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Development of a highway noise prediction model using an $L_{eq}20\,s$ measure of basic vehicular noise

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Abstract

The objective of the study reported here was to build a highway traffic noise simulation model for free-flow traffic conditions in Thailand employing a technique utilizing individual vehicular noise modelling based on the equivalent sound level over 20 s ($L_{eq}20\,s$). This $L_{eq}20\,s$ technique provides a more accurate measurement of noise energy from each type of vehicle under real running conditions. The coefficient of propagation and ground effect for this model was then estimated using a trial-and-error method, and applied to the highway traffic noise simulation model. This newly developed highway traffic noise model was tested for its goodness-of-fit to field observations. The test shows that this new model provides good predictions for highway noise conditions in Thailand. The concepts and techniques that are modeled and tested in this study can also be applied for prediction of traffic noise for local conditions in other countries.

1. Introduction

Traffic noise is a major environmental impact of highways [1–3]. A better highway, in term of lower traffic noise [4,5], can be achieved through planning and design prior to its construction if its noise levels, and their impact on the surrounding land uses can be predicted using a highway traffic noise model (TNM) [6–8]. Valid prediction models allow different type of noise control techniques to be evaluated before construction, allowing for the most effective control measures to be incorporated in the designs [9,10]—much better than attempting to respond to complaints from people in the vicinity of the highway after it is constructed, and then attempting to retrofit high-cost post-construction protection measures [11–14].

For the highways being constructed in Thailand, traffic noise is generally different in nature and characteristics from the stop-and-go traffic in urban areas such as Bangkok [15]. Further, it is potentially different to that in other (particularly western) countries because of some different vehicle types in Thailand, different levels of vehicular maintenance, and possibly different modes of operation and driver behavior.

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A specific Thai approach to modelling this free-flow highway noise [2,7,16] on highways in Thailand is justified.

The FHWA highway TNM was developed for predicting the $L_{eq}(1\,h)$ of free-flow highway conditions in the USA based on the reference energy mean emission level (L_{0Ei}) for each of three vehicle types. These vehicle types consisted of automobile (<4500 kg), medium truck (4500–12,000 kg), and heavy truck (>12,000 kg). The basis of the model, in terms of vehicular emission levels, was the L_{max} (maximum noise level) of a passing vehicle of each of these three vehicle types. Their assumption was that each vehicle is an acoustical monopole, or single point source, moving along the traffic lane. The overall highway noise model was then analyzed based on this monopole propagation of vehicle noise along the traffic lane of that highway by using the noise reduction of 6 dBA for every double of distance farther from the noise source, and the volume of each vehicle type on that particular highway section together with the propagation coefficient based on two types of ground surface as hard site and soft site [17].

In the UK, The Department of Transport CORTN [18] prediction model estimates the basic noise level in L_{10} (the sound pressure level that is exceeded 10% of the measuring time period), both for 1 and 18 h predictions. The basic noise was obtained from a reference distance of 10 m away from the nearside of the carriageway edge for the highway traffic noise prediction model. Basic noise level was analyzed from the traffic flow, speed of the traffic, composition of heavy vehicle in the traffic, gradient of the road, and the type of road surface. The model includes adjustments for the percentage of heavy vehicles (>1525 kg), traffic speed, gradient, road surface, and propagation. This model utilizes the overall traffic flow base with the consideration of percentage of heavy vehicle in traffic stream without considering of other different type of vehicles.

TNM [19], which is the new version of the one being used in the USA, provided the reference energy mean emission level, or basic noise level, for five vehicle types. These vehicle types consisted of automobile (vehicles with two axles and four tires carry nine or fewer people or cargo i.e. passenger car, van, light truck with gross weight <4500 kg), medium truck (cargo vehicles with two axles and six tires with gross vehicle weight between 4500 and 12,000 kg), heavy truck (cargo vehicles with three or more axles with gross weight >12,000 kg), bus (vehicles designed to carry more than nine passengers), and motorcycle (vehicles with two or three tires and an open-air driver/passenger compartment). The emission level for each type of vehicle was still obtained using the L_{max} measurement of vehicle passby. These noise emission levels consisted of A-weighted sound levels, one-third octave-band spectra, and subsource-height strengths for the following pavement types: dense-graded asphaltic concrete, portland cement concrete, open-graded asphaltic concrete, and a composite pavement type consisting of data from the first two types of pavement combined. The highway noise model was then analyzed in the form of noise energy perceived based on noise emission and traffic volume from each vehicle type together with physical characteristics of that particular highway section to provide the predicted highway noise levels in L_{eq} 1 h (hourly A-weighted equivalent sound level), day–night average sound level (Ldn), community noise equivalent level in day/evening/night (Lden).

Since the L_{max} of individual vehicles types, or the derived reference energy mean emission data, cannot be assumed to fit real-world running vehicle noise data of vehicles on Asian roads, Pamanikabud [20] first used the equivalent sound level, measured over a time period of 10 s-$L_{eq}(10\,s)$, (replacing the maximum noise level (L_{max}) in the modelling of the basic noise of each vehicle type) for estimation of vehicle noise in an Asian country, This technique was then applied to build a traffic noise simulation model appropriate for major highways in sub-urban area of Bangkok based on noise emissions from vehicles found in local traffic [7]. The basic noise model for six groups of vehicle found on highways in Thailand was developed by Pamanikabud and Vivitjinda [2]. A motorway TNM was also formulated by Pamanikabud and Tansatcha [16]. This model utilized $L_{eq}(10\,s)$ measurements of eight vehicle types in its formulation, and showed a highly significant goodness-of-fit to the field-observed data from the Bangkok-Chonburi Motorway—the first motorway in Thailand. Tansatcha et al. [21] formulated a motorway noise model in 2005 based on perpendicular analysis of traffic noise along the highway centerline together with the application of new sets of basic vehicular noise measurements based on $L_{eq}(10\,s)$.

Even though individual vehicular noise measurements using $L_{eq}(10\,s)$ can provide reasonable input to highway noise prediction results for a Thai highway noise model, it is believed that they sometimes still cannot provide the full contribution to energy emissions from some types of very heavy, and very slow-speed, vehicles.

Some errors to these basic vehicular noise levels measurements are also likely from operator error in the undertaking the 10-s measurement of emissions from these vehicles.

Therefore, this study is directed at investigating, and building, a more accurate highway TNM by means of developing a more effective measurement of the vehicle noise source levels, or basic noise, of each vehicle type. It does this by using the technique of measuring source levels of individual vehicle over a longer time period of 20 s-L_{eq}(20 s).

2. Vehicle noise level using equivalent sound level measured over 20 s L_{eq}(20 s)

At the present time, there is no official standard for individual vehicle noise under real running condition in any government office in Thailand. There is also no standard highway traffic noise prediction model for Thailand. However, the basic noise model generated from the equivalent sound levels over 10 s-L_{eq}(10 s) is currently used for research and development works in Thailand [2,7,16,22]. The highway traffic noise simulation model that is developed using these L_{eq}(10 s) basic noise levels can provide better predictions for highway traffic noise than the previous highway noise models that were developed from the L_{max} measure of individual vehicle noise [2,7,21]. This is due to the fact that noise generated by a passing vehicle is normally not the pure monopole source assumed by the L_{max} methodology, but a multipole source arising from many parts of the moving vehicles [23,24], and this is particularly the case for long-body and slow-speed vehicles such as full-trailers, semi-trailers, buses, and heavy trucks (10 wheels trucks). In the L_{eq} approach, there is no need for the monopole assumption, since this measurement technique allows the sound level measurement to include all noise emission energy generated by a vehicle pass-by (over the measurement time interval) [25].

However, a measurement technique using an L_{eq}(10 s) may still cause some errors. This is because an observer who operates a noise meter has to estimate when to start the noise measurement, normally 5 s before that vehicle passes the meter. An observer may not start the noise meter exactly at that time due to human error, and also because of the difference in spot speed of each particular vehicle. An early or late start of the meter results in missing some parts in the sound energy as the vehicle passes.

To overcome this problem, an improved estimate of individual vehicle basic noise in the form of L_{eq}(20 s), the equivalent sound levels over 20 s, was initiated in this study. The technique of measuring L_{eq}(20 s) largely eliminates the unreliable judgment of an observer. An observer starts the measurement when the vehicle passes in front of the meter. This meter automatically records the emission noise energy of the passing vehicle until the meter stops at the end of 10 s time period. The measuring characteristics of this new technique in L_{eq}(10 s) starting from $t_1 = 0$ s to $t_2 = +10$ s in comparison to the measurement in L_{eq}(20 s) that starts from $t_1 = -10$ s to $t_2 = +10$ s are shown in Fig. 1. Transformation of the measured equivalent sound levels in 10 s L_{eq}(10 s) (starting from $t_1 = 0$ s to $t_2 = +10$ s) into L_{eq}(20 s) (starting from $t_1 = -10$ s to $t_2 = +10$ s) are

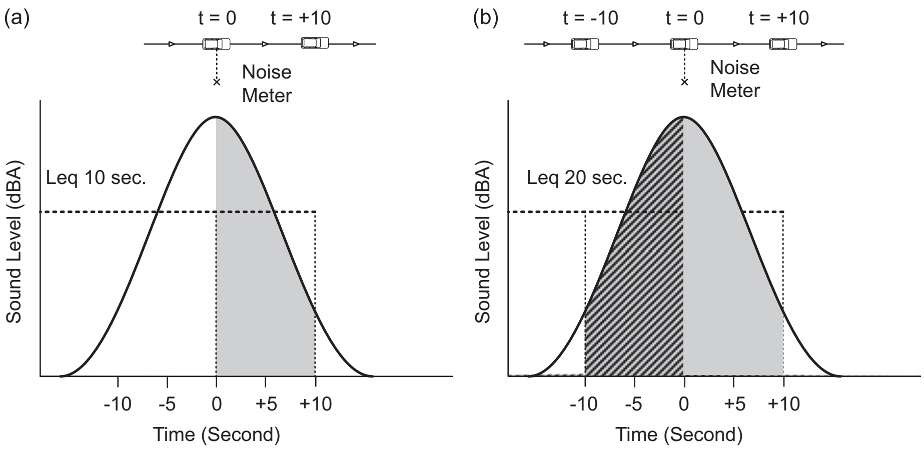

Fig. 1. Transformation of L_{eq}(10 s) from $t_1 = 0$ s to $t_2 = +10$ s measurement to L_{eq}(20 s) from $t_1 = -10$ s to $t_2 = +10$ s: (a) L_{eq}(10 s) from $t_1 = 0$ s to $t_2 = +10$ s; (b) L_{eq}(20 s) from $t_1 = -10$ s to $t_2 = +10$ s.

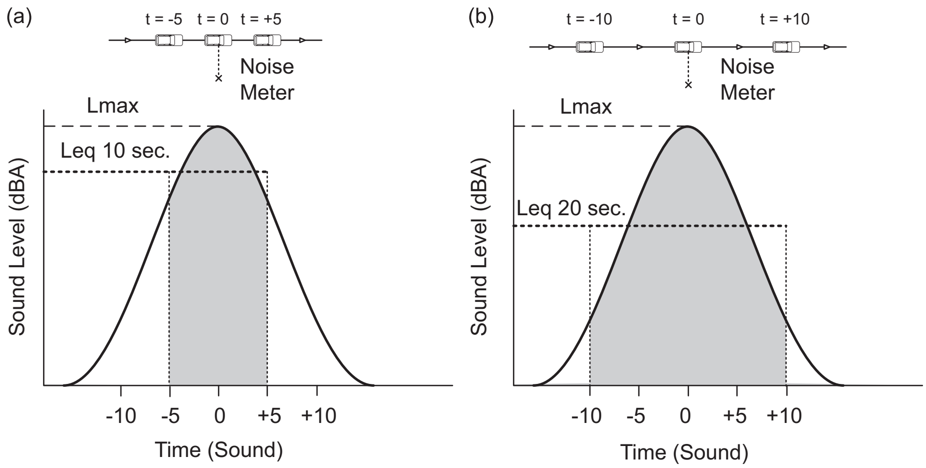

Fig. 2. Noise energy curve comparison between $L_{eq}(10\,s)$ and $L_{eq}(20\,s)$ of a pass-by vehicle.

mathematically described in Eqs. (1)–(7). This shows that the average mean energy of $L_{eq}(20\,s)$ ($t_1 = -10\,s$ to $t_2 = +10\,s$) is equal to that of $L_{eq}(10\,s)$ ($t_1 = 0\,s$ to $t_2 = +10\,s$). Further, this $L_{eq}(20\,s)$ techniques ensures measurement of the energy contribution of the full pass-by of all vehicles, including those heavy vehicles with a long body and slow speed.

The theoretical sound level characteristics of a passing vehicle can be presented as in Fig. 2. Examples from field observation of the pass-by of actual vehicles, based on instantaneous noise levels at 0.1 s intervals, for each vehicle type are shown in Fig. 3.

From the equivalent sound level in the time period from t_1 to t_2 [13],

$$L_{eq} = 10\,\log\left[\left(\frac{1}{t_2 - t_1}\right)\int_{t_1}^{t_2}\frac{p(t)^2}{p_{ref}^2}\,dt\right] \tag{1}$$

From Fig. 1(a), when $t_1 = 0\,s$, $t_2 = +10\,s$,

$$L_{eq}(10\,s) = 10\,\log\left[\left(\frac{1}{10}\right)\int_{0}^{10}\frac{p(t)^2}{p_{ref}^2}\,dt\right] \tag{2}$$

From Fig. 1(b), when $t_1 = -10\,s$, $t_2 = 10\,s$,

$$L_{eq}(20\,s) = 10\,\log\left[\left(\frac{1}{20}\right)\int_{-10}^{10}\frac{p(t)^2}{p_{ref}^2}\,dt\right] \tag{3}$$

From Fig. 2(b), $t_1 = -10\,s$, $t_2 = 10\,s$,

$$\int_{-10}^{10}\frac{p(t)^2}{p_{ref}^2}\,dt = 2\times\int_{0}^{10}\frac{p(t)^2}{p_{ref}^2}\,dt$$

Eq. (3) becomes

$$L_{eq}(20\,s) = 10\,\log\left[\left(\frac{1}{10}\right)\int_{0}^{10}\frac{p(t)^2}{p_{ref}^2}\,dt\right] \tag{4}$$

Eq. (2) is equal to Eq. (4), therefore,

$$L_{eq}(20\,s)_{(t_1=-10\,,\;t_2=+10\,)} = L_{eq}(10\,s)_{(t_1=0\,,\;t_2=+10\,)} \tag{5}$$

where $L_{eq}(10\,s)$ is the equivalent sound levels in 10 s (dBA), $L_{eq}(20\,s)$ the equivalent sound levels in 20 s (dBA), $p(t)$ the instantaneous sound pressure at time t (N/m^2), p_{ref} the reference sound pressure of 2×10^{-5} N/m^2, and t_2–t_1 the duration of integration of the pass-by sound energy (s).

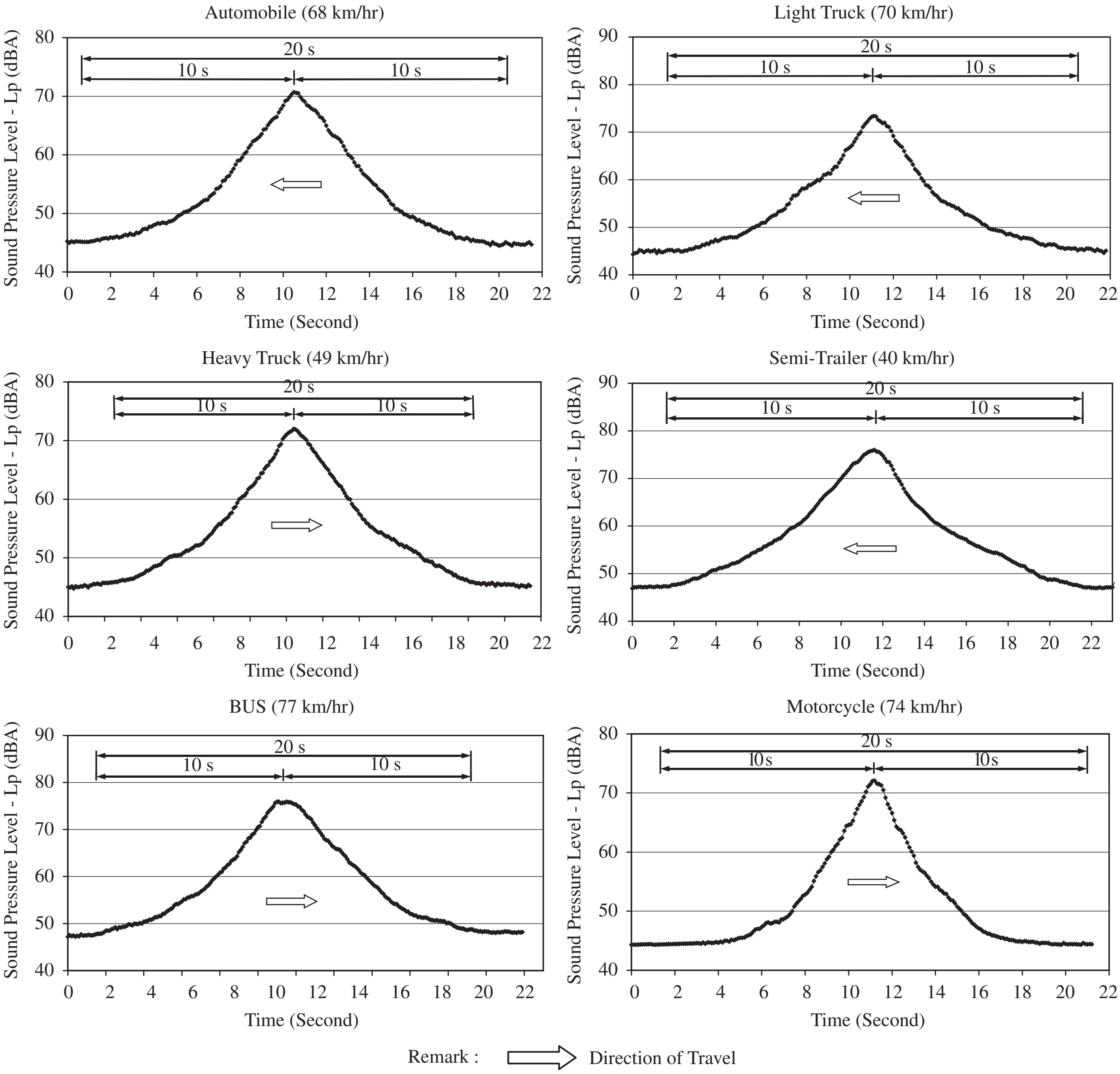

Fig. 3. Examples of instantaneous noise levels of pass-by vehicles.

In this study, the $L_{eq}(20\,s)$ of individual vehicles were measured by sound level meters located at a standard distances of 15 m from the source. The speed of each vehicle was measured simultaneously by using a radar gun, or stopwatch and markers.

The layout for these measurements of free-flow pass-by noise levels of individual vehicles is shown in Fig. 4. In order to prevent the contamination of the pass-by vehicle noise from the other vehicles, measurement of individual vehicles was conducted with a large headway between vehicles to ensure other distant vehicles did not contribute to the measured sound level. This was achieved when the ‘‘clearance distance’’ both upstream and downstream of the noise meter location was a minimum distance of 500 m so that a single vehicle was present on this data collection zone at a time. Three traffic cone markers were set by the side of roadway at location A, B, and C at 50 m intervals, with the center cone B set opposite the location of the noise meter. These markers were used to identify the vehicle spot speed measurement zone, and the radar gun set at the

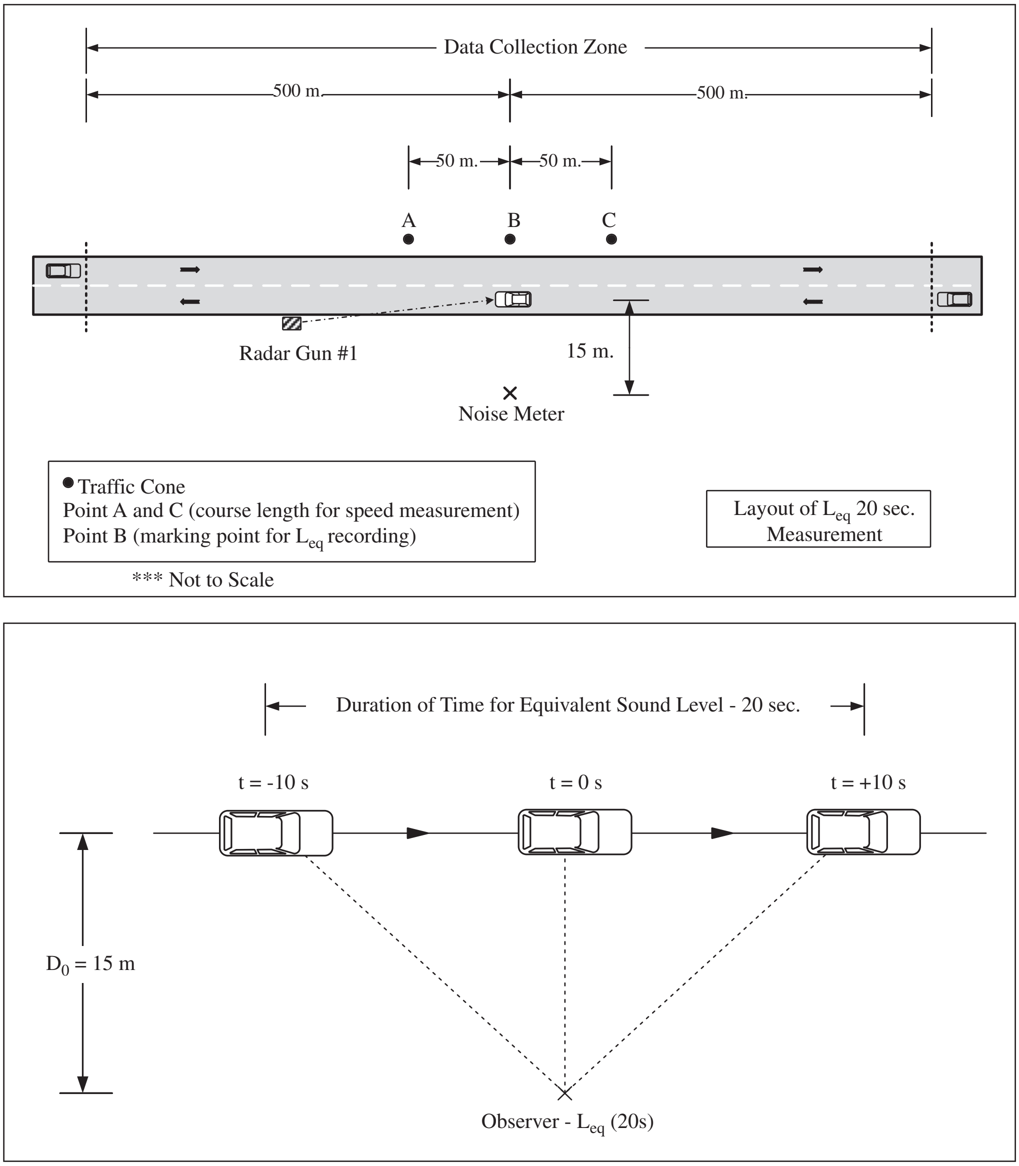

Fig. 4. Diagram of field measurement layout for $L_{eq}(20\,s)$.

distance of 100 m from B. Therefore, the angle between the radar gun and the centerline of the traffic lane kept at a small angle of between 1° and 3°.

3. Modelling of the basic noise level

The commonly found nine types of vehicle on highways in Thailand were investigated in this study, namely, automobile, light truck, medium truck, heavy truck, semi-trailer, full-trailer, bus, motorcycle, and tuk-tuk (motor-tricycle in common use in Thailand). All data for the development of the basic noise model were collected at the standard distance of 15 m from the center line of the traffic lane with the precision sound level meter at a height of 1.20 m from road surface. Pass-by noise levels of the vehicles of each type were measured in $L_{eq}(10\,s)$, starting when that particular vehicle passed the noise meter and stopped 10 s after that. The spot speed of that vehicle was also measured simultaneously.

Table 1
Basic noise data and statistical values for each vehicle type

Vehicle type	Sample size	$L_{eq}(20\,s)$ (dBA)			Spot speed (km/h)		
		Max	Min	Mean	Max	Min	Mean
Automobile (AU)	308	73.6	50.3	61.7	125.7	38.8	77.5
Light truck (LT)	293	72.1	55.2	63.8	100.0	36.0	63.7
Medium truck (MT)	193	71.2	61.2	66.0	85.8	37.9	59.5
Heavy truck (HT)	322	81.0	60.1	69.5	87.3	20.4	43.8
Full trailer (FT)	214	80.3	60.5	70.0	82.0	21.8	45.8
Semi trailer (FT)	215	76.9	60.1	70.3	82.8	10.1	38.6
Motorcycle (MC)	196	74.5	36.5	59.5	94.7	21.9	58.2
Bus (BUS)	194	74.9	58.2	67.7	77.5	30.5	56.1
Tuk-tuk (TT)	211	75.6	57.3	64.2	63.0	30.1	43.9

The measured $L_{eq}(10\,s)$ from $t_1 = 0\,s$ to $t_2 = +10\,s$ was then used as the noise level $L_{eq}(20\,s)$ from $t_1 = -10\,s$ to $t_2 = +10\,s$ of each pass-by vehicle as illustrated above. The results for each type of vehicle, in terms of maximum, minimum and mean $L_{eq}(20\,s)$, and vehicle speed, is shown in Table 1. Sample sizes for each vehicle type in this study ranged from 193 to 308.

This data set were then analyzed by using linear regression technique in order to identify the relationship between $L_{eq}(20\,s)$ and speed—for each type of vehicle. Fig. 5 shows the plot of the relationships between $L_{eq}(20\,s)$ and the logarithm of vehicle speed for automobile, light truck, medium truck, heavy truck, semi-trailer, full-trailer, bus, motorcycle, and tuk-tuk, respectively. From this plot of regression line overlays on the scattered data of each type of vehicle, it shows the model residuals that are distributed along the regression line of each model. All of these residual distributions show the random error characteristics along the regression line. The basic noise models in $L_{eq}(20\,s)$ for all vehicle types in Thailand are summarized in Table 2 together with the coefficient of determination (R^2) of each model. The low coefficient of determination is the typical characteristic of noise in related to vehicular speed due to the highly variation of vehicle noise in each type of running vehicle on the highway [1,7,16,20,21]. The statistical result from the regression analysis of each basic noise model is shown in Table 3. These results represent a comprehensive data set of basic noise levels of the vehicle types found on the highway system in Thailand.

4. Free-flow traffic noise modelling in perpendicular propagation to traffic lane

Equivalent sound level measured in 1 h period, $L_{eq}(1\,h)$, is an appropriate traffic noise scale for use in Thailand. This is due to the fact that the highest traffic noise impact to people living nearby normally occurs during the peak hour period. Therefore, the further step in the development of a highway traffic stream prediction model is to utilize the basic noise levels that are collected for each type of vehicle in $L_{eq}(20\,s)$ to predict the $L_{eq}(1\,h)$ of a traffic stream composed of different types of vehicles. Such a model can then predict levels adjacent to any particular roadway segment in any single hour, given information on the traffic composition and flows of vehicles on that segment in that hour.

In this study, the computation of the $L_{eq}(1\,h)$ for the entire traffic stream is based on noise propagation analysis in the perpendicular direction from the centerline of traffic lane [21]. The basic noise levels of individual vehicles is measured as $L_{eq}(20\,s)$ in this study, and this is the average energy emission level of the entire 20 s period of the passage of a vehicle along the roadway—effectively the integration of energy emissions from the vehicle as it moves over a considerable length of the roadway. To an approximation, it is reasonable to consider the vehicle source over this 20 s as a line source rather than a point source. Propagation from a line source results in a 3 dBA reduction for every doubling of distance [8]. By utilizing this approach, there is no requirement for the assumption of monopole or single point source propagation of vehicular noise, since the overall noise energy emitted from that particular vehicle (either monopole or multipole noise source) is taken into account—even the long-body vehicles such as heavy trucks, semi-trailers, full trailers, and buses.

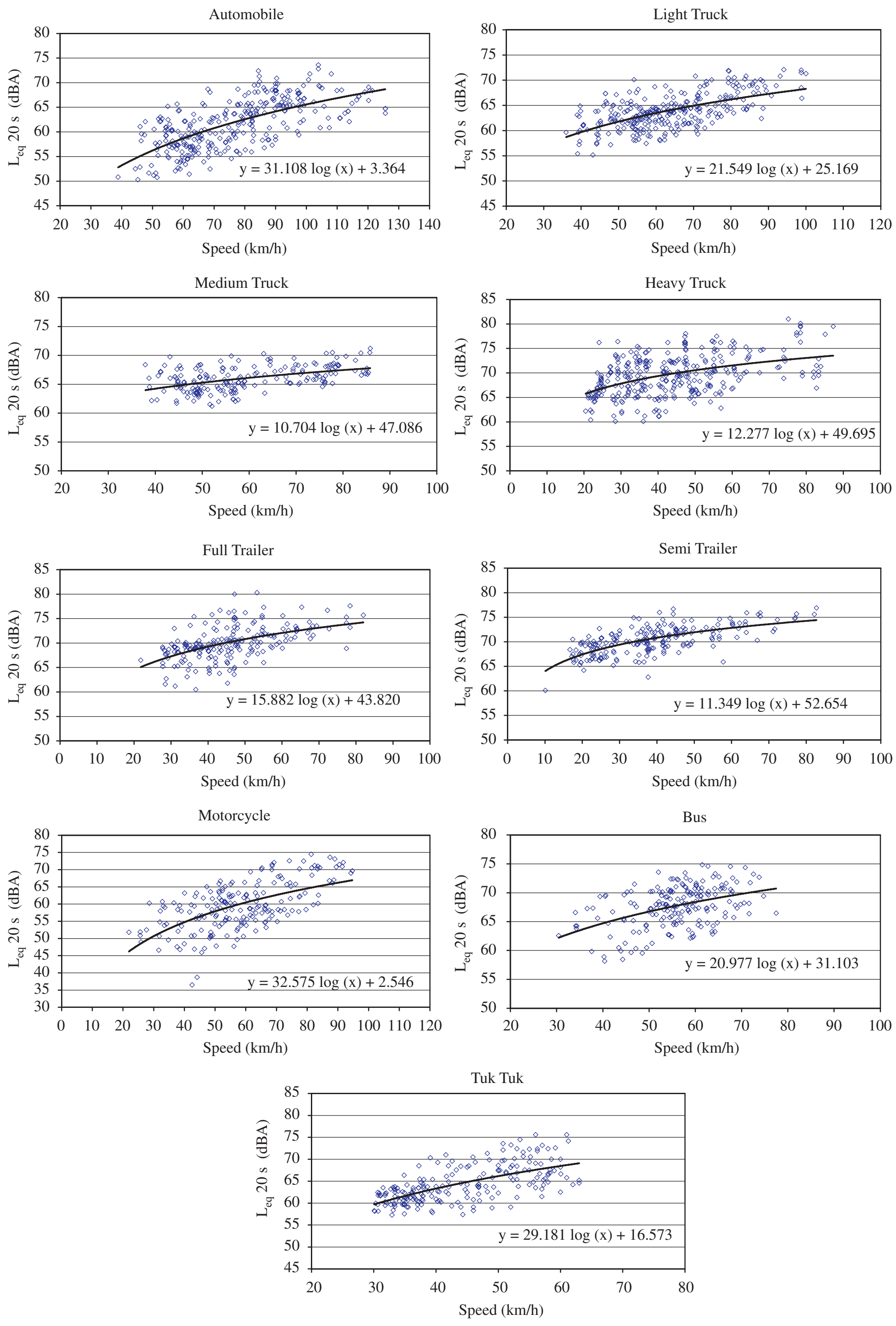

Fig. 5. Relationship between L_{eq}(20 s) and speed for each vehicle type.

Table 2
Basic noise model in $L_{eq}(20\,s)$ for each vehicle type

Vehicles type	Uninterrupted flow basic noise model $L_{eq}(20\,s)$	R^2	Data	$L_{eq}(20\,s)$ statistics	
				Mean	Standard deviation
Automobile (AU)	$y = 31.108\log(x) + 3.364$	0.451	308	61.74	4.94
Light truck (LT)	$y = 21.549\log(x) + 25.169$	0.364	293	63.82	3.35
Medium truck (MT)	$y = 10.704\log(x) + 47.086$	0.220	193	65.98	2.13
Heavy truck (HT)	$y = 12.277\log(x) + 49.695$	0.212	322	69.52	4.08
Full trailer (FT)	$y = 15.882\log(x) + 43.820$	0.272	214	69.97	3.41
Semi trailer (ST)	$y = 11.349\log(x) + 52.654$	0.464	215	70.30	2.80
Motorcycle (MC)	$y = 32.575\log(x) + 2.546$	0.353	196	59.49	6.91
Bus (BUS)	$y = 20.977\log(x) + 31.103$	0.191	194	67.66	3.53
Tuk-tuk (TT)	$y = 29.181\log(x) + 16.573$	0.414	211	64.22	4.14

y: noise level in L_{eq20s} (dBA), x: speed (km/h).

Table 3
Statistical results from regression analysis of $L_{eq}(20\,s)$

Statistics	AU	LT	MT	HT	ST	FT	BUS	MC	TT
	$L_{eq}(20\,s)$ (dBA)								
Mean	61.74	63.82	65.98	69.52	70.30	69.97	67.66	59.49	64.22
Standard error	0.282	0.196	0.153	0.228	0.191	0.233	0.253	0.494	0.285
Median	62.05	63.70	65.98	69.50	70.30	69.60	67.91	59.03	63.47
Mode	65.40	63.86	65.30	70.10	71.60	69.80	67.98	58.40	61.77
Standard deviation	4.94	3.35	2.13	4.08	2.80	3.41	3.53	6.91	4.14
Sample variance	24.42	11.22	4.53	16.68	7.86	11.65	12.43	47.75	17.11
Kurtosis	−0.70	−0.18	−0.55	−0.25	0.14	0.44	−0.16	0.09	−0.26
Skewness	−0.05	0.27	0.07	0.19	−0.14	0.13	−0.45	−0.10	0.65
Range	23.30	16.94	10.00	20.90	16.80	19.79	16.68	38.00	18.32
Minimum	50.30	55.16	61.20	60.10	60.10	60.50	58.17	36.50	57.28
Maximum	73.60	72.10	71.20	81.00	76.90	80.29	74.85	74.50	75.60
Count	308	293	193	322	215	214	194	196	211
Sum of square error	4116.70	2083.73	679.32	4219.90	901.96	1806.07	1940.25	6022.46	2105.70
Mean error	−0.0001	0.0006	−0.0005	−0.0008	−0.0007	0.0004	0.0010	−0.0007	−0.0010
Mean % error	−0.0092	−0.0850	−0.1751	−0.1281	−0.0234	−0.0380	0.0414	−0.7067	−0.0759
Mean absolute error	3.022	2.105	1.551	2.954	1.592	2.109	2.595	4.650	2.513
Mean absolute % error	161.895	117.630	88.705	182.683	103.955	128.702	149.506	267.554	152.058
Mean squared error	13.366	7.112	3.520	13.105	4.195	8.440	10.001	30.727	9.980
Root mean squared error	3.656	2.667	1.876	3.620	2.048	2.905	3.163	5.543	3.159
Index of agreement	0.778	0.723	0.588	0.580	0.788	0.627	0.547	0.708	0.755

In the development of the FHWA [17] traffic noise prediction model, the relationship between mean square sound pressure (P^2) at some distance (R) and the reference mean square sound pressure (P_0^2) at reference distance (D_0) (see Fig. 6) is given by Eq. (6):

$$(P^2) = (P_0^2)\left(\frac{D_0}{R}\right)^2\left(\frac{D_0}{R}\right)^\beta \tag{6}$$

where P^2 is the mean square sound pressure (N/m^2), P_0^2 the mean square sound pressure at the reference distance (N/m^2), D_0 the perpendicular reference distance (15 m), R the distance from source to observer point (m), and β the ground effect adjustment [26,27]. This model is based on using the maximum noise level as a vehicle passes, and propagation from the vehicle is based on the assumption that it is a moving point source.

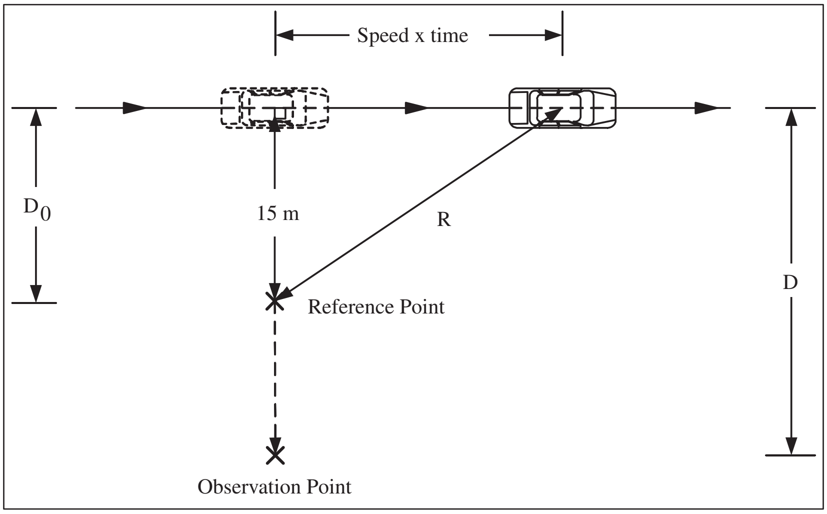

Fig. 6. Diagram for analysis of a single pass-by vehicle with perpendicular propagation to traffic flow.

However, as explained above, when individual vehicle noise is measured, as in this study, as $L_{eq}(20\,\mathrm{s})$, together with a perpendicular propagation analysis approach of vehicle noise from traffic lane, the mathematical relationship can be described by Eq. (7):

$$(P^2) = (P_0^2)\left(\frac{D_0}{D}\right)\left(\frac{D_0}{D}\right)^{\beta} \tag{7}$$

where D is the perpendicular distance from observer point to centerline of traffic lane (m).

The equivalent sound level (L_{eq}) is the average energy mean emission level of noise during the measuring time period or the level of average intensity for the time period under consideration, and its mathematical description is in the following equation [8]:

$$L_{eq} = 10\log\left[\frac{1}{T_2 - T_1}\int_{T_1}^{T_2}\frac{(P^2)}{(P_{ref}^2)}\,dt\right] \tag{8}$$

where L_{eq} is the equivalent sound level for the time period (dBA), P the sound pressure ($\mathrm{N/m^2}$), P_{ref} the reference sound pressure ($2\times10^{-5}\,\mathrm{N/m^2}$), and T_2–T_1 the time interval (s).

Substituting P from Eq. (7) into Eq. (8), results in Eq. (9):

$$L_{eq} = 10\ \log\left[\frac{1}{T_2 - T_1}\int_{T_1}^{T_2}\left[\frac{(P_0^2)}{(P_{ref}^2)}\left(\frac{D_0}{D}\right)^{1+\beta}\right]dt\right] \tag{9}$$

The equivalent sound level in 1 h (3600 s) period-$L_{eq}(1\,\mathrm{h})$—can be estimated based on the equivalent sound level in 20 s-$L_{eq}(20\,\mathrm{s})$, as follows:

$$L_{eq}(1\,\mathrm{h}) = 10\ \log\left[\frac{1}{3600}\left[\int_{-1800}^{-10}0\,dt + \int_{-10}^{10}\left[\frac{(P_0^2)}{(P_{ref}^2)}\left(\frac{D_0}{D}\right)^{\varepsilon}\right]dt + \int_{10}^{1800}0\,dt\right]\right] \tag{10}$$

where $L_{eq}(1\,\mathrm{h})$ is the equivalent sound level for a 1 h period (dBA), ε the coefficient of propagation and ground effect which is equal to $1+\beta$, this is the coefficient that represents propagation characteristics of noise based on the distance and ground condition on the noise path:

$$L_{eq}(1\,\mathrm{h}) = 10\ \log\left[\frac{1}{3600}\left(\frac{D_0}{D}\right)^{\varepsilon}\int_{-10}^{10}\left[\frac{(P_0^2)}{(P_{ref}^2)}\right]dt\right] \tag{11}$$

For a number of vehicles (N) in a 1 h period:

$$L_{eq}(1\,\mathrm{h}) = 10\,\log\left[\frac{N}{3600}\left(\frac{D_0}{D}\right)^{\varepsilon}\int_{-10}^{10}\left[\frac{(P_0^2)}{(P_{ref}^2)}\right]\mathrm{d}t\right] \tag{12}$$

$$L_{eq}(1\,\mathrm{h}) = 10\,\log\left[\frac{1}{20}\int_{-10}^{10}\left[\frac{(P_0^2)}{(P_{ref}^2)}\right]\mathrm{d}t\right] + 10\,\log\left(\frac{D_0}{D}\right)^{\varepsilon} + 10\,\log\left(\frac{N}{180}\right) \tag{13}$$

The first term in Eq. (13) is the basic noise level of vehicle measured as $L_{eq}(20\,\mathrm{s})$; therefore, Eq. (13) can be transformed into Eq. (14):

$$L_{eq}(1\,\mathrm{h}) = L_{eq}(20\,\mathrm{s}) + 10\,\log\left(\frac{D_0}{D}\right)^{\varepsilon} + 10\,\log N - 22.553 \tag{14}$$

The $L_{eq}(1\,\mathrm{h})$, i for each vehicle type (i) is

$$L_{eq}(1\,\mathrm{h}),\ i = L_{eq}(20\,\mathrm{s}),\ i + 10\,\log\left(\frac{D_0}{D}\right)^{\varepsilon} + 10\,\log N_i - 22.553 \tag{15}$$

where $L_{eq}(20\,\mathrm{s})$, i is the equivalent sound level in 20 s of the basic noise level of vehicle class i (dBA), N_i the number of vehicles of class i in 1 h, D the perpendicular distance from the observer to the center line of the traffic lane (m), D_0 the reference distance at which the emission levels are measured (15 m), ε the coefficient of propagation and ground effect, and i the class of vehicle (1–9) (automobile, light truck, medium truck, heavy truck, full trailer, semi-trailer, bus, motorcycle, and tuk-tuk).

5. Estimation of the coefficient of propagation and ground effect

The coefficient of propagation and ground effect (ε) of the highway noise model can be estimated from the field-observed data that were collected from a range of highways in Thailand using a trial-and-error technique [26,27]. These field data consisted of measured road traffic noise levels from the whole traffic stream on highways, $L_{eq}(1\,\mathrm{h})$, together with measured vehicle volumes and combination average spot speed of each type of vehicle in the traffic stream (traffic noise levels, speed, and traffic counts were measured simultaneously, and traffic data were collected for both near side and far side carriageways). A total of 216 data sets were collected for this analysis, from 10 different locations in six different provinces in Thailand. The summary of traffic and highway characteristics, together with traffic noise in $\underline{L}_{eq}(1\,\mathrm{h})$, in this data set is shown in Table 4. It can be noted that $L_{eq}(1\,\mathrm{h})$ ranged from 69 to 83 dBA, which is typical of the high levels of noise beside highways in Thailand. The relatively limited range of distances of the noise measurement sites from the highway is also typical of Thai conditions, where sensitive receptors tend to be located close to roadways.

In this analysis, a trial-and-error technique was used to find the most appropriate value of the coefficient of propagation and ground effect (ε). The predicted noise levels of the highway calculated from different values of ε were tested for their goodness-of-fit to the field-observed data by using a paired t-test test. The analysis provides the highest accuracy with minimum mean difference (measured-predicted) of -0.01 at $\varepsilon = 0.66$. This analysis is shown in Table 5.

Using this optimum value for the coefficient of propagation and ground effect, the mathematical description of the final highway TNM is presented in Eq. (16):

$$L_{eq}(1\,\mathrm{h}),\ i = L_{eq}(20\,\mathrm{s}),\ i + 10\,\log\left(\frac{D_0}{D}\right)^{0.66} + 10\,\log\,N_i - 22.553 \tag{16}$$

where $L_{eq}(1\,\mathrm{h})$, i is the equivalent sound level of vehicle class i in 1 h (dBA), $L_{eq}(20\,\mathrm{s})$, i the basic noise level of vehicle class i in equivalent sound level in 20 s (dBA), N_i the number of vehicles per hour in class i, D the perpendicular distance from observer to the center line of the traffic lane (m), D_0 the reference distance at which the emission levels were measured (15 m), and i the class of vehicle (1–9) (automobile, light truck, medium truck, heavy truck, full trailer, semi-trailer, bus, motorcycle, and tuk-tuk).

Table 4
Summary of traffic, distance, and noise level characteristics in the highway data set

Carriageway location	Data characteristics	Statistic	Vehicle type									
			AU	LT	MT	HT	FT	ST	MC	BUS	TT	Total
Near side	Volume (veh/h)	Min	10	101	4	8	0	0	0	0	0	123
		Max	1437	1075	153	129	64	98	491	33	5	3485
		Average	199	384	41	52	22	19	63	8	0	788
	Volume ratio (%)	Average	25.31	48.73	5.19	6.57	2.80	2.35	7.95	1.06	0.03	100
	Speed (km/h)	Min	62.82	71.03	52.51	56.08	0.00	0.00	0.00	0.00	0.00	68.79
		Max	129.39	116.77	99.86	94.91	92.65	101.15	87.52	118.03	80.00	114.26
		Average	93.54	87.42	70.90	68.11	62.47	61.86	58.63	66.98	8.62	82.30
	Distance from C.L. of carriageway to noise meter (m)	Min	3.65									
		Max	28.25									
		Average	8.81									
Far side	Volume (veh/h)	Min	10	101	4	8	0	0	0	0	0	123
		Max	1437	1075	153	129	64	98	491	33	5	3485
		Average	199	384	41	52	22	19	63	8	0	788
	Volume ratio (%)	Average	25.31	48.73	5.19	6.57	2.80	2.35	7.95	1.06	0.03	100
	Speed (km/h)	Min	62.82	71.03	52.51	56.08	0.00	0.00	0.00	0.00	0.00	68.79
		Max	129.39	116.77	99.86	94.91	92.65	101.15	87.52	118.03	80.00	114.26
		Average	93.54	87.42	70.90	68.11	62.47	61.86	58.63	66.98	8.62	82.30
	Distance from C.L. of carriageway to noise meter (m)	Min	7.15									
		Max	42.00									
		Average	23.57									
Both side	Volume (veh/h)	Min	27	210	13	16	0	0	0	0	0	266
		Max	2768	1897	269	255	103	179	763	56	7	6297
		Average	399	768	82	103	44	37	125	17	1	1576
	Volume ratio (%)	Average	25.31	48.73	5.19	6.57	2.80	2.35	7.95	1.06	0.03	100
	Speed (km/h)	Min	74.76	72.12	56.98	59.34	0.00	0.00	0.00	0.00	0.00	70.88
		Max	126.14	114.40	95.72	92.08	87.73	90.70	81.77	93.16	58.47	111.72
		Average	93.89	87.67	71.15	68.39	62.72	62.03	58.86	66.98	8.46	82.57
	Distance from C.L. of carriageway to noise meter (m)	Min	5.40									
		Max	32.50									
		Average	16.19									
	Highway noise level in $L_{eq}(1\,h)$ (dBA)	Min	68.7									
		Max	82.8									
		Average	77.1									

Table 5
Summarized results of analysis of coefficient of propagation and ground effect at significance level $\alpha = 0.05$

t-Test: paired two sample for means	Coefficient of propagation and ground effect (ε)					
	0.50	0.60	*0.66*	0.70	0.80	1.00
Mean of L_{eq}(1 h) measured	77.10					
Mean of L_{eq}(1 h) predicted	76.88	77.02	*77.11*	77.17	77.33	77.67
Mean difference (measured–predicted)	0.22	0.08	*−0.01*	−0.07	−0.23	−0.57
Observations	216					
Hypothesized mean difference	0					
df	215					
t Stat	1.43	0.57	*−0.05*	−0.52	−1.89	−5.71
t Critical two-tail	±1.97					

Table 6
Statistical results of measured and predicted traffic noise levels in L_{eq}(1 h)

Statistics	Measured	Predicted
Mean	77.100	77.110
Median	77.550	77.778
Standard deviation	3.334	2.887
Sample variance	11.119	8.336
Kurtosis	−0.511	0.989
Skewness	−0.620	−1.015
Range	14.1	14.391
Minimum	68.7	67.139
Maximum	82.8	81.530
Sum	16653.7	16653.724
Count	216	216

6. Statistical goodness-of-fit of the highway TNM

As part of the propagation and ground effect coefficient estimation described above, the statistical goodness-of-fit test is provided to test prediction from the highway TNM against the field-observed data. The final model from this study provides a good estimate (a highly significant result in the goodness-of-fit test with $\alpha = 0.05$, as shown in Table 5 (df = 215, t stat = −0.05, and t critical two-tail = ±1.97). The final statistic values of the measured and predicted traffic noise in L_{eq}(1 h) from the test are also shown in Table 6. Therefore, this new highway noise model can be used effectively in the analysis and prediction of highway traffic noise conditions in Thailand.

7. Conclusion

This study utilized the approach of measurement of individual vehicle noise on Thailand's highways employing equivalent sound levels measured over a period of 20 s-L_{eq}(20 s). The use of L_{eq}(20 s), which is the real time measurement of average energy mean emission level of the entire noise path of 20 s of individual vehicles, can provide a more accurate measurement of individual vehicle noise. In particular, this is a better representation of the contributions to overall energy emission from the roadways by all types of vehicles found in Thailand including the long-body and slow-speed vehicles of heavy trucks, full-trailer trucks, semi-trailers trucks, and buses. A coefficient of propagation and ground effect (ε) has been estimated for conditions in Thailand. These have been incorporated into a new highway noise prediction model, which can significantly improve traffic noise forecasting from highways in Thailand. The techniques can be applied in any other country where it is possible that different vehicular and driving conditions suggest that the use of overseas developed prediction models may be inappropriate.

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