:

Type 1: Material properties are considered as independent variables, and the noise levels are computed directly from the material properties;

Type 2: The model consists of two sub-models. Type 2(a) links the surface characteristics to material properties while Type 2(b) deduces the noise level from surface characteristics. Models are developed independently for these two parts;

Type 3: Combinations of the material properties and the surface characteristics are used as predictors to evaluate the noise levels.

The diagram in FIGURE 1 is considered as the modeling framework.

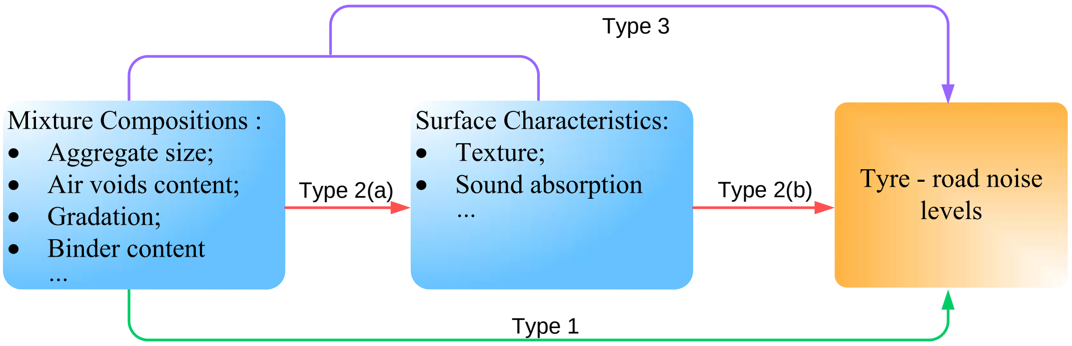


FIGURE 1 Three models for predicting tyre - road noise levels

Data Sources

In this study, data used for the statistical modelling are from two sources:

1) Database of Kloosterzande trial sections (*12*). There are 18 thin layer surfacing sections based on 9 different designs. The thickness of the surfaces are between 20 mm and 30 mm. Data measured from these 18 sections were taken into account in the regression.
2) Material properties and the surface characteristics measured on thin layer surface samples in the laboratory of Delft University of Technology. Details about the measurement methods and test results refer to authors' previous work (*13*).

Initial Variable Selection

It is known that there are different indices to express the mixture composition, surface properties and tyre - road noise respectively (*14-16*). TABLE 1 shows the specific indicators for the three groups. In the table, six parameters are given to describe the mixture compositions. In a strict sense, thickness is not a material property. The thickness mainly influences the positions of the peak sound absorption on frequency bands, and does not directly influence the level of tyre - road noise (*14*, *15*). Hence, layer thickness is considered as an indirect parameter and belongs to the same group as the material properties.

For surface characteristics, the two most important factors, namely surface texture and sound absorption coefficient are taken into account. From previous studies, it is known that the surface texture can be denoted by MPD or texture level with various wavelengths (*16*). The sound absorption can be expressed by either the maximum absorption coefficient or absorption coefficients at frequency bands. Thus there are different combinations of indicators for surface texture and sound absorption available for model development. In this study, three combinations of surface characteristics are adopted: 1) MPD and maximum absorption coefficient; 2) selected surface texture levels and sound absorptions on the frequency band; 3) selected surface texture levels and maximum absorption coefficients.

According to TABLE 1, tyre - road noise is considered as output of the model. The overall noise level and noise levels in the frequency range from 315 Hz up to 3150 Hz are all taken into account. The noise levels in this study were measured by the Close Proximity tests (CPX) with passenger car tyres (*17*). Data used in the regression are the average CPX noise levels from the 10 types of passenger cars. Noise levels at different speeds can be deduced from the noise at a reference speed (*12*). In this research, the speed is not considered as an independent variable in the model. The noise levels used in the regression are all collected at a speed of 80 km/h.

TABLE 1 Initial selection of the input and output variables

Mixture composition	Unit	Surface characteristic combination		Unit	Noise level	Unit
Maximum aggregate size;	mm	Combination 1	MPD;	mm	Overall level (from CPX test with passenger tyre);	dB(A)
Coarse aggregate content;	% by mass		Maximum Absorption coefficient.	-		
Fine aggregate content;	% by mass	Combination 2	Selected texture levels with various wavelengths;	dB, ref 10^{-6} mm		
Air voids content;	% by volume		Absorption level on 1/3 octave band of frequency.	-	Noise levels on 1/3 octave band of frequency (from CPX test with passenger tyre).	
Binder content;	% by mass ratio with the mineral aggregate	Combination 3	Selected texture levels with various wavelengths;	dB, ref 10^{-6} mm		
Thickness	mm		Maximum Absorption coefficient.	-		

Regression Methods

Overall noise levels and noise levels at each frequency band are modelled. The target model is a set of linear regression equations. Certain equations are developed corresponding to the overall noise level and the noise level at each frequency band (350 Hz to 3150 Hz on 1/3 octave band). As there is more than one independent variable in the regression, multivariate linear equations are constructed. Multivariate regression estimates an equation with the form:

$$\mathbf{y} = a + \mathbf{X}\boldsymbol{b} \qquad (1)$$

Where $\mathbf{y}$ is the vector of response variable; it presents a certain noise level or, in case of model Type 2(a), a certain surface characteristic. $\boldsymbol{X}$ is an $n \times p$ matrix, containing n observations of p predictor variables, which can be mixture composition, surface characteristics, or a combination of the two when different types of models are concerned. a is the constant, $\boldsymbol{b}$ is the vector of regression coefficients for the predictor variables. a and $\boldsymbol{b}$ are to be determined via the regression process.

The ordinary least squares approach is used to develop the linear regression models for each type of model with different variable input combinations. In addition, alternative models are also set up by means of variable selection methods. This aims to reduce the dimension of the independent variable vector and to simplify the structure of the model. The algorithms used in this study are backward elimination and the stepwise selection (*18*).

It should be noticed that multicollinearity may exist between the input parameters. As the input variables are not completely independent, the regression coefficients achieved in the model do not reflect the influence of a certain input parameter on the noise levels. However, the multicollinearity does not influence the prediction ability of the model as a whole (*19*). In this paper, the goal is to find the model with the best prediction accuracy. Therefore, the multicollinearity is not examined or eliminated on purpose.

MODEL DEVELOPMENT

A complete overview of the modeling process is given in FIGURE 2. By taking into account all the conditions, a total of 14 models were constructed. Each of these models is given a number as shown in FIGURE 2. An initial selection was then performed on the 14 models to choose those with the best fit to the measured data. The selected models were validated using measurement data from practical road sections. The final models were determined based on the results of the validation.

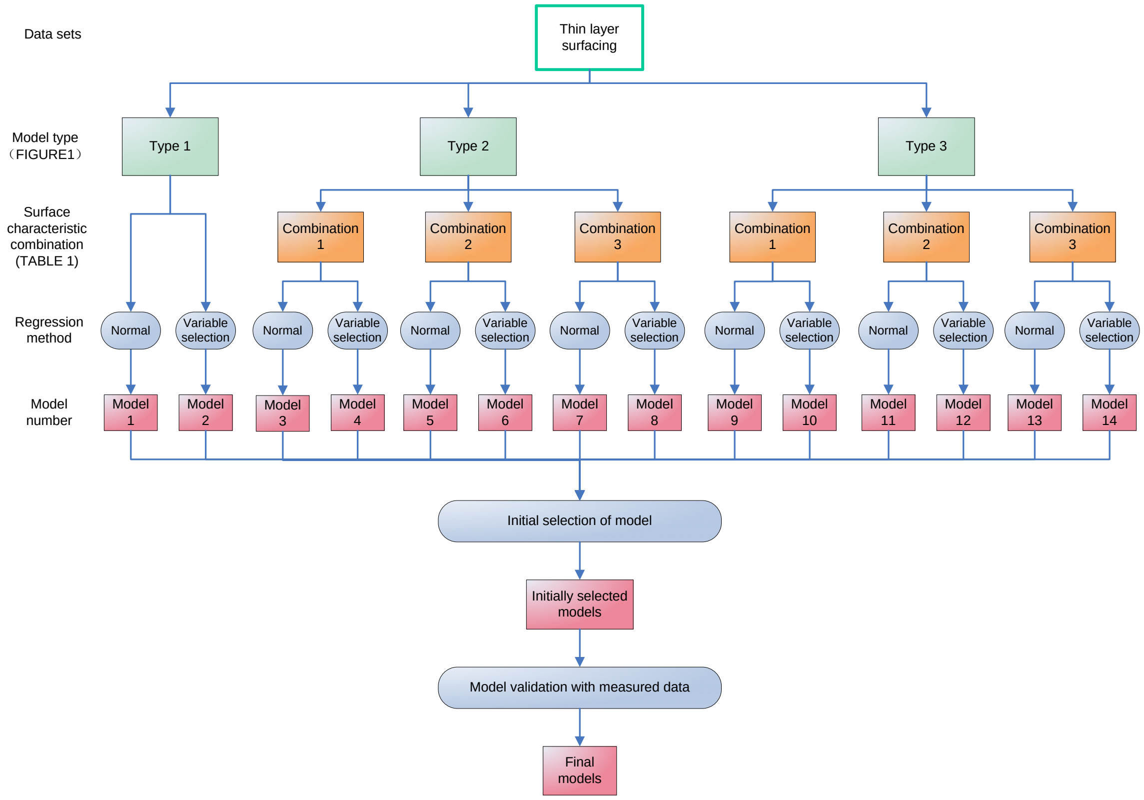


FIGURE 2 Complete model development process

Regression Results

As there are 14 models in total, only the regression results of Model 8 are shown as an example. TABLE 2 and TABLE 3 show the modeling results for Model 8. Previous study has shown that the generation of tyre - road noise levels is attributed to surface characteristics in three groups (*20*, *21*):

1) texture level at long wavelengths (≥8 mm);
2) texture level at short wavelength (≤4 mm);
3) sound absorption coefficients.

Certain variables from these three groups are selected as predictors of the regression, namely energetic averaged surface texture level at wavelength 63 mm TL_{63} and at wavelength1 mm TL_1, and the maximum sound absorption coefficient A_{max}.

Some of the regression equations from Model 8 are listed below as examples, the acceptable ranges for input values for thin layer surfacing are also given:

$$TL_{63}=19.39+2.85\ MS+0.19\ \Omega, \qquad R^2=0.95 \tag{2}$$

$$L_{A,eq}=79.90+0.35\ TL_{63}-1.79\ A_{max}, \qquad R^2=0.90 \tag{3}$$

where

$L_{A,eq}$ – the overall noise level, dB (A);
MS – maximum aggregate size, mm, for thin layer surfacing, 4 mm≤MS≤8mm;
Ω – air voids content, % by volume, for thin layer surfacing, 4%≤Ω<25%.

As shown in TABLE 2, the maximum absorption is linearly related with the coarse aggregate content and the air voids content; a high R^2 of 0.86 is obtained. In TABLE 3, model 8(b) provides a good prediction of the noise levels with the three surface parameters in combination 3.

TABLE 2 Regression results for Model 8(a)

	TL_{63}	TL_1	Max. Absorption
Constant	19.39	33.14	-0.42
Max. Aggregate size	2.85	0.29	-
Coarse aggregate content	-	-	0.01
Fine aggregate content	-	-	-
Binder content	-	-	-
Air voids content	0.19	0.18	0.02
Thickness	-	-	-
R^2	0.95	0.88	0.86
Adjusted R^2	0.94	0.86	0.85
Selection method	S*	B&S	B&S

*the results are from stepwise regression, which provides results with higher R^2 in this case;
**backwards selection and stepwise regression show the same results.

TABLE 3 Regression results for Model 8(b)

	$L_{A,eq}$	L_{315}	L_{400}	L_{500}	L_{630}	L_{800}	L_{1000}	L_{1250}	L_{1600}	L_{2000}	L_{2500}	L_{3150}
Constant	79.90	65.10	63.65	63.78	70.38	76.14	64.06	60.22	127.69	114.80	115.15	122.46
TL_{63}	0.35	0.17	0.25	0.36	0.33	0.28	0.55	0.62	0.67	0.45	-	-
TL_1	-	-	-	-	-	-	-	-	-1.95	-1.37	-0.94	-1.21
Max. absorption	-1.79	-	-	-	-	1.00	-1.00	-3.82	0.05	-8.09	-5.94	-1.82
R^2	0.90	0.71	0.80	0.84	0.91	0.92	0.93	0.87	0.76	0.88	0.93	0.90
Adjusted R^2	0.87	0.65	0.76	0.81	0.89	0.90	0.92	0.84	0.71	0.85	0.92	0.88

Initial Model Selection

It is known that the adjusted R^2 helps to check the goodness of fit of the multiple regression models without being influenced by the number of input variables. So an initial selection of the models was performed by investigating the adjusted R^2.

Models of Type 2 consist of two parts. Type 2(a) relates the surface characteristics to the material properties, and Type 2(b) generates the tyre - road noise from the surface characteristics. The models of Type 2(a) are firstly discussed. The adjusted R^2 values for various models are shown in TABLE 4. The regression method and surface characteristic combination for each model are also listed. From the table, it can be seen that most of the regression models show a good fit except for those used for evaluating the sound absorption from 1000 to 2500 Hz. This reveals that the sound absorption on 1/3 octave band cannot be explained well by a linear combination of material properties. Therefore models 5(a), 6(a) are excluded from the selection.

As to modeling with different regression methods, the adjusted R^2 from the least square regressions and the variable selection methods are similar. It reveals that variables with less effect on the regression fit are eliminated from the model. After the selection, there are generally less input variables in an equation, and such an equation is more appropriate for being used in practice. Therefore only these models are considered for further testing in a next step.

In summary, two sub-models are selected based on investigating the adjusted R^2 and considering the number of the input variables. They are Model 4(a) and 8(a) in TABLE 4. Because those models do not predict directly the noise levels, the final selection was made after models of Type (b) were evaluated.

TABLE 4 Adjusted R^2 for sub-models relating material properties to surface characteristics

Surface group	Model number	Regression method	Surface characteristic combination	MPD	TL_{63}	TL_{1}	Max. absorption	AL_{1000}	AL_{1250}	AL_{1600}	AL_{2500}
Thin layer surfacing	3(a)	Least square	1	0.93			0.83				
	4(a)	Variable selection	1	0.92			0.85				
	5(a)	Least square	2		0.95	0.85		0.24	0.04	0.64	0.61
	6(a)	Variable selection	2		0.94	0.86		0.00	0.24	0.68	0.62
	7(a)	Least square	3		0.95	0.85	0.83				
	8(a)	Variable selection	3		0.94	0.86	0.86				

The second round of model selection is accomplished by investigating the adjusted R^2 of the regression models which work for evaluating noise levels. The adjusted R^2 for all the models are shown in TABLE 5.

Nearly all the models are able to predict the noise levels by using different input variables, with R^2 higher than 0.7. Considering the first round of model selection, both the (a) and (b) parts for model 4 and 8 show good regression results. Therefore, model 4 and 8 are selected for further testing. Models numbered 3, 5, 6 and 7 are left out. However, model 6(b) has a good fit with the data, and can be used independently to calculate the noise levels from known surface characteristic parameters. Moreover, models from the variable selection method generally possess similar adjusted R^2 as those from the least square regressions but with less input variables. Herein, models with selected variables are retained. In summary, the models selected for the thin surface group are model 2, 4, 6(b), 8, 10, 12 and 14. They are to be validated by comparing predicted values with the measurement data from practical road surfaces.

TABLE 5 Adjusted R^2 of models for calculating noise levels

Model number	Model Type	Regression method	Surface characteristic combination	$L_{A, eq}$	L_{315}	L_{400}	L_{500}	L_{630}	L_{800}	L_{1000}	L_{1250}	L_{1600}	L_{2000}	L_{2500}	L_{3150}
1	1	Least square	-	0.89	0.74	0.92	0.92	0.91	0.93	0.92	0.85	0.78	0.84	0.91	0.94
2		Variable selection	-	0.90	0.71	0.91	0.91	0.92	0.94	0.92	0.86	0.78	0.77	0.92	0.94
3(b)	2	Least square	1	0.75	0.72	0.89	0.93	0.96	0.91	0.86	0.72	0.53	0.77	0.80	0.67
4(b)		Variable selection	1	0.75	0.73	0.89	0.93	0.96	0.90	0.86	0.72	0.53	0.77	0.80	0.65
5(b)		Least square	2	0.88	0.57	0.69	0.77	0.86	0.90	0.94	0.89	0.84	0.93	0.90	0.92
6(b)		Least square	2	0.88	0.57	0.69	0.77	0.86	0.90	0.94	0.89	0.84	0.93	0.90	0.92
7(b)		Least square	3	0.87	0.65	0.76	0.81	0.89	0.90	0.92	0.84	0.71	0.85	0.92	0.88
8(b)		Least square	3	0.87	0.65	0.76	0.81	0.89	0.90	0.92	0.84	0.71	0.85	0.92	0.88
9	3	Least square	1	0.88	0.77	0.95	0.97	0.97	0.93	0.90	0.83	0.77	0.89	0.93	0.93
10		Variable selection	1	0.90	0.73	0.95	0.97	0.97	0.94	0.92	0.86	0.78	0.90	0.94	0.94
11		Least square	2	0.97	0.59	0.90	0.93	0.93	0.96	0.97	0.96	0.91	0.93	0.97	0.98
12		Variable selection	2	0.92	0.75	0.91	0.93	0.93	0.95	0.94	0.91	0.94	0.94	0.93	0.97
13		Least square	3	0.95	0.72	0.92	0.91	0.90	0.96	0.95	0.90	0.83	0.89	0.94	0.96
14		Variable selection	3	0.90	0.75	0.91	0.93	0.93	0.94	0.92	0.86	0.86	0.89	0.95	0.97

VALIDATION OF THE MODELS

Road Surfaces for Validation

Validation of the model is performed by comparing the predicted noise levels with those measured on practical road sections. The data used for validation are from 24 thin layer surfacing sections on highway A6 in the Netherlands. The sections were built in 2006 with four different mixture designs. CPX noise levels, surface texture and sound absorption coefficients were measured on the newly built sections in 2006 as well as after half a year service of the road in 2007. In this study, as the material properties are given for the newly produced mixtures, only the measurement data in 2006 are used.

It should be noted that just the MPD was recorded for denoting the surface texture on highway A6, and no texture level on the octave band of wavelength was provided. However, for certain models, texture levels TL_{63} and TL_1 are required for performing the evaluation. In this study, the TL_{63} and TL_1 are determined by using the Model 8(a), see TABLE 2. It should be noted that measured data are always to be preferred for model validation. The author strongly recommends that the models with TL_{63} and TL_1 are validated with measured data in the future. In terms of the CPX measurements, different types of tyres were involved. As the present model is developed purely with a passenger car tyre moving at 80 km/h, only the CPX noise levels measured by using the standard passenger car tyre, namely type A in ISO/CD 11819-2 (*16*), are used in the validation. The driving speed was 80 km/m.

Final Model Selection

Noise levels are calculated by using the initially selected models. The root mean square error (RMSE) is calculated to assess the predictive power of the model. RMSE is a measure for the difference between predicted value from a model and the value actually observed. A smaller RMSE implies higher accuracy of the prediction. Calculation of RMSE is based on the following equation:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (Y_{obs,i} - Y_{model,i})^2}{n}} \qquad (4)$$

where $Y_{obs,i}$ is the observed values and $Y_{model,i}$ is the predicted value from the model. n is the number of observations. In this study, n=24. RMSE has the same units as the quantity being estimated.

The calculated RMSE values are given in TABLE 6. The models are listed in decreasing sequence of RMSE for the overall noise level $L_{A, eq}$. In addition, the maximum number of input parameters required by each model and the input parameter type are also shown. A final selection of the model was made based on the following considerations:

1) A high adjusted R^2 of the regression equation. This has been examined in last section, and all the candidate models included in the validation process have a high adjusted $R^{2.}$

2) A low RMSE value when comparing the predicted with the measured data.

3) A low number of input variables.

4) Material properties used as input variables are preferred.

5) The regression relationship is physically correct.

Based on these considerations, the following models were finally selected.

TABLE 6 RMSE between the observed and predicted noise levels

Model	$L_{A, eq}$	L_{315}	L_{400}	L_{500}	L_{630}	L_{800}	L_{1000}	L_{1250}	L_{1600}	L_{2000}	L_{2500}	L_{3150}	Maximum number of input parameter	Input variable type
Model 4(b)	1.84	0.97	1.89	2.48	3.13	3.49	3.11	2.51	3.25	5.89	4.87	1.35	2	Surface
Model 8(b)	2.23	0.89	1.76	2.43	2.72	3.44	3.43	3.33	4.37	3.85	2.72	1.53	3	Surface
Model 8	2.45	0.91	1.78	2.47	2.76	3.42	3.52	3.63	4.44	4.02	2.95	1.80	3	Material
Model 12	2.50	0.81	2.17	2.48	3.08	2.41	4.17	6.01	5.18	3.20	3.01	3.28	12	Material and surface
Model 2	2.53	1.07	2.17	2.57	2.98	3.03	3.70	4.11	6.40	3.74	2.37	3.23	6	Material
Model 14	2.53	0.81	2.17	2.48	3.08	3.02	3.70	4.11	6.52	6.38	2.27	3.28	9	Material and surface
Model 10	2.53	0.97	2.01	2.66	3.38	3.33	3.70	4.11	6.40	7.10	2.30	3.23	8	Material and surface
Model 4	2.68	1.01	1.77	2.47	2.91	3.67	3.71	3.89	4.68	4.07	3.38	1.68	4	Material
Model 6(b)	3.05	0.89	1.76	2.43	2.72	2.52	4.95	6.03	3.27	3.20	2.96	1.83	6	Surface

1) Modeling tyre - road noise from surface characteristics

Model 4(b) and Model 8(b) calculate the noise levels from the surface characteristics, and have a better prediction power in comparison with other models on most of the noise levels. Model (4) provides the best prediction of the overall noise level and shows a good fit with the measured data at frequencies below 2000 Hz. This reveals that these noise levels can be well predicted from the linear combination of MPD and the maximum absorption coefficient. In previous studies, the MPD is not always considered as a good predictor for tyre - road noise. However, from this research, it is found that when concentrating on a certain type of surface, the thin layer surfacing in this study, the MPD can be used very well to predict the tyre - road noise levels.

In the 2000 Hz and 2500 HZ frequency band, the RMSEs for Model 8(b) are lower which denotes a better prediction power. This is because the noise level at a high frequency is greatly influenced by the short wavelength texture level (*20*, *21*), and using

TL_1 as an input variable is thought to improve the prediction capability of Model 8(b). Towards a better prediction, a new model is set up by combining certain equations selected from Model 4(b) and Model 8(b). The combination is marked by the blue color in TABLE 6. The new model is called Model I, and it can be used to predict the noise levels on thin layer surfacings with MPD, maximum absorption coefficient, TL_{63} and TL_1 as input parameters. A summary of the regression coefficient of Model I is given in TABLE 7.

TABLE 7 Regression coefficients for Model I

	$L_{A,\,eq}$	L_{315}	L_{400}	L_{500}	L_{630}	L_{800}	L_{1000}	L_{1250}	L_{1600}	L_{2000}	L_{2500}	L_{3150}
Constant	90.08	69.95	70.77	74.07	80.01	84.21	79.96	78.08	78.88	114.80	115.15	122.46
MPD	6.32	2.33	4.70	6.06	4.22	4.33	9.47	10.85	9.92	-	-	-
TL_{63}	-	-	-	-	-	-	-	-	-	0.45	-	-
TL_1	-	-	-	-	-	-	-	-	-	-1.37	-0.94	-1.21
Max. absorption	-4.56	0.00	-2.18	-1.59	1.46	0.00	-4.93	-8.44	-14.97	-8.09	-5.94	-1.82
R^2	0.78	0.75	0.90	0.94	0.96	0.91	0.87	0.75	0.59	0.88	0.93	0.90
Adjusted R^2	0.75	0.73	0.89	0.93	0.96	0.90	0.86	0.72	0.53	0.85	0.92	0.88

2) Modeling tyre - road noise from material properties

As shown in TABLE 6, Model 8 performs the best among the models for predicting noise level from material properties. The model calculates the noise level from the evaluated TL_{63} and TL_1 and maximum absorption coefficient based on the material properties. Only three material properties, namely maximum aggregate size, coarse aggregate content and air voids content are required as input variables. This means that the tyre - road noise can be evaluated from the three material properties. According to TABLE 2, the sign of the regression coefficients for the three material parameters are also in accordance with the analysis of the laboratory measurement results described in previous research (*13*), which means the regression relationship is physically correct.

This model is suggested to be used for predicting noise levels from material properties (green colour in TABLE 6), and it is renamed as Model II. For the regression coefficients of Model II, the reader is referred to TABLE 2 and TABLE 3.

For other models, the amount of input variables is generally large, and the RMSE values are higher than those of Model I and Model II. These models are excluded from the investigation.

Validation of the Final Models

Model I and Model II are finally selected. The noise levels predicted with these two models are compared to the noise levels measured on the sections with the four mixtures. The results are shown in FIGURE 3 and FIGURE 4 respectively. The error bars in the figures denote the standard deviation of the measured or predicted values on a certain road surface.

From FIGURE 3 (a), it can be seen that Model I makes very good predictions of the overall tyre - road noise levels on sections 1, 2 and 4. On section 3, the model underestimates the noise level with around 3 dB (A). In FIGURE 4 (a), the overall noise level is perfectly predicted by Modell II on surface 1. On other sections, the difference between the prediction and the measurement is between 2.5 dB (A) to 3 dB (A).

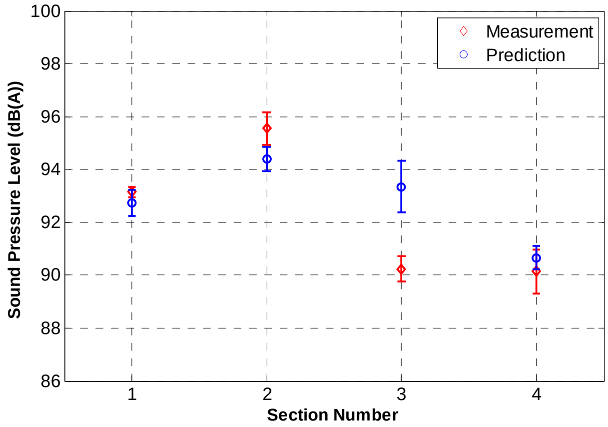
For noise levels on 1/3 octave band, as shown in FIGURE 3 (b) to (e) and FIGURE 4 (b) to (e), the modeled curves generally have similar shapes as those from the measurements. At most of the frequencies, especially frequencies below 800 Hz, the predicted noise levels are in agreement with the measured ones, with a difference not larger than 2 dB (A). The noise levels are underestimated between 1600 Hz and 2500 HZ on surface 1, and between 1000 Hz and 2500 Hz for surface 2. There are overestimations of noise levels between 630 Hz and 1250 Hz on surface 3. The best predictions are obtained for surface 4 by means of Model I and Model II.

It should be noticed that the models are developed based on the averaged CPX levels from 10 different passenger car tyres. In the validation, the measurement data are just from one type of tyre. Considering the variations of noise among the tyres, the prediction results are rather good, as the predicted noise levels are generally close to the measured data, and the distribution of the noise levels over the frequencies is also fairly well predicted by the models.

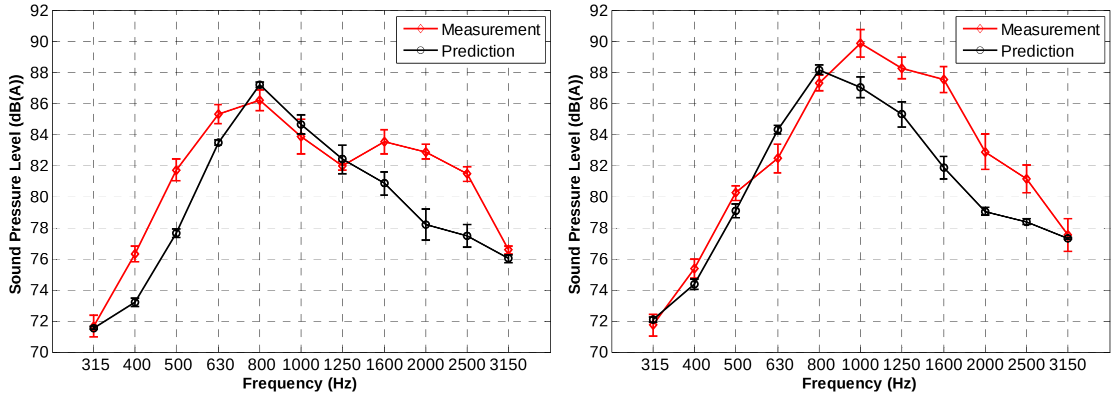
The fact that both models only need a small amount of input variables is considered to be an advantage. The change of noise level with changing basic material properties can also be determined with Model II. Therefore, the models are recommended to be used for the following applications:

1) prediction of the tyre - road noise level when designing thin layer surfacings (Model II);

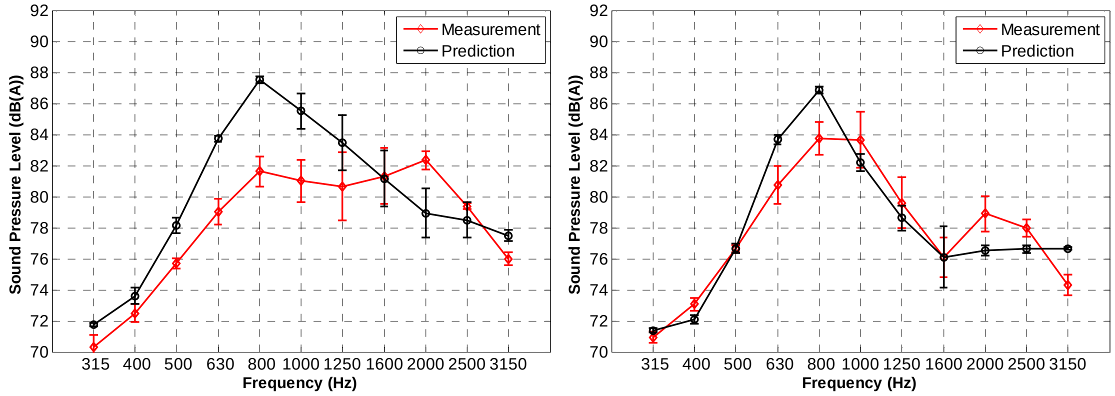
2) evaluation of the tyre - road noise level based on collected surface characteristic data (Model I).



(a) Overall noise level

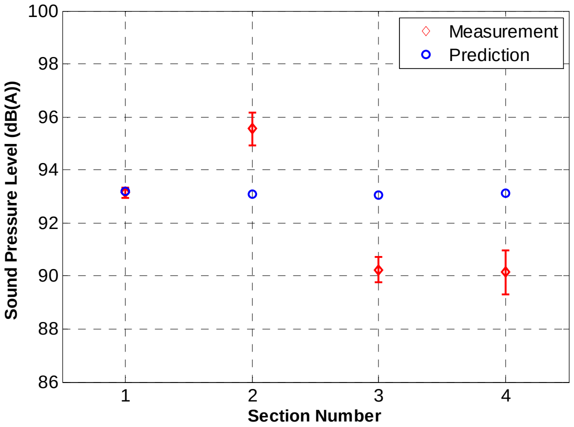


(b) Validation mixture 1 (c) Validation mixture 2

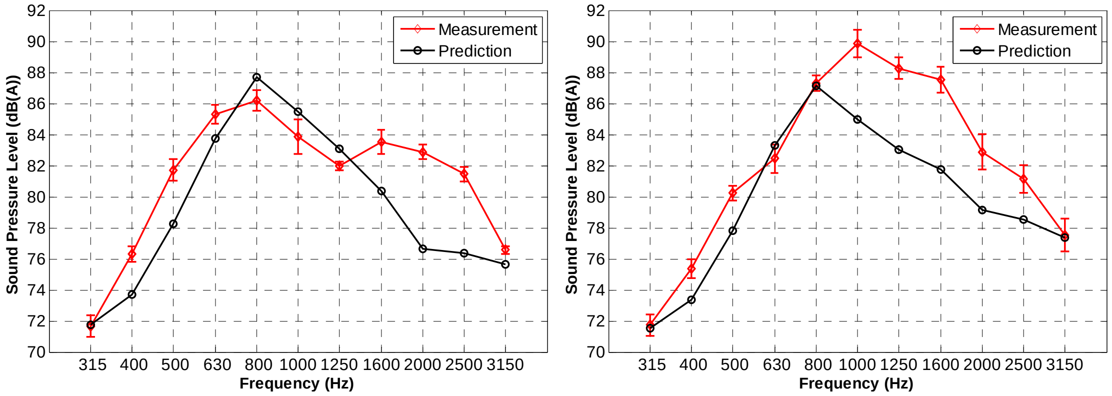


(d) Validation mixture 3 (e) Validation mixture 4

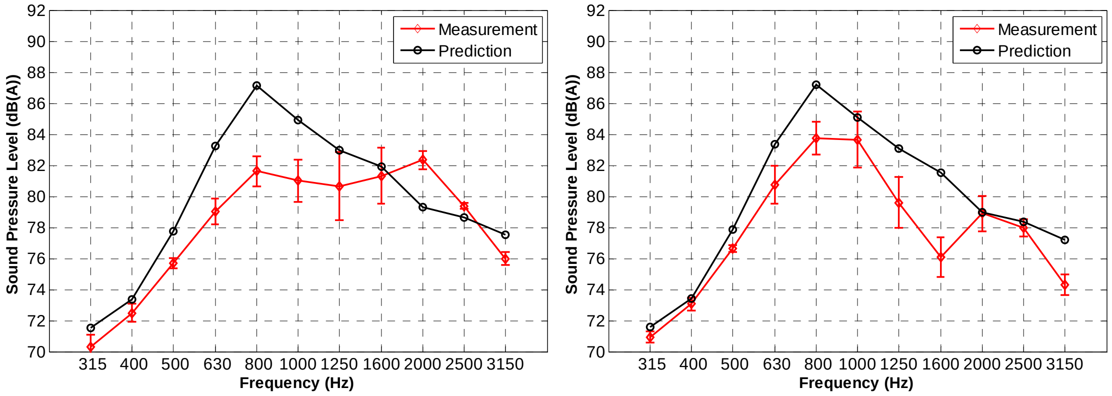
FIGURE 3 Noise levels from measurements and predictions with Model I



(a) Overall noise level



(b) Validation mixture 1 (c) Validation mixture 2



(d) Validation mixture 3 (e) Validation mixture 4

FIGURE 4 Noise levels from measurements and predictions with Model II

CONCLUSIONS AND RECOMMENDATIONS

The goal of this paper was to develop models for predicting tyre - road noise levels from material properties and surface characteristics of thin layer surfacings. The modeling was accomplished by linear regression with data from laboratory and field measurements. The statistical models are validated with measurement data from thin layer surfacings on highway in the Netherlands. By comparing the prediction results obtained with the candidate models from the measured values and considering the number and type of the input variables, two models were finally proposed as outcome of the study.

The validation results show that the predictions are reliable. The models are of importance for road engineers. Model I can be used to determine the tyre - road noise levels from existing thin layer surfacings of which the surface characteristics are measured. Model II is applicable for making predictions of tyre - road noise during the design process, before the pavements are constructed. It would help the road engineers to compare the noise levels from surfaces with different material properties and in turn to optimize the designs. However, it is suggested to further validate the models with extra data from practical road surfaces. Improvements could be made towards a higher prediction accuracy. Moreover, the present models need to be extended by considering different types of road surfaces and truck tyres.

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REFERENCES

1. Sandberg, U. Tyre/road Noise-Myths and Realities. In *Proceedings 2001 International Congress and Exhibition on Noise Control Engineering*. 2001. The Hague, The Netherlands.
2. Beckenbauer, T. and W. Kropp. *A hybrid Model for Analysis and Design of Low Noise Road Surfaces*. In *EuroNoise 2006 conference*. 2006. Tampere, Finland.
3. Bernhard, R. J., and R. S. McDaniel. Basics of Noise Generation for Pavement Engineers. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1941, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 161–166.
4. Bekke, D.A., Y. H. Wijnant, and A. Boer de. Experimental Review on Interior Tire-road Noise Models. In *International Conference on Noise and Vibration Engineering, ISMA 2010*. 2010, Katholieke Universiteit Leuven: Leuven, Belgium.
5. Klein, P. and J. F. Hamet. END$_T$, *Expected Pass-By Noise Level Difference from Texture Level Variation of the Road Surface*. Piblication SILVIA Report SILVIA-INRETS-021-01-WP2-070705. 2005.
6. Hamet, J.F. and P. Klein. *ENRa, Expected Pass-By Noise Level Reduction from Acoustic Absorption of the Road Surface*. Piblication SILVIA Project Report SILVIA-INRETS-018-02-WP2-040505. 2005.

7. Losa, M., P. Leandri and R. Rand Bacci. Empirical Rolling Noise Prediction Models Based on Pavement Surface Characteristics. *International Journal of Road Materials and Pavement Design.* EATA10, 2010. **11**(special issue): pp. 487-506.

8. Schutte, A., *Numerical Simulation of Tyre/Road Noise*. 2011, University of Twente: Enschede, The Netherlands.

9. Larsson, K., S. Barrelet and W. Kropp , The Modelling of the Dynamic Behaviour of Tyre Tread Blocks. *Applied Acoustics*, 2002. **63**(6): pp. 659-677.

10. O'Boy, D.J. and A. P. Dowling, Tyre/Road Interaction Noise—Numerical Noise Prediction of a Patterned Tyre on a Rough Road Surface. *Journal of Sound and Vibration*, 2009. **323**(1–2): p. 270-291.

11. Li, M., W. van Keulen, M. van de Ven and A.A.A. Molenaar. Development of a New Type of Prediction Model for Predicting Tyre/Road Noise. In *Sustainable Construction Materials 2012*. pp. 408-420.

12. Kuijpers, A.H.W.M., H.M.Peeters, W. Kropp, and T. Beckenbauer. *Acoustic Optimization Tool, RE4 - Modelling Refinements in the SPERoN Framework*. In M+P Report DWW.06.04.7. 2007: Vught, the Netherlands.

13. Li, M, W. van Keulen, M. van de Ven, A.A.A. Molenaar, G. Tang. Investigation on Material Properties and Surface Characteristics related to Tyre–Road Noise for Thin Layer Surfacings. *Construction and Building Materials*, 2014. 59(0): pp. 62-71.

14. Nelson, J. T., E. Kohler, A. Öngel, and B. Rymer. Acoustical Absorption of Porous Pavement, In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2058, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 125–132.

15. Crocker, M. J., D. Hanson, Z. Li, R. Karjatkar, and K. S. Vissamraju. Measurement of Acoustical and Mechanical Properties of Porous Road Surfaces and Tire and Road Noise. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1891, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 16–22.

16. Wayson, R. L. *NCHRP Synthesis 268 - Relationship between Pavement Surface Texture and Highway Traffic Noise*. Transportation Research Board, National Academy Press, Washington D.C., 1998.

17. ISO/CD-11819-2. *Method for Measuring the Influence of Road Surfacings on Traffic Noise - Part 2: The Close Proximity Method*. 2000.

18. Hocking, R.R. The Analysis and Selection of Variables in Linear Regression. *Biometrics*, 1976. **32**:pp. 1-49.

19. Hamilton, L.C. *Regression with Graphics : a Second Course in Applied Statistics*. 1992, Belmont, Calif.: Duxbury Press.

20. Sandberg, U. and J. Ejsmont. *Tyre/Road Noise Reference Book*. Kisa, Sweden: Informex, 2002.

21. Anfosso-Lédée, F. and M.-T. Do. Geometric Descriptors of Road Surface Texture in Relation to Tire-Road Noise. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1806, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 160–167.