



EMPIRICAL ACOUSTIC MODEL FOR ASPHALT SURFACE MIXES

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Abstract. In this paper, an empirical acoustic model was developed for four asphalt surface mixes, including conventional dense-graded asphalt concrete (DGAC), open-graded asphalt concrete (OGAC), rubberized open-graded asphalt concrete (RAC-O), and rubberized gap-graded asphalt concrete (RAC-G). Tire/pavement noise data were collected and converted from in-service flexible pavements using an on-board sound intensity (OBSI) method, for four consecutive years. Because the panel structured noise data contain potential violations to basic assumptions of ordinary least square models, several econometric techniques were used to address the violations and develop rational models. Specifically, instrumental variables and a multinomial logit (MNL) model were used to address endogeneity, and a two-way random-effect model was used to capture the unobserved heterogeneity. The estimated model suggests that tire/pavement noise increases with pavement age and mean profile depth (MPD), and decreases with air-void content of surface mixes. The noise levels of the four asphalt surface mixes rank as: RAC-O < OGAC < RAC-G < DGAC.

Keywords: on-board sound intensity, asphalt mixes, panel data, econometrics, empirical model, noise.

1. Introduction

A quiet pavement, which produces lower tire/pavement noise than conventional pavements, has attracted significant attention from pavement community due to the increasing influence of traffic noise on the life quality and health of neighbouring residents and high costs of sound barrier walls. There has been an extensive body of research on tire/pavement noise, ranging from establishment of noise generation mechanisms to development of noise level prediction models.

Highway noise arises from vehicles in motion. Primary sources of vehicle noise include (Nelson, Phillips 1997):

- aerodynamic noise that originates from turbulent airflow around moving vehicles;
- power-unit noise that comes from the engine, exhaust, power train and so on;
- tire/pavement noise that emits from a rolling tire due to the interaction between tire and pavement, which may be reduced by suitable pavement design.

Among the three sources of traffic noise, tire/pavement noise dominates when vehicle speed exceeds 50 km/h. Therefore, by reducing tire/pavement noise, the overall highway noise is significantly alleviated. Tire/pavement noise generation mechanisms are further divided into several categories:

1. block snap-out phenomenon that results from the contact between tire tread and pavement surface (Bermann 1980);

2. air-pumping effects that comes from the aerodynamic process between the tire and pavement surface. It tends to produce significant level of noise over a frequency of 1,000 Hz when pavement surface is nonporous and smooth (Sandberg, Descornet 1980);

3. adhesion mechanism that is caused by tire vibrations associated with the forces at the contact patch between tire and pavement surface (Ongel *et al.* 2008a).

Two approaches are taken to reduce the tire/pavement noise: one is to optimize the tire tread patterns, and the other is to improve the running conditions of pavement (Zheglov 2005). From a pavement engineer's perspective, pavement surface needs to be designed appropriately following the noise generation mechanisms. The effects of pavement surface mix design variables on tire/pavement noise and the durability, in terms of both acoustic and other performance indices, of various mix designs, therefore, need to be understood before an optimum design is achieved.

The generation of tire/pavement noise has been analyzed theoretically and through simulation. Cao *et al.* (2008) integrated as many as ten components of tire/pavement noise together to form a theoretical noise generation

model. However, no case study was provided using the model. Dai and Lou (2008) assessed the noise level on porous and nonporous asphalt pavement, suggesting porous asphalt pavement to be quieter, and validated their findings via Finite Element Model (FEM). Larsson *et al.* (2002) built a FEM to incorporate the dynamic behaviour into the model to simulate a rolling tire on a rough road. The simulation results were in good agreement with tire measures for radial direction but poor agreement for tangential direction. More examples of FEM simulations are included in the publications by Biermann *et al.* (2007), Brinkmeier *et al.* (2008), Wullens and Kropp (2004), and Ghoreishy (2008). Although the theoretical analysis and simulation have addressed the noise generation mechanisms qualitatively, they are limited to some predetermined and simplified pavement mix properties and typically unable to model the acoustic durability of a specific pavement surface type. Empirical study with data collected from in-service pavements, therefore, is necessary to develop comprehensive models that directly address the acoustic property of a pavement under actual traffic and environmental conditions.

In 2005, a multi-year research project to investigate the surface performance of various asphalt mixes, including noise, durability, permeability and friction trend, was initiated in California (Bendtsen *et al.* 2010; Ongel *et al.* 2008a, 2008b). One primary goal of the project was to determine the level and trend of tire/pavement noise on various asphalt pavements. Multiple regression analysis was performed to determine key mixture variables that affect tire/pavement noise, and to develop empirical acoustic models for various asphalt surface mixes (Lu *et al.* 2009, 2010). The multiple regression analysis assumed independence between individual observations, which may not be true for observations repeated over years on the same sample unit. Conclusions from that study, therefore, might be biased.

The objective of the study presented in this paper is to develop an empirical acoustic model for various surface mixes, following a more strict econometric statistical approach to assure the reliability and stability of the model.

2. Data source and conversion

Tire/pavement noise was measured on about 80 pavement sections using one version of the on-board sound intensity (OBSI) method developed in California. These sections include four major asphalt surface mixes: conventional dense-graded asphalt concrete (DGAC), open-graded asphalt concrete (OGAC), rubberized open-graded asphalt concrete (RAC-O), and rubberized gap-graded asphalt concrete (RAC-G). Since the sound intensity measurement is highly affected by test conditions including test vehicle speed, air density, test tire type, and others, the noise measurements were converted to the same set of conditions before analysis using a series of calibration equations developed in the same study (Lu *et al.* 2009). The on-board sound intensity (OBSI) is presented in terms of spectral content in 1/3 octave bands, covering a frequency range from 500 Hz

to 5000 Hz (Lu *et al.* 2009). The overall A-weighted sound intensity level is calculated by summing sound intensity levels at each frequency using the following equation:

$$\text{Overall OBSI}(dB(A)) = 10 \times \log \sum_i 10^{\frac{f_i}{10}}, \quad (1)$$

where f_i – A-weighted sound intensity level at each 1/3 octave frequency, dB (A).

The frequencies included in the analysis in this study are between 500 Hz and 5000 Hz. The data used for estimation were collected during 4 years.

3. Methodology

When using field data or observations of in-service pavements for performance modelling, several statistical issues may severely jeopardize the credibility and applicability of the developed model if they are not properly addressed. These issues may include error term autocorrelation, heteroscedasticity, unobserved heterogeneity, endogeneity, and selection bias. In statistics, autocorrelation describes the correlation between error terms at different points in time; a sequence of random variables is heteroscedastic if the random variables have different variances; unobserved heterogeneity is one instance where correlation between observables and un-observables are expected; endogeneity exists if independent variables are correlated with the error term; selection bias is a statistical bias in which there is an error in choosing observations to take part in the model development. In the context of this study in which panel data were collected, two of the above issues, unobserved heterogeneity (both cross-sectional and time serial) and endogeneity, may exist and need to be addressed explicitly. One may find more information about the model construction in another paper of the authors (Yu, Lu 2012).

3.1. Unobserved heterogeneity

In the development of the empirical model, not only the difference in acoustic performance of various surface mixes needs to be addressed, but also the acoustic aging properties of various mixes should be considered. Under this requirement, a panel structured data set, which consists of repeated observations on various pavement sections over several years, was collected and used for modelling. Thus, there are multiple observations for each pavement section. With panel data, unobserved heterogeneity is unavoidable and must be captured in modelling. Generally speaking, unobserved heterogeneity refers to differences across sections and/or time that may not be appropriately reflected in the available explanatory variables of a classical linear regression model.

$$Y_{it} = \beta' X_{it} + \mu_{it}, \quad i = 1, \dots, n, \quad t = 1, \dots, T, \quad (2)$$

where Y_{it} – explained variables; β' – a vector of parameters to be estimated; X_{it} – a vector of explanatory variables; μ_{it} – a disturbance term; i – pavement section; n – total number of pavement sections; t – time period.

Two approaches are developed to capture the unobserved heterogeneity: fixed-effect model and random-effect model. The fixed-effect model examines cross-sectional and/or time-serial difference in the intercept term. If both cross-sectional and time-serial differences are examined, the model is called two-way fixed-effect model; if only cross-sectional or time serial difference is examined, it is called one-way fixed-effect model. Ordinary least-squares (OLS) regression method is frequently used to estimate the parameters of the fixed-effect model. The two-way fixed-effect model is written as:

$$Y_{it} = \mu_i + \mu_t + \beta' X_{it} + v_{it}, \quad (3)$$

where μ_i – a random error characterizing the i^{th} section and being constant over time; μ_t – a random error characterizing the t^{th} year and being constant across sections; v_{it} – an uncorrelated error; and all the other variables have the same meanings as those in Eq (1).

The two-way fixed-effect model suffers from a shortcoming for its prohibitive estimation of many parameters (i.e. constant terms, u_i and u_t) and associated loss of degree of freedom. A two-way random-effect model, however, overcomes this shortcoming. A random-effect model, by contrast, estimates variance components for cross sections, time series and error, assuming the same intercept and slopes. The difference among cross sections and time series lies in the variance of the error term. The generalized least squares (GLS) method is used to estimate the random effect model. Reflected in the formula, the disturbance term is:

$$u_{it} = u_i + u_t + v_{it}, \quad (4)$$

where all the variables have the same meanings as those in Eq (3).

Rewriting Eq (3) using Eq (4), the two-way random-effect model is given by

$$Y_{it} = \beta' X_{it} + \mu_{it}, \quad (5)$$

where all the variables have the same meanings as those in Eq (3).

3.2. Endogeneity bias correction

In econometrics, the problem of endogeneity occurs when an independent variable is correlated with the error term in a regression model. This implies that the regression coefficient in an OLS regression is biased. In the context of this study, three variables are likely to be endogenous since they are designed by engineers, including: surface mix thickness, air-void content of surface mix, and surface mix type. For the first two variables, instrumental variables (IVs) were used to substitute the original variables in the model constructions, which possess a property to be uncorrelated with the error term while still correlated with the original variables (Stock, Trebbi 2003). The IVs were represented by the other variables that would be used

in the model specifications, including *Age*, *AADTC*, *Pre*, *MPD*, *IRI* (Eqs (6)–(7)). For the four asphaltic mixes, it is a probability issue to select a specific mix type given certain traffic volume, weather condition, and pavement structure so a multinomial logit (MNL) model is considered.

Eqs (6)–(7) were used to calculate the predicted values:

$$\ln(\text{Thickness}) = a_0 + a_1 \ln(\text{Age}) + a_2 \ln(\text{AADTC}) + a_3 \ln(\text{Pre}) + a_4 \ln(\text{MPD}) + a_5 \ln(\text{IRI}) + \varepsilon, \quad (6)$$

$$\ln(\text{AirVoid}) = a_0 + a_1 \ln(\text{Age}) + a_2 \ln(\text{AADTC}) + a_3 \ln(\text{Pre}) + a_4 \ln(\text{MPD}) + a_5 \ln(\text{IRI}) + \varepsilon, \quad (7)$$

where *Thickness*, mm; *AirVoid*, %, – dependent variables, representing the thickness and air-void content of the mix; *Age* – the number of years of a pavement section being open to traffic; *AADTC* – Annual Average Daily traffic on the Coring Lane, vpd; *Pre* – Annual Total Precipitation, mm; *MPD* – Mean Profile Depth, micron, according to *ASTM E 1845-09 Standard Practice for Calculating Pavement Macrotecture Mean Profile Depth*; *IRI* – International Roughness Index, m/km, according to *ASTM E 1926-08 Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements*; ε – an error term; $a_0 \dots a_5$ – coefficients to be estimated.

The regression results of Eqs (6)–(7) are shown in Tables 1.

The results in Table 1 were used to calculate the predicted values of *Thickness* and *AirVoid* variables, which would serve as substitutes of the original values to continue the research in order to correct for the endogeneity brought by the predetermined nature of the two variables.

The probability of an agency selecting a certain mix type depends on specific structural conditions, climate variables, and traffic volume. Thus mix types are correlated with the error term if they are not differentiated. A MNL model was used to correct the mix type endogeneity. Four types of surface mixes, including DGAC, OGAC, RAC-G, and RAC-O, form four groups. Their selection probabilities are calculated by:

$$P(i) = \frac{\exp(V_i)}{\sum_{i=1}^4 \exp(V_i)}, \quad (8)$$

$$V_i = \eta_0 + \eta_1 \text{Thickness} + \eta_2 \text{AADTC} + \eta_3 \text{Pre}, \quad (9)$$

where $P(i)$ – the probability of selecting one specific surface mix i ; i – a mix index representing DAGC, OGAC, RAC-G, RAC-O; V_i – utility function of a certain mix; $\eta_0 \dots \eta_3$ – coefficients to be estimated.

The regression results of Eqs (8)–(9) are summarized in Table 2.

4. Development of empirical model

A panel data set of 296 observations covering 74 sections over 4 years was used to develop the empirical model for tire/pavement noise, which is given as:

Table 1. Parameter estimates of *Thickness* and *AirVoid*

Variables	Eq (6)			Eq (7)		
	Coefficient	<i>t</i> -statistics	<i>P</i> -value	Coefficient	<i>t</i> -statistics	<i>P</i> -value
Intercept	7.343	15.37	< 0.001	-6.635	-13.41	< 0.001
Ln(<i>Age</i>)	0.016	0.65	0.518	-0.102	-3.94	< 0.001
Ln(<i>AADTC</i>)	0.055	2.96	0.003	0.029	1.53	0.127
Ln(<i>Pre</i>)	-0.023	-1.02	0.307	0.036	1.53	0.127
Ln(<i>MPD</i>)	-0.578	-8.47	< 0.001	1.254	17.75	< 0.001
Ln(<i>IRI</i>)	0.231	3.99	0.004	-0.197	-3.29	0.001
Number of observations – 296; Adjusted R^2 – 0.32			Number of observations – 296; Adjusted R^2 – 0.51			

Table 2. Parameter estimation and Goodness-of-Fit measures of MNL model

Variables	DGAC			OGAC		
	Coefficient	<i>t</i> -statistics	<i>P</i> -value	Coefficient	<i>t</i> -statistics	<i>P</i> -value
Intercept	-0.34	-1.63	0.10	0.12	0.65	0.51
<i>Thickness</i>	-0.025	-3.31	0.001	-0.026	-3.49	0.0005
<i>AADTC</i>	4.86E ⁻⁴	1.61	0.108	4.67E ⁻⁴	1.56	0.118
<i>Pre</i>	1.3E ⁻³	3.38	0.0007	1.27E ⁻³	3.33	0.0009
Variables	RAC-O			RAC-G		
	Coefficient	<i>t</i> -statistics	<i>P</i> -value	Coefficient	<i>t</i> -statistics	<i>P</i> -value
Intercept	0.38	2.17	0.03	-2.98	-1.44	0.38
<i>Thickness</i>	-0.027	-3.62	0.0003	-0.025	-3.32	0.027
<i>AADTC</i>	4.54E ⁻⁴	1.53	0.126	4.85E ⁻⁴	1.60	4.54E ⁻⁴
<i>Pre</i>	1.25E ⁻³	3.29	0.001	1.29E ⁻³	3.37	1.25E ⁻³
Number of observations – 296; Likelihood ratio – 37.9; Pseudo- R^2 – 0.21						

$$OBSI = a_0 + a_1 Age + a_2 AirVoid + a_3 MPD + a_4 \ln AADTC + a_5 Pre + a_6 NewThickness + u_i + u_t + v_{it} \quad (10)$$

where *NewThickness* – product of thickness of one surface mix and its corresponding probability as estimated from the MNL model; all the other variables remain the same meanings as those in Eqs (1) and (6)–(7). For example, *NewThickness* of DGAC is equal to the thickness of DGAC multiplied by the probability of selecting DGAC.

It is intuitively reasonable that the tire/pavement noise level decreases with air-void content of mixes and increases with pavement age. The first inference is explained by the following reasons: first, higher air-void content of the mix will significantly attenuate the air expelling effect during tire/pavement contact, and the sudden air suction effect after tire/pavement contact (Hayden 1971); second, since air voids form cavities that absorb noise radiations, more air voids absorb more noise (Lacour *et al.* 2000). The second inference is explained by several mechanisms that either increase surface roughness or decrease air voids with time, including aging of pavement materials, further pavement compaction after exposure to traffic, and clogging of air voids. Based on the above reasoning, a positive coefficient of *Age* and a negative coefficient of *AirVoid* are expected in the empirical model. Furthermore, it

is also expected that *MPD* will have a positive coefficient because higher *MPD* is associated with a rougher surface. Estimation results of the regression model (Eq (10)) are summarized in Table 3.

As reflected in Table 3, the *P*-values indicate that all the variables are significant at a 95% confident level except for *Age* and *AADTC*. *Age* is significant at a confidence level of 90%. The results confirm our prior expectations in terms of the signs of coefficients for *AirVoid*, *Age*, and *MPD*. Specifically, tire/pavement noise increases with pavement age and *MPD*, while decreases with air-void content. The magnitudes of the estimated coefficients for variables *AirVoid* and *NewThickness* suggest that increase of air void leads to more significantly reduce the noise level than the increase of surface layer thickness.

The fraction of the total error term that is due to unobserved heterogeneity is defined by a parameter, *Rho1*, which is given by:

$$Rho1 = \frac{(\sigma_i)^2 + (\sigma_t)^2}{(\sigma_i)^2 + (\sigma_t)^2 + (\sigma_v)^2}, \quad (11)$$

where *Rho1* – fraction of the total error term due to unobserved heterogeneity; σ_i – standard deviation of in Eq (10), which accounts for cross-sectional unobserved heterogeneity. σ_t – the standard deviation of in

Table 3. Parameters, distribution of the error terms, and Goodness-of-Fit measures of the regression model

Variables	Coefficient		<i>t</i> -statistics	<i>P</i> -value
Intercept	102.0		162.61	< 0.001
Age	0.092		1.74	0.080
AirVoid	−0.180		−7.11	< 0.001
MPD	9.85E ^{−4}		2.84	0.0048
AADTC	1.24E ^{−4}		1.29	0.200
Pre	1.99E ^{−4}		2.41	0.017
NewThickness	−0.019		−2.21	0.028
Standard deviation of error term	Value	<i>t</i> -statistics	<i>P</i> -value	Number of observations – 296; number of cross sections – 74; time series length – 4; <i>R</i> ² – 0.23.
<i>Sigma_i</i>	0.95	3.47	< 0.001	
<i>Sigma_t</i>	0.03	−2.73	0.0068	
<i>Sigma_v</i>	1.24	4.19	< 0.001	

Eq (10), accounting for time serial unobserved heterogeneity. *Sigma_v* – the standard deviation of the random disturbances in Eq (10), accounting for random error term.

The *Rho1* value for the estimated empirical model (Eq (10)) is 0.37, indicating that the unobserved heterogeneity does exist, which may significantly affect the regression results. It demonstrates the necessity and effectiveness of the two-way random-effect model to capture the unobserved heterogeneity.

The proportion of variances due to the two unobserved heterogeneity sources, cross section and time series, is denoted by

$$Rho2 = \frac{(\sigma_i)^2}{(\sigma_i)^2 + (\sigma_t)^2}, \tag{12}$$

where *Rho* – fraction of variance of time series among variance of unobserved heterogeneity; all the other variables remain the same meanings as those in Eq (11).

The calculated *Rho2* for the regression model is 0.001, which is almost negligible. However, this does not mean the time serial unobserved heterogeneity is negligible because the panel data only consists of four years’ observations. With the accumulation of observations along with time periods, the time serial unobserved heterogeneity may also increase to an un-negligible level and thus influence the regression results.

5. Model predictions

The estimated empirical model (Eq (10)) is used to perform some predictions. First, the influence of surface mix type is investigated. The tire/pavement noise levels are predicted for four mix types at different pavement ages using Eq (10), with all other variables taking mean values (Fig. 1).

As observed from Fig. 1, the surface mixes rank in an order of RAC-O < OGAC < RAC-G < DGAC in terms of their noise levels. The noise level of DGAC is significantly higher than that of OGAC, with a difference reaching 2 dB(A). The difference in noise levels is less significant among OGAC, RAC-G, and RAC-O mixes. The obvious shortcoming of combining all 4 surface mixes together is

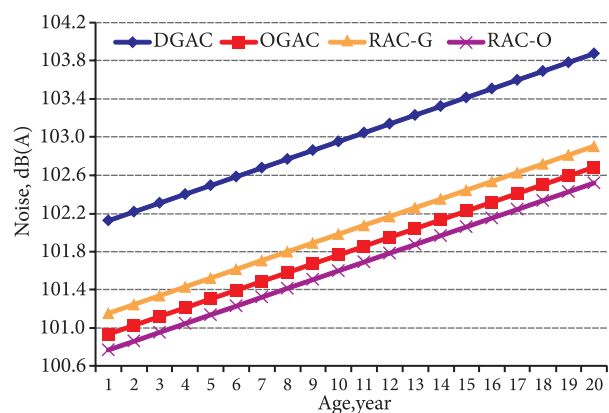


Fig. 1. Noise level development of each mix

its inability to differentiate the noise increase rates among mixes since a uniform *Age* coefficient is assigned. Individual model for each mix has been estimated, but with errors during regression process due to the small sample size. Therefore their results are not presented here.

Air-void content is a critical design factor affecting the acoustic performance of pavement. Both the 25th percentile and the 75th percentile air-void contents of the 4 mixes are selected to establish an air-void content range versus noise relationship (Fig. 2).

Fig. 2 is plotted from Eq (10) with all variables, except *AirVoid* and *Age*, taking their mean values. The same rank of mixes as in Fig. 1 is also observed here. It indicates that the air-void content significantly influences the noise level for all surface mix types. Fig. 2 shows that the noise level of DGAC with the 25th percentile air-void content is greater than any of other curves, which again suggests DGAC to be noisier than the other mixes. RAC-O still behaves best for its lowest noise levels.

MPD is also a significant factor that affects tire/pavement noise. Its role is reflected in Fig. 3, in which a range of *MPD* defined by its 25th and 75th percentiles is presented for each mix type.

Fig. 3 is plotted from Eq (10) with all variables, except *MPD* and *Age*, taking their mean values. A higher *MPD*

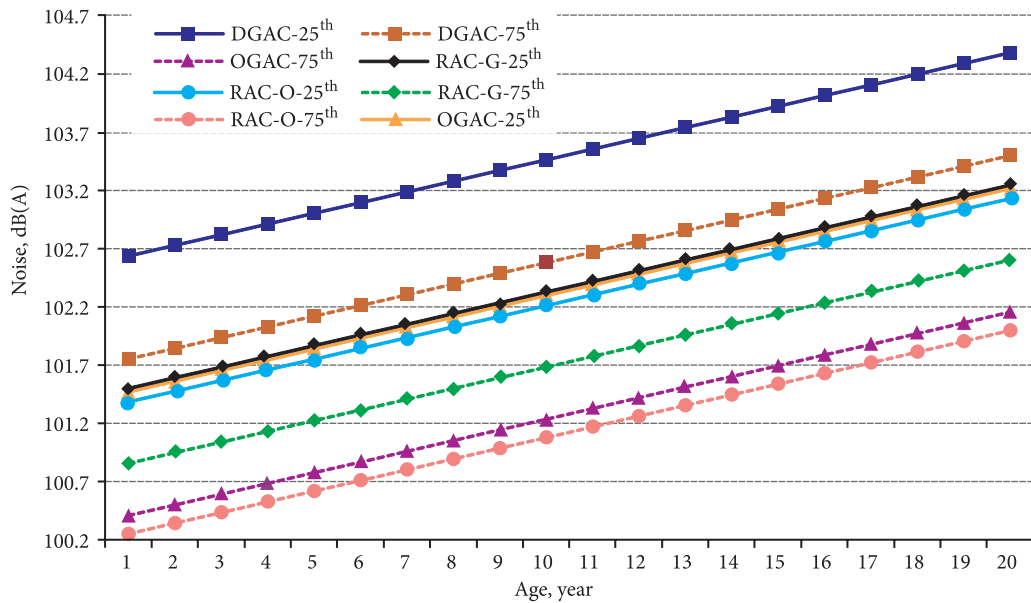


Fig. 2. Noise level development of each mix of various air void content

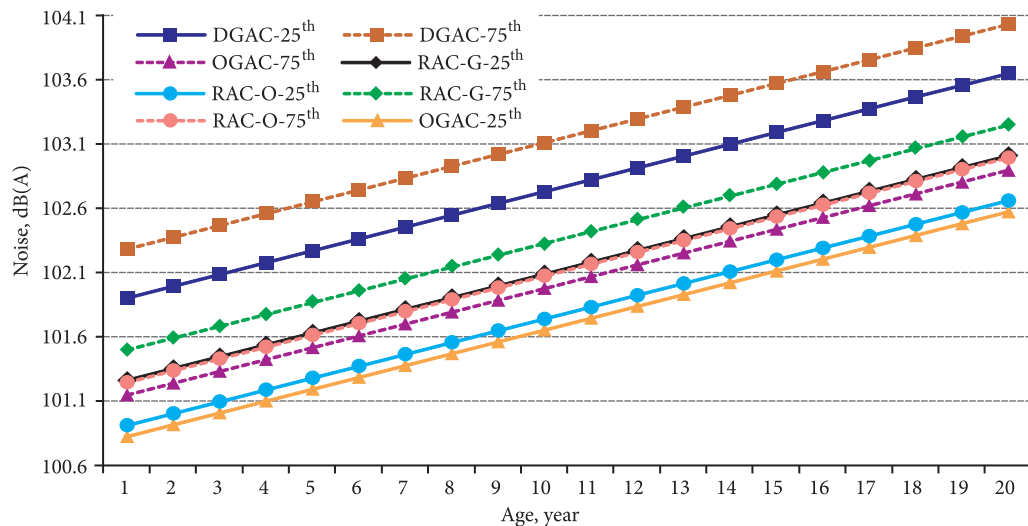


Fig. 3. Noise level development of each mix of various MPD

will cause more tire vibrations, leading to higher noise, as reflected in Fig. 3. The noise level of DGAC is much greater than those of the other three mixes.

6. Conclusions

This paper describes the development of an empirical acoustic model with panel data for 4 types of surface mixes. Econometric approach was used to correct the deficiency of repeated field data from endogeneity bias to unobserved heterogeneity. The estimated model treated tire/pavement noise as a function of pavement surface properties (i.e. mix type, air-void content, mean profile depth, and surface layer thickness, traffic and environmental variables, and pavement age). It was revealed that tire/pavement noise levels for 4 asphalt surface mixes rank as RAC-O < OGAC < RAC-G < DGAC, and tire/pavement noise increases with pavement age and MPD, while decreases with air-void content and surface layer thickness.

Predictions of tire/pavement noise were performed under different scenarios with the estimated model.

The obtained model integrated 4 surface mixes instead of describing each surface mix separately. Such an integrated model has the advantage of conciseness in appearance and abundance in degrees of freedom, which provides a general noise level estimation and basic understating of the trend. However, it also suffers the deficiency of lack of understanding of each mix's performance, especially the individual noise increase rate. This will be addressed in future research when noise data from more years are available.

References

Bendtsen, H.; Lu, Q.; Kohler, E. 2010. *Acoustic Aging of Asphalt Pavements: a Californian/Danish Comparison*. Report No. UCPRC-RP-2010-01, University of California, Davis.

- Bermann, M. 1980. Noise Generation by Tire Vibration, in *Proc. of the International Conference Noise Control Engineering "Noise Control for the 80's Inter-Noise 80"*. December 8–10, 1980, Miami, Florida, USA. Vol. 1: 239–244.
- Biermann, J.; Estorff, O. V.; Petersen, S.; Schmidt, H. 2007. Computational Model to Investigate the Sound Radiation from Rolling Tires, *Tire Science and Technology* 35(3): 209–225. <http://dx.doi.org/10.2346/1.2768608>
- Brinkmeier, M.; Nackenhorst, U.; Petersen, S.; Estorff, O. V. 2008. A Finite Element Approach for the Simulation of Tire Rolling Noise, *Journal of Sound and Vibration* 309(1–2): 20–39. <http://dx.doi.org/10.1016/j.jsv.2006.11.040>
- Cao, P.; Yan, X. P.; Xiao, W. X.; Chen, L. J. 2008. A Prediction Model to Coupling Noise of Tire Tread Patterns and Road Textures, in *Proc. of the 8th International Conference of Chinese Logistics and Transportation Professionals*. Ed. by Liu, R. F.; Zhang, J.; Guan, C. Q. October 8–10, 2008, Chengdu, China, 2332–2338. [http://dx.doi.org/10.1061/40996\(330\)344](http://dx.doi.org/10.1061/40996(330)344)
- Dai, L. M.; Lou, Z. 2008. An Experimental and Numerical Study of Tire/Pavement Noise on Porous and Nonporous Pavements, *Journal of Environmental Informatics* 11(2): 62–73. <http://dx.doi.org/10.3808/jei.200800112>
- Ghoreishy, M. H. Z. 2008. State of the Art Review the Finite Element Modelling of Rolling Tyres, *Iranian Polymer Journal* 17(8): 571–597.
- Hayden, R. E. 1971. Roadside Noise from the Interaction of a Rolling Tire with Road Surface, in *Proc. of Purdue Noise Control Conference*. Ed. by Crocker, M. J. July 14–16, 1971, Purdue University, 62–67.
- Lacour, O.; Galland, M. A.; Thenal, D. 2000. Preliminary Experiments on Noise Reduction in Cavities Using an Active Impedance Changes, *Journal of Sound and Vibration* 230(1): 69–99. <http://dx.doi.org/10.1006/jsvi.1999.2614>
- Larsson, K.; Barrelet, S.; Kropp, W. 2002. The Modelling of the Dynamic Behaviour of Tyre Tread Blocks, *Applied Acoustics* 63(6): 659–667. [http://dx.doi.org/10.1016/S0003-682X\(01\)00059-7](http://dx.doi.org/10.1016/S0003-682X(01)00059-7)
- Lu, Q.; Kohler, E.; Harvey, J. T. 2010. Field Investigation of Acoustic Performance of Various Asphalt Surface Mixes, in *Proc. of ICCTP: Integrated Transportation System – Green, Intelligent, Reliable*. Ed. by Wei, H.; Wang, Y. H.; Rong, J.; Weng, J. C. August 4–8, 2010, Beijing, China, 3937–3947. [http://dx.doi.org/10.1061/41127\(382\)425](http://dx.doi.org/10.1061/41127(382)425)
- Lu, Q.; Kohler, E.; Harvey, J. T.; Ongel, A. 2009. *Investigation of Noise and Durability Performance Trends for Asphalt Pavement Surface Types: Three-Year Reports*. Report No. UCPRC-RR-2009-01, University of California, Davis.
- Nelson, P. M.; Phillips, S. M. 1997. *Quieter Road Surfaces*. TRL Annual Review, Transportation Research Laboratories, United Kingdom, 25–36.
- Ongel, A.; Harvey, T. J.; Kohler, E.; Lu, Q.; Steven, D. B. 2008a. *Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results*. Report No. UCPRC-RR-2007-03, University of California, Davis.
- Ongel, A.; Harvey, T. J.; Kohler, E.; Lu, Q.; Steven, D. B.; Monismith, L. C. 2008b. *Summary Report: Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphalt Pavement Surface Types: First- and Second-Year Results*. Report No. UCPRC-SR-2008-01, University of California, Davis.
- Sandberg, U.; Descornet, G. 1980. Road Surface Influence on Tire/Road Noise-Part 1, in *Proc. of the International Conference Noise Control Engineering "Noise Control for the 80's Inter-Noise 80"*. December 8–10, 1980, Miami, Florida, USA. Vol. 1: 259–266.
- Stock, J. H.; Trebbi, F. 2003. Retrospectives: Who Invented Instrumental Variable Regression?, *Journal of Economic Perspectives* 17(3): 177–194. <http://dx.doi.org/10.1257/089533003769204416>
- Wullens, F.; Kropp, W. 2004. A Three-Dimensional Contact Model for Tyre/Road Interaction in Rolling Conditions, *Acta Acustica/Acustica* 90(4): 702–711.
- Yu, B.; Lu, Q. 2012. Individual Acoustic Models of Asphalt Surface Mixes at Various Frequencies, in *TRB 91st Annual Meeting Compendium of Papers DVD*, Washington D.C. USA, 2012.
- Zheglov, L. F. 2005. Measurement of the Spectral Characteristics of a Road Surface, *Measurement Techniques* 48(10): 45–47. <http://dx.doi.org/10.1007/s11018-006-0011-1>

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