

2015

Statistical Model of Tyre-Road Noise for Thin Layer Surfacing

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Recommended Citation

Li, M.; van Keulen, W.; Ceylan, Halil; van de Ven, M.F.C; and Molenaar, A.A.A, "Statistical Model of Tyre-Road Noise for Thin Layer Surfacing" (2015). *Civil, Construction and Environmental Engineering Conference Presentations and Proceedings*. 41.
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Statistical Model of Tyre-Road Noise for Thin Layer Surfacing

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.

Keywords

tyre-road noise, statistical model, thin layer surfacing, surface texture, sound absorption

Disciplines

Civil and Environmental Engineering | Construction Engineering and Management

Comments

This paper was peer-reviewed by TRB and presented at the Annual Meeting of the Transportation Research Board, Washington, D.C. It can be cited as Li, M., W. van Keulen, H. Ceylan, M. F. C. van de Ven, and A. A. A. Molenaar, "Statistical Model of Tyre-Road Noise for Thin Layer Surfacing." Transportation Research Board 94th Annual Meeting, no. 15-5544. 2015. Posted with permission.

Statistical Model of Tyre - Road Noise for Thin Layer Surfacing

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Word count: 4,716 + (7TABLEs + 4FIGUREs) = 7,466

Submission date: Aug. 01, 2014

1 **ABSTRACT**

2

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

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

21

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

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1 INTRODUCTION

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

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

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

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

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

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

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

42 DESCRIPTION OF THE MODEL

43 *Framework of the Model*

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47 FIGURE 1 shows three possibilities to relate tyre - road noise with the mixture
48 composition and the surface characteristics. The figure shows that the noise levels can be
49 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.

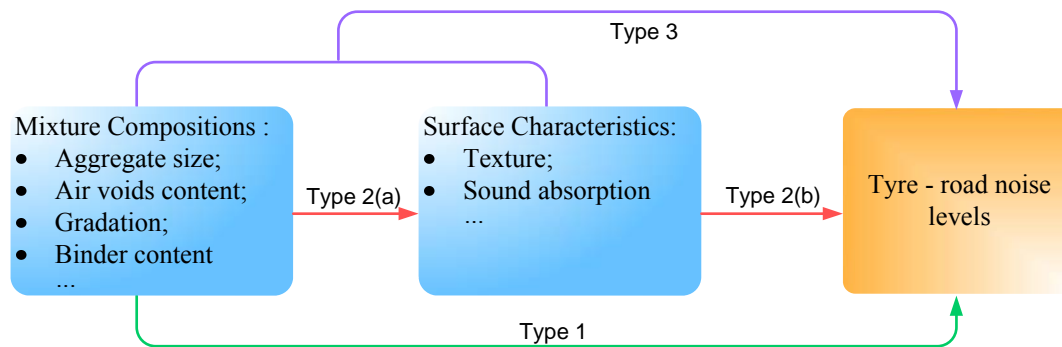


FIGURE 1 Three models for predicting tyre - road noise levels

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

1 different combinations of indicators for surface texture and sound absorption available for
 2 model development. In this study, three combinations of surface characteristics are
 3 adopted: 1) MPD and maximum absorption coefficient; 2) selected surface texture levels
 4 and sound absorptions on the frequency band; 3) selected surface texture levels and
 5 maximum absorption coefficients.

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

14
 15 **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; Maximum Absorption coefficient.	mm	Overall level (from CPX test with passenger tyre);	
Coarse aggregate content;	% by mass		-		
Fine aggregate content;	% by mass	Combination 2 Selected texture levels with various wavelengths; Absorption level on 1/3 octave band of frequency.	dB, ref 10 ⁻⁶ mm	Noise levels on 1/3 octave band of frequency (from CPX test with passenger tyre).	dB(A)
Air voids content;	% by volume		-		
Binder content;	% by mass ratio with the mineral aggregate	Combination 3 Selected texture levels with various wavelengths; Maximum Absorption coefficient.	dB, ref 10 ⁻⁶ mm		
Thickness	mm		-		

16
 17 *Regression Methods*

18
 19 Overall noise levels and noise levels at each frequency band are modelled. The target
 20 model is a set of linear regression equations. Certain equations are developed
 21 corresponding to the overall noise level and the noise level at each frequency band (350
 22 Hz to 3150 Hz on 1/3 octave band). As there is more than one independent variable in the
 23 regression, multivariate linear equations are constructed. Multivariate regression
 24 estimates an equation with the form:

$$25 \quad \mathbf{y} = \mathbf{a} + \mathbf{X}\mathbf{b} \quad (1)$$

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

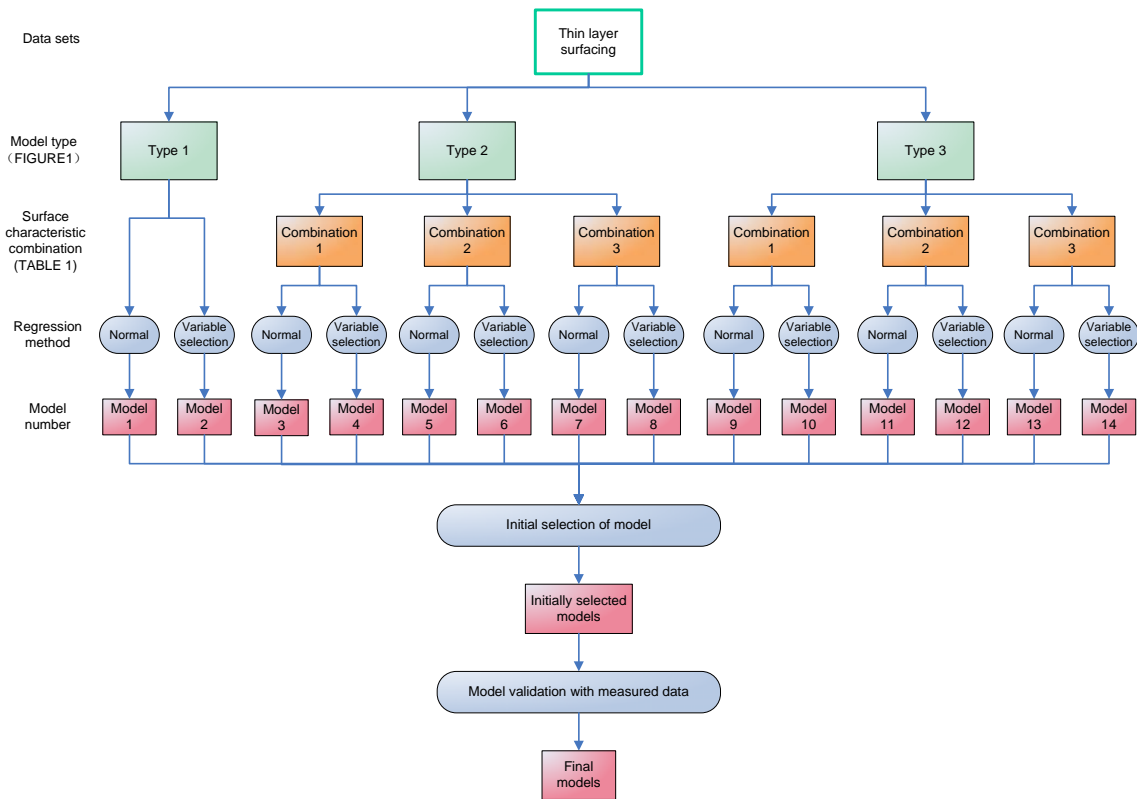
32 The ordinary least squares approach is used to develop the linear regression
 33 models for each type of model with different variable input combinations. In addition,
 34 alternative models are also set up by means of variable selection methods. This aims to
 35 reduce the dimension of the independent variable vector and to simplify the structure of

1 the model. The algorithms used in this study are backward elimination and the stepwise
 2 selection (18).

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

10 **MODEL DEVELOPMENT**

11 A complete overview of the modeling process is given in FIGURE 2. By taking into
 12 account all the conditions, a total of 14 models were constructed. Each of these models is
 13 given a number as shown in FIGURE 2. An initial selection was then performed on the 14
 14 models to choose those with the best fit to the measured data. The selected models were
 15 validated using measurement data from practical road sections. The final models were
 16 determined based on the results of the validation.
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20
 21
 22 **FIGURE 2 Complete model development process**
 23

24 *Regression Results*

25
 26 As there are 14 models in total, only the regression results of Model 8 are shown
 27 as an example. TABLE 2 and TABLE 3 show the modeling results for Model 8. Previous
 28 study has shown that the generation of tyre - road noise levels is attributed to surface
 29 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 wavelength 1 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:

$$TL_{63} = 19.39 + 2.85 MS + 0.19 \Omega, \quad R^2 = 0.95 \quad (2)$$

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

where

$L_{A,eq}$ – the overall noise level, dB (A);

MS – maximum aggregate size, mm, for thin layer surfacing, $4 \text{ mm} \leq MS \leq 8 \text{ mm}$;

Ω – air voids content, % by volume, for thin layer surfacing, $4\% \leq \Omega < 25\%$.

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 .

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

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

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

20
 21 **TABLE 4 Adjusted R^2 for sub-models relating material properties to surface**
 22 **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}
	3(a)	Least square	1	0.93			0.83				
	4(a)	Variable selection	1	0.92			0.85				
Thin layer surfacing	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				

23
 24 The second round of model selection is accomplished by investigating the
 25 adjusted R^2 of the regression models which work for evaluating noise levels. The adjusted
 26 R^2 for all the models are shown in TABLE 5.

27 Nearly all the models are able to predict the noise levels by using different input
 28 variables, with R^2 higher than 0.7. Considering the first round of model selection, both the
 29 (a) and (b) parts for model 4 and 8 show good regression results. Therefore, model 4 and
 30 8 are selected for further testing. Models numbered 3, 5, 6 and 7 are left out. However,
 31 model 6(b) has a good fit with the data, and can be used independently to calculate the
 32 noise levels from known surface characteristic parameters. Moreover, models from the
 33 variable selection method generally possess similar adjusted R^2 as those from the least
 34 square regressions but with less input variables. Herein, models with selected variables
 35 are retained. In summary, the models selected for the thin surface group are model 2, 4,
 36 6(b), 8, 10, 12 and 14. They are to be validated by comparing predicted values with the
 37 measurement data from practical road surfaces.

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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)		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)	2	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		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	3	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

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VALIDATION OF THE MODELS

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Road Surfaces for Validation

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Final Model Selection

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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:

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

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 Model 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

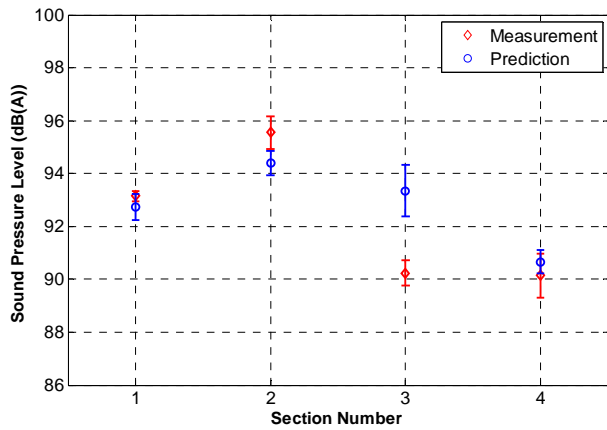
1 measurements. At most of the frequencies, especially frequencies below 800 Hz, the
2 predicted noise levels are in agreement with the measured ones, with a difference not
3 larger than 2 dB (A). The noise levels are underestimated between 1600 Hz and 2500 HZ
4 on surface 1, and between 1000 Hz and 2500 Hz for surface 2. There are overestimations
5 of noise levels between 630 Hz and 1250 Hz on surface 3. The best predictions are
6 obtained for surface 4 by means of Model I and Model II.

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

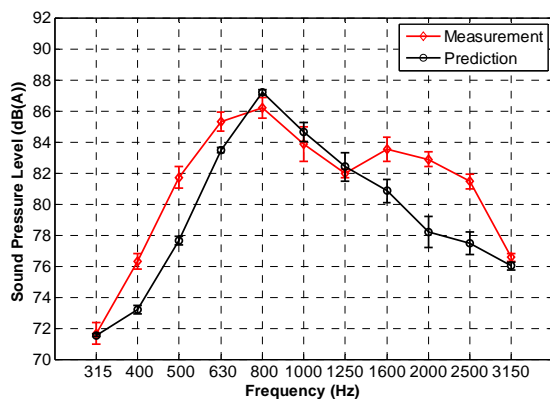
13 The fact that both models only need a small amount of input variables is
14 considered to be an advantage. The change of noise level with changing basic material
15 properties can also be determined with Model II. Therefore, the models are recommended
16 to be used for the following applications:

- 17 1) prediction of the tyre - road noise level when designing thin layer surfacings
18 (Model II);
- 19 2) evaluation of the tyre - road noise level based on collected surface characteristic
20 data (Model I).

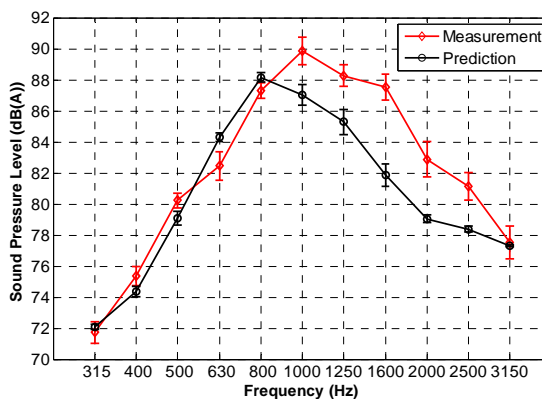
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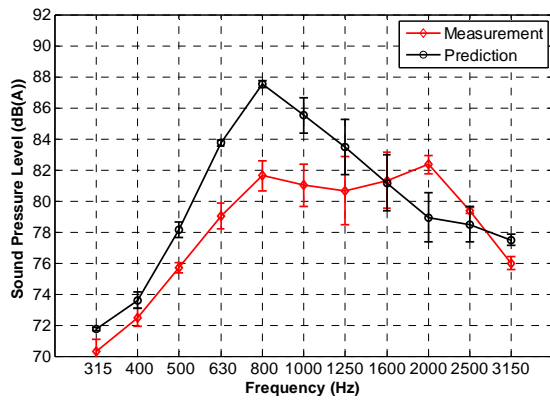
(a) Overall noise level



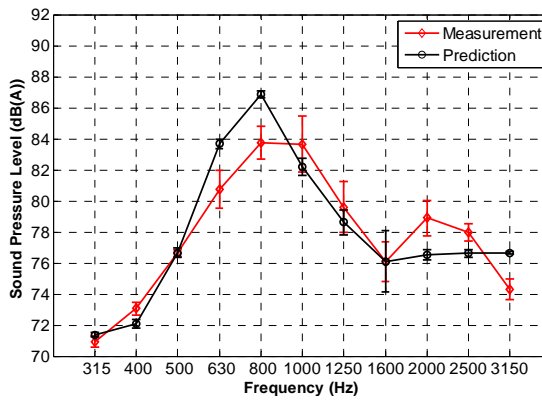
(b) Validation mixture 1



(c) Validation mixture 2

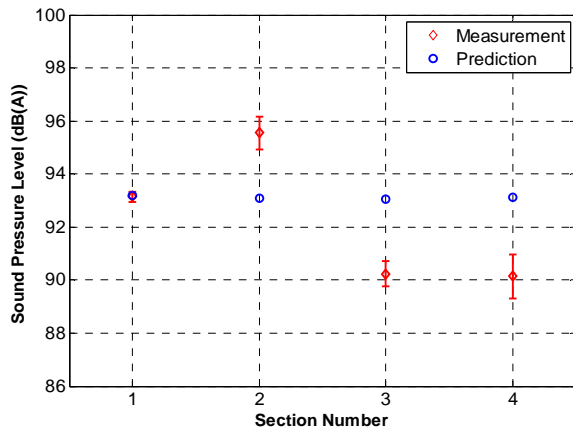


(d) Validation mixture 3

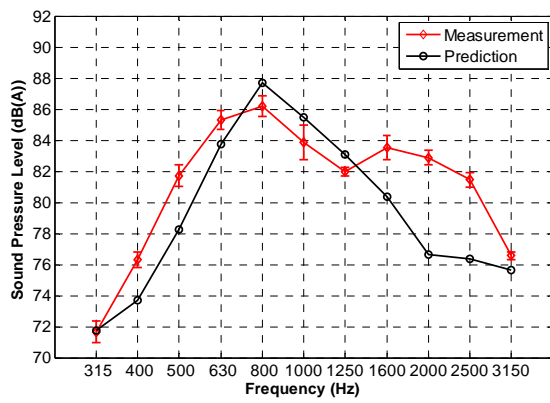


(e) Validation mixture 4

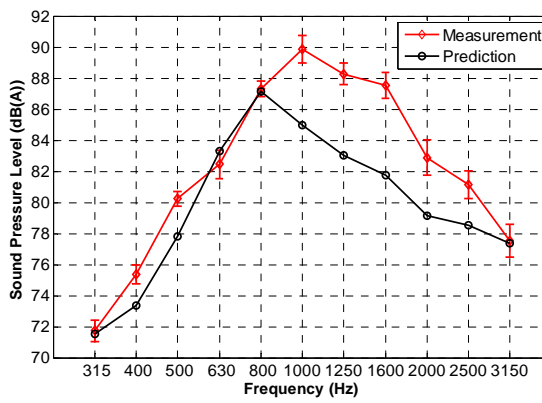
FIGURE 3 Noise levels from measurements and predictions with Model I



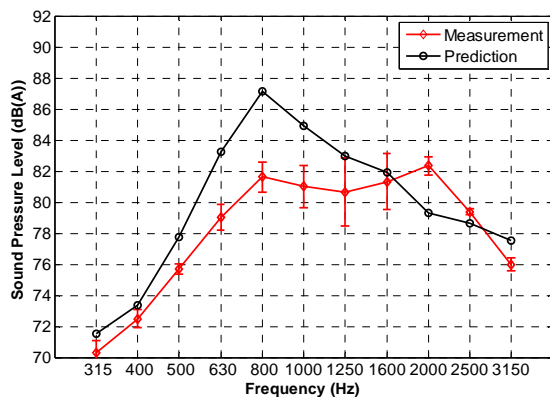
(a) Overall noise level



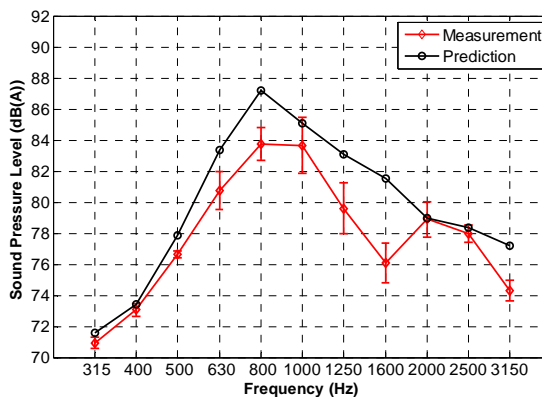
(b) Validation mixture 1



(c) Validation mixture 2



(d) Validation mixture 3



(e) Validation mixture 4

FIGURE 4 Noise levels from measurements and predictions with Model II

1 CONCLUSIONS AND RECOMMENDATIONS

2
3 The goal of this paper was to develop models for predicting tyre - road noise levels from
4 material properties and surface characteristics of thin layer surfacings. The modeling was
5 accomplished by linear regression with data from laboratory and field measurements. The
6 statistical models are validated with measurement data from thin layer surfacings on
7 highway in the Netherlands. By comparing the prediction results obtained with the
8 candidate models from the measured values and considering the number and type of the
9 input variables, two models were finally proposed as outcome of the study.

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

21 ACKNOWLEDGMENTS

22
23 The authors would like to thank Centre for Transport and Navigation (DVS) in the
24 Netherlands for providing filed measurement data and advices.

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