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Development of a road shoulder's equivalent sound source traffic noise prediction model

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The accuracy of traffic noise prediction models (TNMs) is impaired by affecting factors and system errors. In addition, the traditional traffic noise source cannot be tested as the sound source is generated in the centreline of the road. To address these limitations, a TNM based on the equivalent sound source at the road shoulder was developed. First, the equivalent traffic flow based on the acoustic-equivalent conversion coefficient was calculated and the traffic noise source intensity model was deduced. The shoulder's sound pressure level (SPL) data were then used to formulate a single-vehicle equivalent SPL model and correct the traffic noise source intensity model. The propagation model was fitted according to the attenuation law that traffic noise strength attenuates gradually from the shoulder to the road outside and fluctuates periodically. The results of a case study showed that the absolute percentage error of the proposed model's prediction was 2·3% compared with the measured value, which was better than the performance of the current model suggested in the Chinese specification. The proposed prediction model provides a friendly and less time-consuming approach for city planners and traffic engineers to conduct freeway traffic noise prediction and assessment.

Notation

c_k	constant
d	distance from road shoulder
d_i	distance of the interpolation point
d_k	distance from lane's centreline to shoulder
K_{ij}	acoustic-equivalent conversion coefficient for vehicle j with speed i
L	single-vehicle radiated sound pressure level (SPL) at origin point
L_{eq}	total equivalent SPL at the origin within time t_0
L_{eq1}	total equivalent SPL within t_0
$L_{\text{eq}d}$	predicted radiated equivalent SPL at distance d metres to the shoulder
$L_{\text{eq}k}$	radiated equivalent SPL of all small vehicles at the origin in lane k within time t_0
L_{eqp}	propagation SPL at distance of d metres to the shoulder
L_{ij}	radiated SPL of vehicle j with speed i in the road shoulder
L_{r1}	radiated SPL of a small vehicle with representative speed r (average speed v_r) in the road shoulder
L_{r1k}	radiated SPL of a small vehicle with representative speed r (average speed v_r) in lane k
L_{st}	total-vehicle radiated SPL
m_1	serial number of vehicles in $x < 0$, from -1 to m_1
m_2	serial number of vehicles in $x > 0$, from 1 to m_2
n	number of equivalent small vehicles
q	number of acoustic-equivalent small vehicles passing the measuring section within counting time t
r	representative speed (average speed v_r)
t	counting time
t_0	time headway of vehicles
v	speed
v_j	speed of vehicle j
v_k	average speed of vehicles in lane k
v_r	average speed
x	horizontal distance of vehicle to the measurement point line (y axis)

1. Introduction

Traffic noise has many negative impacts on human lives and a traffic noise assessment is usually required in the environmental impact statement for roadway design and construction according to national regulations or standards (Steele, 2001). Traffic noise prediction models (TNMs) have therefore become a vital tool of civil engineers for noise prediction and assessment (Quartieri *et al.*, 2009). TNMs usually consider source emissions, sound propagation, road characteristics and other impact factors (Givargis and Mahmoodi, 2008) and many efforts have been made to improve traffic noise prediction accuracy as it is the prerequisite to guarantee a reasonable noise assessment (Li *et al.*, 2016).

The TNM of the US Federal Highway Administration (FHWA) was first developed by Barry and Reagan (1978) and then developed into version 1.0 by Menge *et al.* (1998). The model allowed a convention adjustment for different conditions and was reported to have a fair success when adapted to Ontario (Jung *et al.*, 1986). With the rapid development of

Chinese freeway construction beginning in the 1980s, Chinese traffic engineers reviewed the FHWA's TNM for the environmental impact assessment of freeway construction and many scholars have discussed the applicability of this model in China (Tu, 1995). Subsequently, the Ministry of Transport of the People's Republic of China officially introduced a TNM based on a modified version of the FHWA TNM (MTPRC, 1996, 2006) and special impetus was given to scholars to investigate and modify the FHWA TNM further for better adaptation to Chinese conditions (Dai *et al.*, 2014).

The TNM used in the current Chinese specification (MTPRC, 2006) calculates the source emission based on the acoustic point source in the road centreline; however, in this case, noise source data are hard to measure and it is thus unfeasible to validate the source model's accuracy. In addition, too many factors in the propagation model make it quite cumbersome for traffic engineers to select and construct the appropriate model.

Many other developed countries have also developed their own TNMs, as summarised in Table 1. Quartieri *et al.* (2009) reviewed six main TNMs used in Europe and noted that the statistical basis adopted for parameter evaluation to correct the sound level function was the main limitation of these models. In fact, all of these models, including the fit of experimental data (e.g. CoRTN in the UK) and the use of experimental plots (e.g. NMPB-routes-2008 in France), neglect the intrinsic random nature of traffic flow. Garg and Maji (2014) provided an exhaustive review of the principal TNMs in developed countries. They investigated source characterisation in terms of sound pressure level (SPL) and sound propagation through different meteorological conditions and addressed reflection, diffraction and absorption phenomena. Their study concluded that a harmonised methodology along with a simple and less time-consuming approach in conjunction with uncertainty calculations would be more suitable for civil engineers.

A TNM is often composed of a noise source model and a sound propagation model (Can and Aumond, 2018). Source emissions are often segregated into propulsion and rolling noise, and this separation allows for relating the increase in noise emissions with slope only to engine noise and an increase in speed to tyre noise (Jonasson, 2007). Outdoor sound propagation in complex environments has occasionally been a vital issue of research for improving the accuracy of TNMs (Gallo *et al.*, 2016). The factors involved in sound propagation mainly include geometrical divergence, atmospheric absorption, meteorological effects, ground effects, the diffraction effect and other miscellaneous effects (Garg and Maji, 2014). Numerical propagation methods (e.g. the parabolic equation (PE) for weather influence, the boundary element method (BEM) for terrain shape and the straight-ray model (Ray) with curved rays for a refractive atmosphere) have been applied to compute the sound propagation effect (Defrance *et al.*, 2007). However, noise prediction accuracy does not always increase when adding more factors to a TNM because there is a measurement error for these factors in practice (Garg and Maji, 2014). In addition, the more factors considered in a model, the more

Table 1. Main TNMs in developed countries

Model	User	Application	Input data	Reference
FHWA TNM	USA, Canada, Japan, Mexico	Highways (L_{eq}), not architectural; grid, excellent source base; road networks	Traffic type, flow, speed, road and emission data, local characteristics	Barry and Reagan (1978), Menge *et al.* (1998)
NMPB-routes-2008	France	Highways, road networks (L_{Aeq}, L_{Aeq}, L_{T}), architectural; point source, excellent propagation; simple streams	Average hourly flow rate for each category of vehicle; speed and traffic flow type of each vehicle category; road platform surface category and road gradient	Dutilleux *et al.* (2010)
CoRTN	UK, Australia, New Zealand	Highways (quasi L_{10}); point; single traffic streams	Percentage of heavy vehicles, flow, speed, road and environmental data, gradient	Givargis and Mahmoodi (2008)
RLS-90	Germany	Highways and car parks (L_{eq}), not architectural; point, good propagation; simple streams	Traffic type, traffic flow, parking or road data	BFV (1990)
SonRoad	Switzerland	Highways, road networks (A-weighted sound power level L_{w}), architectural; point; simple streams	Vehicle type, speed, grade of road and surface type	Heutschi (2004)
ASJ RTN-2008	Japan	Highways (L_{WA}, L_{A}, L_{Aeq}), point, constant speed, in different traffic conditions	Traffic type, speed, barrier geometry, road surface and gradient, flow (steady/non-steady), mean wind speed and density of buildings	Yamamoto (2010)
Harmonoise	EU members	Roads and railways (L_{Aeq}, T, L_{den} & L_{night}); grid; constant speed, acceleration/deceleration mode	Traffic speed, composition, intensity (flow), flow characteristics (i.e. acceleration/deceleration)	Jonasson (2007)

complicated and time-consuming it is. There is thus a need for planners and engineers to have a simplified and user-friendly TNM with good accuracy.

In the work reported in this paper, a freeway TNM based on the equivalent sound source at the road shoulder was constructed. The actual traffic volume was converted into the acoustic-equivalent traffic volume at the representative speed in order to calculate the equivalent sound source at the freeway shoulder. In this way, the sound source models of different vehicle types could be integrated and simplified. In addition, the road shoulder's SPL data can be measured and used to test the sound source prediction error and correct the source model. There are many factors that influence outdoor sound propagation and many of them, such as air humidity and land roughness, are hard to measure in practice (Bies *et al.*, 2017). This work thus used field data to describe the sound attenuation law based on the cubic spline interpolation method. In this way, the propagation model was simplified while maintaining good prediction performance. In summary, the TNM proposed in this paper can provide good prediction results and is feasible for validation of source models. For civil planners and traffic engineers collecting field data and constructing TNMs, it is user-friendly and less time-consuming.

The rest of the paper is organised as follows. The TNM is introduced in Section 2. A description of the data is provided in Section 3 and the model parameters are calibrated in Section 4. A case study to test the validation and accuracy of the modified model is presented in Section 5 and conclusions are summarised in Section 6.

2. Methodology

The acoustic-equivalent conversion coefficient and the traffic radiated equivalent SPL model at the road shoulder for the sound source model were first deduced. Then, a traffic propagation law was developed based on the cubic spline interpolation method. The developed TNM is composed of a noise source model and a sound propagation model.

2.1 Traffic noise source intensity model

Traffic noise intensity at a road shoulder is a comprehensive result of vehicles in the traffic lane and the overtaking lane. Furthermore, the equivalent sound source at the shoulder can be regarded as the superimposition of the radiated noise of all vehicles (Hamad *et al.*, 2017). The following assumptions were made in this study.

(*a*) The same kind of vehicle has the same physical performance and a single vehicle has the same radiated noise as the point sound source.
(*b*) Converted vehicles travel with the same representative speed and headway in their lanes. The effect of acceleration and deceleration was neglected as the uncertainty of estimation of traffic acceleration can be higher than the effect on noise (Kephalopoulos *et al.*, 2012).
(*c*) The road profile is a straight line with zero longitudinal slope. The roadbed is a standard embankment type and the area outside is open and flat.
(*d*) The Doppler effect of traffic noise and the effect of radiated traffic noise from traffic in the opposite direction are neglected. (The distance between the opposite direction lane and the road shoulder is more than 30 m; therefore the noise from traffic in the opposite direction would be reduced by the absorption and reflection effects of the road surface and the central separation strip, and the results calculated by the noise source intensity model may cause huge system errors.)

Figure 1 shows a diagram of one side of the freeway horizontal surface. A single vehicle was simplified into a point sound source. The radiated SPL at the origin point (0,0) is L_0 when a vehicle is passing section $x = 0$ with speed v at time $t = 0$. Meanwhile, the radiated SPLs of the vehicle in front ($j = 1$) and the rear vehicle ($j = -1$) at point (0,0) are L_j. All vehicles' radiated SPL curves on the traffic lane are shown in Figure 2. This shows that the SPL at the origin varies periodically with the period of the time headway t_0. Therefore, in the long term, the equivalent SPL at the origin point is equal to the equivalent SPL at time t_0.

2.1.1 Single-vehicle radiated equivalent SPL model

The equation used to compute the time headway t_0 is

$$t_0 = t/q = t/\sum K_{ij} \tag{1}$$

where t is the counting time, q is the number of acoustic-equivalent small vehicles passing the measuring section within counting time t and K_{ij} is the acoustic-equivalent conversion coefficient for vehicle j with speed i ($j = 1$, 2 or 3, representing a small, medium or large vehicle, respectively, with classification according to the Chinese specification (MTPRC, 2006).

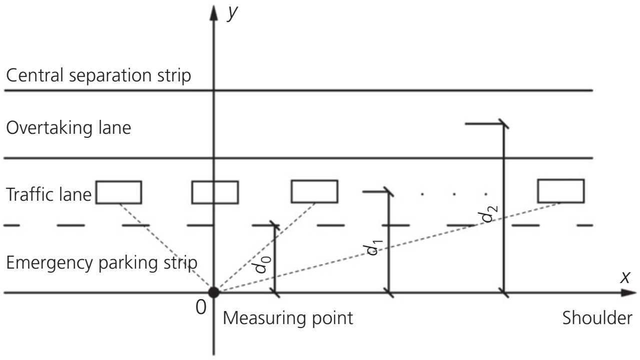

Figure 1. Illustration of traffic flow on freeway horizontal surface and the measuring point at the road shoulder

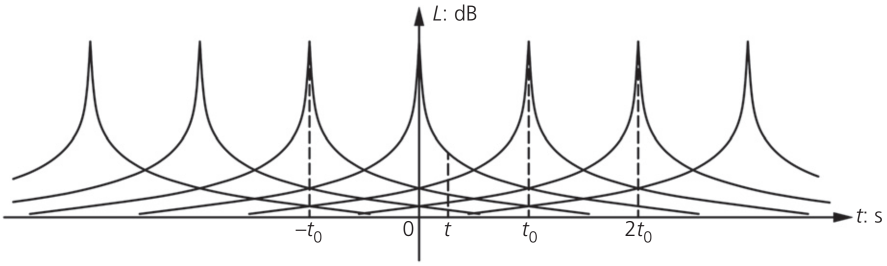

Figure 2. Illustration of radiated SPL curve of all small vehicles on traffic lane at time $t = 0$

In order to determine q, the vehicle acoustic-equivalent conversion coefficient K_{ij} was used to convert different types of vehicles with different speeds into the same type of vehicle with the same speed and radiated noise level (Rajakumara and Gowda, 2009). As small vehicles were the main vehicle type in the traffic flow in this study, a small vehicle was used as the representative vehicle and its average speed was taken as the representative speed. Hence, the radiated SPL of vehicle j with speed i was calculated by n equivalent small vehicles with representative speed according to the noise summation equation given by

$$2. \quad L_{ij} = 10\log\sum_{i=1}^{n} 10^{0\cdot 1L_{r1}} = 10\log(K_{ij}\cdot 10^{0\cdot 1L_{r1}})$$

where L_{ij} is the radiated SPL of vehicle j with speed i in the road shoulder (in dB) and L_{r1} is the radiated SPL of a small vehicle with representative speed r (average speed v_r) in the road shoulder (in dB).

Meanwhile, L_{ij} can also be denoted as the fitting equation of speed with the fitting method (Yamamoto, 2010).

$$3. \quad L_{ij} = f(v_j) = a_j + b_j \log(v_j)$$

where a_j and b_j are regression coefficients for vehicle j with speed v_j.

Because Equation 2 = Equation 3, the function of speed K_{ij} can be obtained as

$$4. \quad K_{ij} = 10^{0\cdot 1[a_j + b_j\log(v_j) - L_{r1}]} = 10^{0\cdot 1[a_j + b_j\log(v_j) - a_1 - b_1\log(v_r)]}$$

2.1.2 Radiated equivalent SPL model of all vehicles

The derivation of the radiated equivalent SPL of all small vehicles in the traffic lane at the origin point within time t_0 is as follows.

The single-vehicle radiated SPL at the origin point (L) is

$$5. \quad L = L_{r1} + 10\log[d^2/(d^2 + x^2)]$$

It is assumed that all vehicles keep the same headway t_0 and $x = vt$. Therefore L is a function of time t as follows.

$$6. \quad L = f(t) = L_{r1} + 10\log\{d^2/[d^2 + v^2(t + nt_0)^2]\}$$

The total-vehicle radiated SPL (L_{st}) is thus

$$7. \quad \begin{aligned} L_{\mathrm{st}} &= 10\log\sum_{i=m_1}^{m_2} 10^{0\cdot 1L} = 10\log\sum_{i=m_1}^{m_2} 10^{0\cdot 1\{L_{r1} + 10\log[d^2/(d^2 + v^2(t + it_0)^2)]\}} \\ &= L_{r1} + 10\log\sum_{i=m_1}^{m_2}\frac{d^2}{d^2 + v^2(t + it_0)^2} \end{aligned}$$

where m_1 represents the origin point's radiated SPL of vehicle m_1 in $x < 0$ and m_2 represents the origin point's radiated SPL of vehicle m_2 in $x > 0$.

In this study, the average SPL within t_0 was used to represent L_{eq1} (the total equivalent SPL within t_0).

$$8. \quad \begin{aligned} L_{\mathrm{eq1}} &= 10\log(1/t_0)\int_0^{t_0} 10^{0\cdot 1L_{\mathrm{st}}}\,\mathrm{d}t \\ &= 10\log(1/t_0)\{t_0 10^{0\cdot 1L_{r1}} \\ &\quad + \int_0^{t_0}\sum_{i=m_1}^{m_2} d^2/[d^2 + v^2(t + it_0)^2]\,\mathrm{d}t\} \\ &= L_{r1} + 10\log(d^2/t_0v^2) \\ &\quad \times \sum_{i=m_1}^{m_2}\int_0^{t_0} 1/[(d/v)^2 + (t + it_0)^2]\,\mathrm{d}t \\ &= L_{r1} + 10\log[d/(vt_0)]\sum_{i=m_1}^{m_2}\{\arctan[(i+1)vt_0/d] \\ &\quad - \arctan[(ivt_0)/d]\} \\ &= L_{r1} + 10\log(d/vt_0)\{\arctan[(m_2+1)vt_0/d] \\ &\quad - \arctan(m_1vt_0/d)\} \end{aligned}$$

When $t = 0$ and letting $f(t) = 0$ (i.e. $L_{r1} + 10\log[d^2/(d^2 + v^2(mt_0)^2] = 0$) and because $m_1 < 0$, in this case

$$9.\quad m_1 = \frac{-d\sqrt{10^{0{\cdot}1Lr1} - 1}}{vt_0}$$

When $t = t_0$ and letting $f(t) = 0$ (i.e. $L_{r1} + 10\log\{d^2/[d^2 + v^2(m+1)^2 t_0^2]\} = 0$), because $m_2 > 0$, in this case

$$10.\quad m_2 = \frac{d\sqrt{10^{0{\cdot}1L_{r1}} - 1}}{vt_0} - 1$$

Therefore

$$11.\quad L_{\mathrm{eq1}} = L_{r1} + 10\log(2d\arctan\sqrt{10^{0{\cdot}1L_{r1}} - 1}/vt_0)$$

The traffic lane's radiated equivalent SPL of all small vehicles at the origin point during time t_0 was derived following the same process. The radiated equivalent SPL of all small vehicles at the origin point within the time t_0 is the summation of these two lanes, which is given by

$$12.\quad L_{\mathrm{eq}} = 10\log(10^{0{\cdot}1L_{\mathrm{eq1}}} + 10^{0{\cdot}1L_{\mathrm{eq2}}})$$

where L_{eq} is the total equivalent SPL at the origin within the time t_0 (in dB) and $L_{\mathrm{eq}k}$ is the radiated equivalent SPL of all small vehicles at the origin in lane k within time t_0 (in dB), with $k = 1$ and $k = 2$ representing the traffic lane and overtaking lane, respectively.

Assumption (*b*) in Section 2.1 is that all small vehicles keep the same headway and assumption (*d*) neglects the Doppler effect of traffic noise and the radiated traffic noise effect of traffic flow in the opposite direction. These assumptions lead to systematic errors in this model. For example, if a heavy vehicle is converted into four acoustic-equivalent small vehicles, these four small vehicles travel with the same headway and pass through section $x = 0$ one by one; thus the total passing time is $3t_0$. However, the heavy vehicle's actual passing time is t_0, which means that these four small vehicles should pass section $x = 0$ at the same time in order that the radiated noise strength of all the small vehicles is equal to that of the heavy vehicle. In order to eliminate or weaken the effects of systematic errors, the model was corrected by adding a constant term to $L_{\mathrm{eq}k}$ based on the measured data. In this way, the model's residual follows a zero-mean normal distribution.

$$13.\quad L_{\mathrm{eq}k} = L_{r1k} + 10\log(2d_k\arctan\sqrt{10^{0{\cdot}1L_{r1k}} - 1}/v_k t_0) + c_k$$

2.2 Traffic noise propagation model

Many researchers have already studied sound attenuation features in different environments (Nilsson *et al.*, 2014). The use of numerical methods such as wave equations to characterise meteorological factors (Bies *et al.*, 2017) improves accuracy but also increases the computation complexities and requires specialised methods for their solution, which may be unfeasible for government planners and roadway engineers. Meanwhile, distance is often used as the independent variable for atmospheric absorption and geometrical divergence, ground effects and barrier attenuation (Garg and Maji, 2014). In this work, an interpolation method was used to develop a traffic noise propagation model based on measured freeway traffic SPL data at different distances from the road shoulder. To this end, cubic spline interpolation, which can describe the variation of data with a simple function, was adopted. The cubic spline interpolation function is

$$14.\quad L_{\mathrm{eqp}} = b_1(d - d_i)^3 + b_2(d - d_i)^2 + b_3(d - d_i) + b_4$$

where L_{eqp} is the propagation SPL at a distance of d metres to the shoulder, d is the distance from the road shoulder, d_i is the distance of the interpolation point and b_1–b_4 are correction coefficients.

2.3 The TNM

The complete TNM was obtained by integrating the source strength model and the attenuation model as follows

$$15.\quad L_{\mathrm{eq}d} = \begin{cases} 10\log(10^{0{\cdot}1L_{\mathrm{eq1}}} + 10^{0{\cdot}1L_{\mathrm{eq2}}}) & d = 0 \\ b_1(d - d_i)^3 + b_2(d - d_i)^2 + b_3(d - d_i) + b_4 & d \geq 0 \end{cases}$$

where $L_{\mathrm{eq}d}$ is the predicted radiated equivalent SPL at a distance of d metres to the shoulder (in dB).

3. Data description

Sound level meters were used to measure traffic SPLs and cameras were used to assess traffic volume, vehicle types and speeds. Two groups of data were used in this study. One group was used for calibrating the model's parameters. The data were collected on Ha-Shuang freeway in Harbin, China on 3 February 2018, which has a design speed of 120 km/h, comprises four lanes with a median strip and is 23·5 m wide, with a pitch layer. The collected data included 1526 vehicles of different types and their speeds, the corresponding instantaneous radiated SPL on different lanes, 90 sets of shoulder equivalent SPLs within 5 min and corresponding traffic volumes, and 1380 SPLs within 1 min at different distances (from 0 to 90 m, with intervals of 2 m) to the shoulder.

The other group of data was used for validating the model's applicability. The data were collected on Kai-yang freeway in

Guangdong, China on 6 March 2018, which has a design speed of 120 km/h, four lanes with a median strip, is 28 m in width, with a pitch layer. The sampling data included 8370 vehicles of different types and speeds, hourly equivalent SPLs and hourly traffic volumes over 24 h at the measuring point of 26 m from the road shoulder.

4. Setting of model parameters

The first group of data was used to formulate different vehicles' instantaneous radiated SPLs, correct the system error of the traffic noise source intensity model and establish the traffic noise propagation model.

4.1 Formulation of the instantaneous traffic radiated SPL model

The vehicle radiated SPL is related to many factors, many of which are hard to measure, so vehicle type and speed are usually identified and used to derive the radiated SPL (Yamamoto, 2010). In the first group of data, 1526 different vehicle speeds and instantaneous radiated SPLs on different lanes were measured. The selected vehicles were passing through the measuring section ($x = 0$) with more than 60 m from the front and rear of the vehicle. Scatter plots of small-vehicle speed and instantaneous radiated SPL on different lanes are shown in Figure 3. The single-variant regression model was then formulated based on Equation 3.

As shown in Table 2, speed can be used to calculate a vehicle's instantaneous radiated SPL with the single-variant linear regression model, which is used in the Chinese specifications for highways environmental impact assessments (MTPRC, 2006). The vehicle acoustic-equivalent conversion coefficient can then be calculated according to Equation 4 and the traffic source intensity model can be formulated.

4.2 Correction of the traffic noise source intensity model

The measured data were used to modify the radiated equivalent SPL model. The data included 90 groups of equivalent SPLs within 5 min measured at the shoulder and the corresponding traffic volumes. Figure 4 shows that the average residuals (predicted SPL of uncorrected traffic noise source intensity model minus measured SPL value) were less than zero. This further indicated that the model contained some systematic errors.

According to the Kolmogorov–Smirnov test (KS test), the residuals followed a normal distribution (−1·916, 1·102) at the 95% confidence level. After the traffic volumes on each lane were converted into acoustic-equivalent small-vehicle traffic volumes, the volume on the traffic lane was found to be two to three times that of the overtaking lane, meaning that traffic flow on the traffic lane contributed more SPL than the overtaking lane. Therefore, the constant c_k in Equation 13 was set to $c_1 = 2$ for the traffic lane and $c_2 = 1$ for the overtaking lane. As shown in Table 2, the minimum SPLs were all greater than 70 dB, hence $\arctan\sqrt{10^{0{\cdot}1L_{r1k}} - 1} \approx \pi/2$. The time interval of noise measurement was 5 min and the headway t_0 was $300/q$ (in seconds). The corrected models were derived as

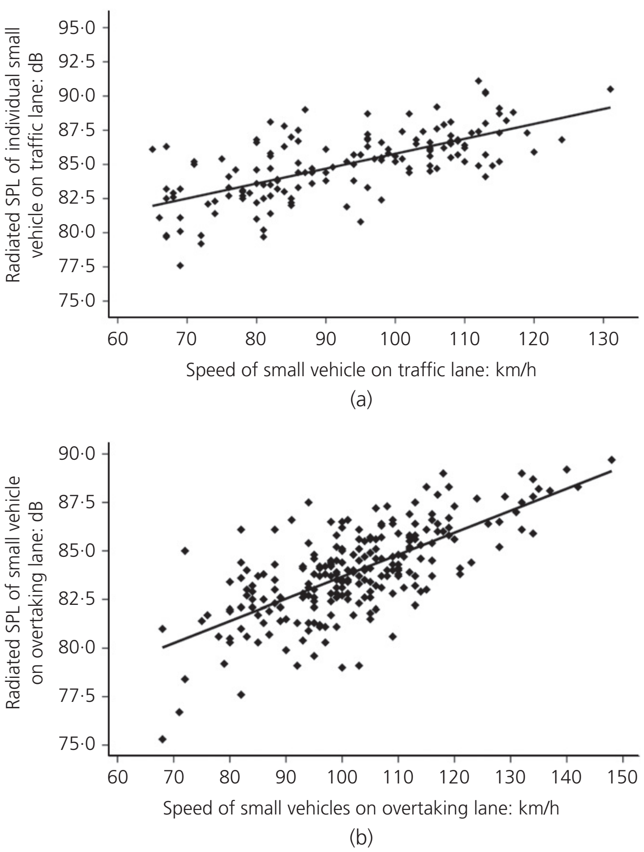

Figure 3. Small vehicle speed's instantaneous radiated SPL on (a) traffic lane and (b) overtaking lane

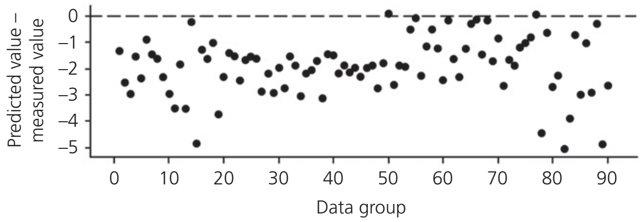

Figure 4. Residuals of the uncorrected traffic noise source intensity model

16. $$L_{\text{eq}1} = L_{r11} + 10\log(\pi d_1 q_1/300v_1) + 2$$

17. $$L_{\text{eq}2} = L_{r12} + 10\log(\pi d_2 q_2/300v_2) + 1$$

Table 2. Instantaneous radiated SPL models

Lane type	Vehicle type	Sample size	Regression model	Adjusted R^2
Traffic lane	Small	262	$L_{r11} = 74{\cdot}89 + 0{\cdot}109\ \log(v_r)$	0·649
	Medium	182	$L_{r21} = 79{\cdot}71 + 0{\cdot}108\ \log(v_r)$	0·439
	Heavy	190	$L_{r31} = 79{\cdot}00 + 0{\cdot}178\ \log(v_r)$	0·472
	Extra-heavy	167	$L_{r41} = 83{\cdot}45 + 0{\cdot}125\ \log(v_r)$	0·390
Overtaking lane	Small	236	$L_{r12} = 72{\cdot}32 + 0{\cdot}114\ \log(v_r)$	0·694
	Medium	161	$L_{r22} = 79{\cdot}30 + 0{\cdot}063\ \log(v_r)$	0·462
	Heavy	175	$L_{r32} = 75{\cdot}31 + 0{\cdot}178\ \log(v_r)$	0·408
	Extra-heavy	153	$L_{r42} = 79{\cdot}46 + 0{\cdot}126\ \log(v_r)$	0·386

where, as before, $k = 1$ represents the traffic lane and $k = 2$ represents the overtaking lane. Hence, $L_{\mathrm{eq}k}$ is the road shoulder's 5 min radiated equivalent SPL (in dB), L_{r1k} is the radiated SPL of a small vehicle with the representative speed (in dB), d_k is the distance from the lane's centreline to the shoulder (in metres), q_k is the converted acoustic-equivalent traffic volume within 5 min (pcu/5 min) and v_k is the representative speed of a small vehicle in lane k (m/s).

The residuals of the corrected model are shown in Figure 5. The residuals' single sample test (H_0: residual = 0, $t = -1{\cdot}603$, $P = 0{\cdot}187$) shows that the residuals approximately followed a zero-mean normal distribution. This indicates that the systematic error was basically eliminated in the corrected model. The average error was within 2·5 dB, in accordance with L_{eq} error analysis for measurements lasting less than 15 min (De Donato, 2007).

4.3 Establishment of the traffic noise propagation model

The measured data were used to describe the traffic noise attenuation phenomenon and the cubic spline interpolation method was used to establish the noise attenuation model. This data set covered 46 measuring points at 2 m intervals from point (0,0) in the shoulder and 30 min SPLs at each measuring point were measured at 1 min intervals. Thus, 1380 groups of SPL data were obtained. The measuring points' average SPL data minus the average SPL measured at the shoulder was used to represent the SPL's attenuation value. As shown in Figure 6, the SPL attenuation showed an overall decreasing trend with increasing distance from the road shoulder and periodically fluctuated within a small range. The attenuation value was found to increase when the distance from the shoulder exceeded 76 m, which might be due to wind disturbance or background noise. Thus, in this work, the cubic spline interpolation method was used to describe the attenuation within 76 m and the noise attenuation model was established according to the cubic spline function.

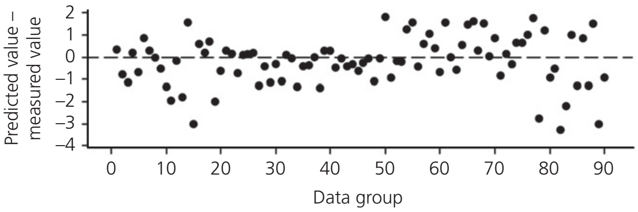

Figure 5. Residuals of the corrected traffic noise source intensity model

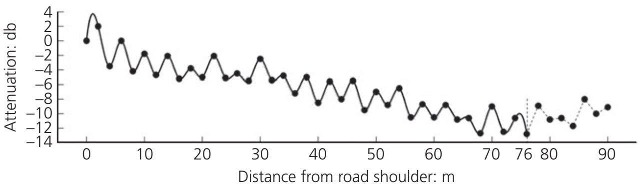

Figure 6. Illustration of the cubic spline interpolation curve of the attenuation model

According to the denoted function parameters and the noise attenuation model, the TNM based on the equivalent sound source at the shoulder was established as

$$
\begin{aligned}
L_{\mathrm{eq1}} &= L_{r11} + 10\log(\pi d_1 q_1/300 v_1) + 2\\
L_{\mathrm{eq2}} &= L_{r12} + 10\log(\pi d_2 q_2/300 v_2) + 1\\
L_{\mathrm{eq}} &= 10\log(10^{0{\cdot}1 L_{\mathrm{eq1}}} + 10^{0{\cdot}1 L_{\mathrm{eq2}}})\\
L_{\mathrm{eqp}} &= b_1(d-d_i)^3 + b_2(d-d_i)^2 + b_3(d-d_i) + b_4
\end{aligned}
\tag{18}
$$

5. Case study

In order to validate the proposed model's applicability, a second group of data (hourly equivalent SPLs, hourly traffic volumes over 24 h and sampling data of 8370 vehicles of different types and speeds) was collected at Kai-yang freeway. As shown in Table 3, the vehicles on the freeway were divided into four types: small, medium, heavy and extra-heavy. The collected speed data were analysed with the KS test using PASW software (Ghasemi and Zahediasl, 2012). The results show that the asymptotic significance (bilateral) of the four vehicle types on the traffic lane and overtaking lane were both greater than 0·05, which means that the speed distributions

Table 3. KS test of the speed data

	Vehicle type			
	Small	Medium	Heavy	Extra-heavy
Traffic lane				
Sample size	1344	1059	1231	853
Mean speed: km/h	107·31	80·27	87·87	77·61
Standard deviation	16·87	13·68	14·18	9·97
KS *Z*-value	1·03	0·91	0·63	1·15
Asymptotic significance (bilateral)	0·17	0·38	0·53	0·14
Overtaking lane				
Sample size	1727	743	985	428
Mean speed: km/h	110·60	98·89	98·53	85·76
Standard deviation	15·59	10·87	6·57	7·88
KS *Z*-value	0·93	0·87	0·64	0·56
Asymptotic significance (bilateral)	0·40	0·44	0·57	0·92

followed a normal distribution. Hence, the mean speed of small vehicles was set as the representative speed.

As the speeds of the different vehicle types on different lanes in the sampling data followed a normal distribution, the speeds were dispersed into serial groups with intervals of 5 km/h within the range of ($\mu - 2\sigma$, $\mu + 2\sigma$), which accounted for 95% of the total sampling data. Using the normal distribution's probability function (Equation 19), which denotes the probability of different vehicles with different speed groups, the hourly traffic volume data were subdivided into different types of vehicles with different speeds.

$$19. \quad P[\mu + (n-1)5 < v < \mu + n5] = \phi\left(\frac{(n-1)5}{\sigma}\right) - \phi\left(\frac{n5}{\sigma}\right)$$

Here, μ is the small-vehicle's mean speed and σ is the standard deviation of small-vehicle speeds.

According to Equation 2, all vehicles with different speeds were transformed into acoustic-equivalent small vehicles with the representative speed. Meanwhile, according to the established TNM in Equation 18, the predicted traffic noise that is assumed to be generated from the road shoulder can be obtained. The measured and predicted traffic noise values by the proposed method and the method suggested in the Chinese specification JTG B03 (MTPRC, 2006) are shown in Figure 7.

The mean absolute error (MAE), mean squared error (MSE) and mean absolute percentage error (MAPE) were used to estimate the performance of the proposed prediction model. As shown in Table 4, the values obtained in this study showed a better prediction performance than the results of the model in the Chinese specification, meaning that the TNM based on the assumption of the road shoulder's equivalent sound source proposed in this paper is applicable in practice.

6. Conclusions

A TNM based on equivalent noise source at the road shoulder was developed. The prediction model comprises a traffic noise source intensity model at the road shoulder and a traffic noise

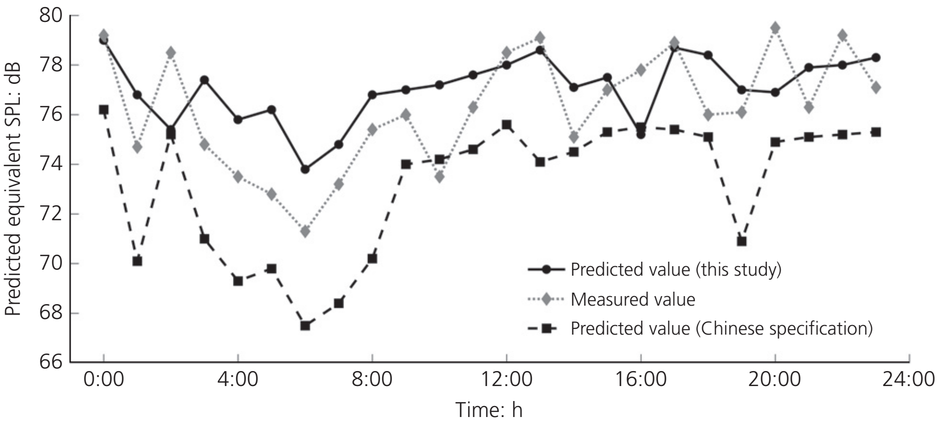

Figure 7. Traffic SPLs predicted by the proposed model and the Chinese specification compared with measured data

Table 4. Model's performance

Predicted value	MAE: dB	MSE: dB	MAPE: %
This study	1·725	3·964	2·29
JTG B03 method (MTPRC, 2006)	3·075	11·58	4·04

propagation model. As different vehicles with different speeds generate different traffic noise, all vehicles were converted into equivalent small vehicles with the representative speed based on the derived vehicle's acoustic-equivalent conversion coefficient. A model for the total-vehicle radiated equivalent SPL was then deduced. In this way, the traffic noise source intensity, which was assumed to be traffic noise at the road shoulder, could be measured in practice. These measured noise source data were then used to formulate an instantaneous single-vehicle radiated SPL model and to correct the systematic error of the total-vehicle radiated equivalent SPL model. The radiated SPLs starting from the shoulder were collected and a cubic spline function was used to study the noise attenuation law. This not only made the model more consistent with the actual situation, but also avoided the linear traffic noise attenuation law assumption and simplified the propagation model. A second set of data was used to test the model's applicability and the results showed that the proposed prediction model showed better prediction performance than the traditional model introduced in the Chinese specification for the common environment of a straight freeway segment. The proposed integrated model is less time-consuming than the current model and is user-friendly. It can thus be used by city planners and traffic engineers and modified to different environments.

This proposed model makes it more practicable to collect sound source SPL data and study the sound attenuation law for straight freeway sections. Moreover, it has good prediction accuracy and is easy for designers and engineers to use and modify. While the model provides a framework for city planners and traffic engineers to construct and modify the TNM to different environments, it is in the interest of researches and engineers to study other issues such as traffic noise environmental impact assessments, percentage annoyance assessments, hot-spot identification, selection of control measures and verification of result uncertainty. The vehicle instantaneous radiated SPL model only uses speed as the explanatory variable and therefore future studies should include other variables, which should be measured quantitatively in practice, to improve the goodness-of-fit of the functions. In addition, noise from the exhaust pipes of sports cars was not considered in this work as the proportion of such cars is relatively few. Future works could take this kind of vehicle into consideration in urban environments or open streets. The model seems promising based on the set of data used, but additional validation data at different distances, different types of cross-sections and other types of terrain are needed before conclusions can be drawn about its general applicability. Other appropriate mathematical methods for the noise attenuation model also deserve further research.

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REFERENCES

Barry TM and Reagan JA (1978) *FHWA Highway Traffic Noise Prediction Model*. US Department of Transportation, Federal Highway Administration, Washington, DC, USA, FHWA-RD-77-108.

BFV (Bundesministerium für Verkehr) (1990) RLS-90: Richtlinien für den Lärmschutz an Strassen. BFV, Bonn, Germany (in German).

Bies DA, Hansen C and Howard C (2017) *Engineering Noise Control*. CRC Press, Boca Raton, FL, USA.

Can A and Aumond P (2018) Estimation of road traffic noise emissions: the influence of speed and acceleration. *Transportation Research Part D: Transport and Environment* **58**: 155–171.

Dai BL, He YL, Mu FH, Xu N and Wu Z (2014) Development of a traffic noise prediction model on inland waterway of China using the FHWA. *Science of the Total Environment* **482**: 480–485.

De Donato SR (2007) Estimation of the minimum integration time for determining the equivalent continuous sound level with a given level of uncertainty considering some statistical hypotheses for road traffic. *Noise Control Engineering Journal* **55(6)**: 526–531.

Defrance J, Salomons E, Noordhoek I *et al.* (2007) Outdoor sound propagation reference model developed in the European Harmonoise project. *Acta Acustica united with Acustica* **93(2)**: 213–227.

Dutilleux G, Defrance J, Ecotière D *et al.* (2010) NMPB-routes-2008: the revision of the French method for road traffic noise prediction. *Acta Acustica united with Acustica* **96(3)**: 452–462.

Gallo M, Mascolino O and Mazza G (2016) A model for estimating road traffic noise in urban areas. In *Proceedings of the 2016 IEEE 16th International Conference on Environment and Electrical Engineering*. IEEE, Piscataway, NJ, USA, pp. 1–5.

Garg N and Maji S (2014) A critical review of principal traffic noise models: strategies and implications. *Environmental Impact Assessment Review* **46**: 68–81.

Ghasemi A and Zahediasl S (2012) Normality tests for statistical analysis: a guide for non-statisticians. *International Journal of Endocrinology and Metabolism* **10(2)**: 486.

Givargis S and Mahmoodi M (2008) Converting the UK calculation of road traffic noise (CORTN) to a model capable of calculating LAeq, 1 h for the Tehran's roads. *Applied Acoustics* **69(11)**: 1108–1113.

Hamad K, Khalil MA and Shanableh A (2017) Modeling roadway traffic noise in a hot climate using artificial neural networks. *Transportation Research Part D: Transport and Environment* **53**: 161–177.

Heutschi K (2004) SonRoad: new Swiss road traffic noise model. *Acta Acustica united with Acustica* **90(3)**: 548–554.

Jonasson HG (2007) Acoustical source modelling of road vehicles. *Acta Acustica united with Acustica* **93(2)**: 173–184.

Jung FW, Blaney CT and Kazakov AL (1986) Noise emission levels for vehicles in Ontario. *Transportation Research Record* **1058**: 33–39.

Kephalopoulos S, Paviotti M and Ledee FA (2012) *Common Noise Assessment Methods in Europe (CNOSSOS-EU)*. Publications Office of the European Union, Luxembourg, Luxembourg.

Li F, Liao SS and Cai M (2016) A new probability statistical model for traffic noise prediction on free flow roads and control flow roads. *Transportation Research Part D: Transport and Environment* **49**: 313–322.

Menge CW, Rossano CF, Anderson GS and Bajdek CJ (1998) *FHWA Traffic Noise Model, Version 1.0 Technical Manual*. Office of Environment and Planning, Federal Highway Administration, Washington, DC, USA, DOT-VNTSC-FHWA-98-2.

MTPRC (Ministry of Transport of the People's Republic of China) (1996) JT J005: Specifications for environment impact assessment of highways. China Communications Press, Beijing, China.

MTPRC (2006) JTG B03: Specifications for environment impact assessment of highways. China Communications Press, Beijing, China.

Nilsson M, Bengtsson and Klæboe R (eds) (2014) *Environmental Methods for Transport Noise Reduction*. CRC Press, Boca Raton, FL, USA.

Quartieri J, Mastorakis NE, Iannone G *et al.* (2009) A review of traffic noise predictive models. In *Recent Advances in Applied and Theoretical Mechanics, Proceedings of the 5th WSEAS International Conference on Applied and Theoretical Mechanics (MECHANICS'09), Puerto De La Cruz, Tenerife* (Bulucea CA, Mladenov V, Pop E, Leba M and Mastorakis N (eds)). World Scientific and Engineering Academy and Society, Athens, Greece, pp. 72–80.

Rajakumara HN and Gowda RM (2009) Road traffic noise prediction model under interrupted traffic flow condition. *Environmental Modeling & Assessment* **14(2)**: 251–257.

Steele C (2001) A critical review of some traffic noise prediction models. *Applied Acoustics* **62(3)**: 271–287.

Tu R (1995) Further discussion in US/FHWA highway noise prediction model. *Environmental Engineering* **13(3)**: 41–45 (in Chinese).

Yamamoto K (2010) Road traffic noise prediction model 'ASJ RTN-Model 2008': report of the research committee on road traffic noise. *Acoustical Science and Technology* **31(1)**: 2–55.