NOISE MODELING IN UNIVERSITI SAINS MALAYSIA AND OFFSHORE OIL AND GAS PLATFORM

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NOISE MODELING IN UNIVERSITI SAINS MALAYSIA AND OFFSHORE OIL AND GAS PLATFORM

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LIST OF SYMBOLS

Symbols	*Descriptions*	*Units*
f	nominal 1/3rd-octave-band center frequency	Hertz
s_i	vehicle speed	kilometer/hour
L_{Aeq} (1 h)	equivalent sound level over one hour time period	dBA
β	ground effect adjustment	dimensionless
W	sound power	Watts
W_{ref}	reference sound power	Watts
W_{abs}	acoustic energy absorbed by the surface	Watts
W_{in}	acoustic energy striking the surface	Watts
p	root-mean-square(rms) sound pressure	Pascal
p_{ref}	reference sound pressure	Pascal
π	the ratio of the circumference to the diameter of a circle (given 3.14159)	dimensionless
Q	ratio of the intensity on a designated axis of a sound radiator	dimensionless
ρc	characteristics impedance of medium	mks rayls
DI	directivity index	dimensionless
r	radial distance of receiver from the source	meter
α	sound absorption coefficient	dimensionless
α_j	absorption coefficient of the j th surface	dimensionless
τ	sound transmission coefficient.	dimensionless
S_j	surface area of the j th surface	meter^2
S_o	total surface area of the room	meter^2
S_w	surface area of external walls	meter^2
$L_{p,image}$	sound pressure levels from image source	dBA
$L_{w,image}$	sound power level of image source	dBA
$L_{w,original}$	sound power levels of original source	dBA
$L_{w,wall}$	sound power transmission level into the enclosure through external walls of surface area	dBA

L_{p1}	average sound pressure level immediately outside of the enclosure	dBA
R	constant for negligible energy attenuation in the room air	dimensionless
ψ	angle subtended by the elemental roadway segment (in degrees).	degrees
H_0	the null hypothesis	dimensionless
H_a	the alternative hypothesis	dimensionless
σ^2	variance of a sample	dimensionless
μ	mean of a sample	dimensionless
N	Fresnel number for noise barrier	dimensionless
ΔE_b	energy-mean adjustment for *B* constant of regression equation	dimensionless
ΔE_c	energy-mean adjustment for C constant of regression equation	dimensionless
∞	infinity	dimensionless
A	constant for speed in regression of tire/pavement noise	dimensionless
A_d	adjustment for distance between the roadway and receiver and for the length of the roadway	dBA
A_s	adjustments for all shielding and ground effects between the roadway and the receiver	dBA
$A_{traff(i)}$	adjustment for traffic flow	dBA
B	constant in tire/ pavement term of regression equation	dimensionless
C	engine/exhaust term of regression equation	dimensionless
C_N	constant for individual noise levels	dimensionless
D	perpendicular distance from observer to the centre line of the traffic lane	meter
d	perpendicular distance to the line representing the roadway segment	meter
D_0	the reference distance	meter
$D1$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$D2$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
D_F	the distance from traffic lane	feet

$E1$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$E2$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
EL_i	vehicle noise emission level	dBA
$F1$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$F2$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$G1$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$G2$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$H1$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$H2$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
i	Index over vehicle types	dimensionless
I	Sound intensity	Watts/meter^2
$I1$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$I2$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$J1$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$J2$	constant of the sixth-order polynomial fit curve for the 1/3rd spectra	dimensionless
$K1$	Calibration of the resulting A-weighted levels from the sixth-order polynomial fit	dimensionless
$K2$	Calibration of the resulting A-weighted levels from the sixth-order polynomial fit	dimensionless
L_{10}	sound levels that exceed 10 percentile of time interval	dBA
L_{50}	sound levels that exceed 50 percentile of time interval	dBA
L_A	permissible noise level in OSHA limits	dBA
$\mathrm{L_{den}}$	community noise equivalent level	dBA
$\mathrm{L_{dn}}$	average day-night sound level	dBA
L_{eq}	Equivalent sound level	dBA

$L_{eq}(10s)$	equivalent sound level in 10 seconds	dBA
L_p	sound pressure level	dBA
$L_{p,total}$	summation of sound pressure levels	dBA
L_N	all sound levels sets in the prediction model	dBA
$\mathrm{L}_{\mathrm{traf}}$	traffic sound level	dBA
L_w	sound power level	dBA
n	number of each type vehicles per hour	dimensionless
p	Index over pavements types	dimensionless
P_H	percentage of heavy trucks	percent
S	mean vehicle speed	miles/hour
TL	sound transmission loss	dBA
V	traffic volume	vehicles/hour
C	time of exposure to a noise level	hours/day
IL	insertion loss	dBA
T	total permitted exposure times at a noise level	hours/day

LIST OF ABBREVIATION

Abbreviation	*Full Description*
BEM	Boundary Element Method
CORTN	Calculation of Road Traffic Noise
DOE	Department of Environment
DOT	Department of Transportation
EPA	Environment Protection Agency
EPMI	Esso Production Malaysia Incorporated
FHWA	Federal Highway Administration
HVAC	Heating, Ventilation and Air-Conditioning
ISO	International Standards Organization
JKR	Jabatan Kerja Raya
log	Base 10 logarithm
Matlab	MATrixLABoratory
MITHRA	Software to predict outdoor propagation developed by a French company
NED	Noise Exposure Dose
NRC	Noise Reduction Coefficient
NSC	New Science Complex
OSHA	Occupational Safety and Healthy Administration
PEL	Permissible Exposure Limits
RLS-90	*Richtlinien fur den Larmschutz an StraBen* (Guidelines for Noise Propagation on Streets)
SHE	Safety, Health and Environment
SPSS	Statistical Package for the Social Sciences
StL-86	Noise Model developed by Swiss Federal Office of Environmental Protection
TNM	Traffic Noise Model
UEG	Underwater and Offshore Engineering Group
USM	Universiti Sains Malaysia
WHO	World Health Organization
WHRU	Waste Heat Recovery Units

PEMODELAN BUNYI BISING DI UNIVERSITI SAINS MALAYSIA DAN PELANTAR MINYAK DAN GAS LEPAS PANTAI

ABSTRAK

Dalam beberapa dekad lepas, pencemaran bunyi bising telah meningkat secara berterusan disebabkan oleh perkembangan perbandaran dan perindustrian yang pesat. Ia telah dikategorikan sebagai salah satu masalah utama alam sekitar dan juga dikaitkan dengan isu-isu bagi kesihatan fizikal dan mental. Oleh itu, beberapa undang-undang mengenai bunyi bising telah dikuatkuasakan di beberapa negara untuk memastikan objektif kesihatan orang ramai and alam sekitar tercapai. Tesis ini akan membentangkan permodelan bunyi bising dengan menggunakan model NOISEPAC dan model bunyi bisng trafik, versi 2.5 (TNM 2.5). Satu penyelidikan telah dimulakan untuk memantau dan memodelkan dengan menggunakan NOISEPAC tahap bunyi bising di Universiti Sains Malaysia, di mana staf and pelajar di Kompleks Sains Baru (NSC) telah menghadapi gangguan bunyi bising yang disebabkan oleh bunyi yang disebarkan oleh system penghawa dingin. Selain itu, TNM 2.5 telah digunakan untuk mengkaji tahap bunyi bising trafik di sekitar Jalan Sungai Dua, iaitu sebatang jalan raya sibuk yang berdekatan dengan kampus utama USM. Tinjauan lapangan dilakukan di sekitar NSC dan kampus USM untuk memperolehi data pengesahan dan parameter masukan dalam implementasi kedua-dua model peramalan. Selanjutnya, NOISEPAC diubahsuai untuk mengkaji tahap bunyi bising di pelantar minyak dan gas lepas pantai. Tahap bunyi bising di atas struktur lepas pantai dijangka tinggi disebabkan oleh kepadatan modul berstruktur keluli dengan berbagai-bagai punca bunyi bising. Model peramalan bunyi bising adalah satu alat untuk menilai bunyi bising alam

sekitar pada tahap rekaan dan keadaan semasa. Ia juga perlu untuk penyediaan dasar dalam pemilihan langkah peringanan bunyi bising.

NOISE MODELING IN UNIVERSITI SAINS MALAYSIA AND OFFSHORE OIL AND GAS PLATFORM

ABSTRACT

Over the last few decades, noise pollution has steadily increased due to rapid urbanization and industrialization. It has been categorized as a major environmental problem as well as being related to physical and mental health issues. Hence, several noise regulations have been implemented in various countries to ensure that broad public health and environmental objectives are met. This thesis will present modeling of noise levels using an in-house noise model, NOISEPAC and Traffic Noise Model version 2.5 (TNM 2.5). A research is initiated to monitor and model, by means of NOISEPAC, noise levels in Universiti Sains Malaysia (USM), where staffs and students in the New Science Complex (NSC) have experienced some noise annoyance due to the sound emitted from air-conditioning system. Apart from that, TNM 2.5 is used to analyze traffic noise levels around Jalan Sungai Dua, a busy roadway located near the USM main campus. Field surveys are conducted around the NSC and USM campus in order to obtain validation data and input parameters for the implementation of both prediction models. Further, NOISEPAC is modified to analyze noise levels on an offshore oil and gas platform. Noise levels on an offshore structure are expected to be high due to the compact steel structure modules with multiple noise sources. Noise prediction models are tools to assess the environment noise in the design and existing stage. They are also essential to provide a basis for the selection of noise mitigation measures.

CHAPTER 1

INTRODUCTION

1.1 Introduction to Noise Pollution Modeling

In recent decades, noise pollution has increased due to the rapid urbanization and industrialization, especially in the developing countries. Some common noise that exists in the environment include machinery noise, transportation noise, construction noise, public works noise, building services noise and noise from leisure activities. According to the Occupational Safety and Healthy Administration (OSHA), exposure to high levels of noise for long durations may lead to hearing loss, create physical and psychological stress, reduce productivity and interfere with communication (OSHA, 2006). The main social consequence of hearing impairment is the incapability to understand speech in normal environment, which is considered as a social handicap (WHO, 2006). Hence, it is important that environmental sound level be maintained at a safe and comfortable condition. However, sound that is classified as noise, such as the warning whistle from a train, is actually beneficial for it acts as a warning for people during a potential dangerous situation (Barron, 2003).

Several major federal agencies in USA, such as the Occupational Safety and Healthy Administration (OSHA), the Environment Protection Agency (EPA), the Federal Highway Administration (FHWA) have adopted noise policies and standards to regulate noise levels. The policy guidelines are used as a basis to ensure that the broad public health and environment objectives are met. In Malaysia, noise regulation is set by Department of Environment (DOE) under the Environment Quality Act, 1974 (DOE, 2007). As a practical measure, the selection of locations and designs for urban buildings is important to avoid excessive noise levels. It is more cost effective to implement noise control at the design stage. For existing building and facilities, noise levels can be controlled by using noise control measures such as enclosures, absorbers, silencers and personal protective equipments, such as earmuffs. However, controlling noise at the source is usually recognized as the most effective solution in noise control problems (Bies, 2003). The controls of noise at the source may involve maintenance and substitution of equipments and machines.

Currently, several noise analysis models have been developed to predict sound pressure levels and to assess mitigation measures. These noise models have become an important and cost effective tool to design a better working and living environment. This thesis will focus on the modeling of noise levels in the Universiti Sains Malaysia (USM), Penang campus including the adjacent road and a typical oil and gas platform. Under the Healthy Campus Program, which strives for a better campus environment, a research program is conducted to assess the noise level emitted by the air conditioning systems in the New Science Complex (NSC) in USM. An in-house noise simulation model, NOISEPAC is developed based upon mathematical and acoustical principles to simulate noise levels in the vicinity of the NSC (Hang et al., 2006). This thesis will also analyze the impact of traffic noise levels on USM compound by using the Federal Highway Administration Traffic Noise Model, version 2.5 (TNM 2.5). The effectiveness of the TNM 2.5 barrier analysis in reducing the traffic noise levels along the roadway will be presented. Finally, this thesis will present noise modeling analysis on an offshore oil and gas platform with complicated alignment of production facilities. The research on offshore platform noise levels will be performed by means of the modified NOISEPAC model simulations.

1.2 New Science Complex (NSC)

The New Science Complex (NSC) was completed in early 2000 to accommodate staffs and students of the School of Computer Sciences and the School of Mathematical Sciences. An air conditioning system known as the "Air Cooled Rotary Screw Flooded Chillers" was installed to provide comfortable environment to the staffs and students in the building. Within the compound of the NSC, the air conditioning system was located at about 3.5 meters above ground level. Staffs working in the NSC have experienced some noise annoyance due to sound emanating from the air-condition exhausts. A concern is raised as to whether the noise level produced by the air conditioning system will pose hazards to the staffs and students who work in the NSC for long duration. For the purpose of assessing noise level in NSC, a field survey has been conducted in the surrounding area of the building. An in-house noise simulation model NOISEPAC is then used to simulate the overall sound field in the NSC.

1.3 Jalan Sungai Dua

Since the British colonial period, Jalan Sungai Dua is used as a main roadway by residents that live in Gelugor, Penang. The roadway consists of two traffic lanes. Rapid development in the Sungai Dua area transforms it from a rural to an urban environment, resulting a high density of vehicles along this roadway. The traffic noise may create high degree of environmental noise impact for the surrounding area, due to the high traffic volume and speed (Tansatcha et al.,2005). Therefore, traffic noise monitoring is conducted to assess whether the traffic noise level would pose health hazards to the occupants of adjacent buildings in the USM Campus, Penang. A computer noise simulation model TNM 2.5 is used to analyze traffic noise impact along Jalan Sungai Dua.

1.4 Offshore Oil and Gas Platform

Safety, health and environment (SHE) are always the primary concerns for the oil and gas industry. Confined within a small space, the design of integrated oil and gas platform is usually complicated by the combination of production facilities as well as living quarters located close to each other. The offshore oil and gas platform is commonly used to explore and process crude oil and gas located in the deep ocean. At the design stage, noise is one of the factors that may affect the decision of design engineers in the selection of instruments and their layout on an offshore oil and gas platform to minimize noise hazards. Due to the long duration of exposure to noise on offshore oil and gas platform, high noise level in the workplace may cause hearing loss and damage to the workers. In our research, significant noise sources are identified and their propagation on the oil and gas platform is predicted by means of the modified NOISEPAC.

1.5 Problem Statement and Objectives of Thesis

The problem statement and objectives for this study are as follows:

1. To model and analyze noise levels in the NSC in USM using an in-house model NOISEPAC under the current conditions;
2. To model and analyze traffic noise levels around USM, Penang campus using Traffic Noise Model version 2.5 (TNM, 2.5);
3. To implement the modified NOISEPAC in predicting the propagation of noise levels on an offshore oil and gas platform;
4. To study noise regulations and noise mitigation methods for reducing noise levels.

1.6 Scope and Organization of Thesis

This thesis is divided into six chapters. Chapter 1 will briefly discuss the overall theme of the thesis and present the study sites, objectives, scope and organization. Chapter 2 will provide a brief description on the literature and scientific papers that are relevant to noise simulation models. This chapter begins with a brief introduction to noise simulation modeling and analysis in industrial areas. Development of traffic noise models since 1950 is also presented, including the well known traffic noise model TNM, which is developed by the Federal Highway Administration (FHWA) of USA for predicting noise levels in the vicinity of highways and for designing highway noise barriers. Further, comparison between some current traffic noise models such as CORTN, *RLS-90*, *MITHRA*, *StL-86* and ASJ Method 1993 are reviewed. Various noise control barriers that are recognized as popular mitigation measures will also be discussed in this chapter.

Chapter 3 begins with a brief introduction to noise pollution for the air-conditioning system. The standards of noise and typical sound levels for several conditions are discussed. An in-house noise prediction model NOISEPAC, which is programmed in FORTRAN language, is developed to simulate the overall sound fields in the NSC. This model is built based upon some mathematical and acoustical formulations typically used. Noise data collection and social survey in NSC will be presented in this chapter. The overall measured data compares well with simulated noise levels, indicating proper performance of NOISEPAC. Further, statistical analysis using the SPSS statistical software package is then performed to assess accuracy of the simulation. Using a graphical package Matlab 6.5, noise contours are plotted to visualize sound fields within the building. By means of the noise contours, we can easily identify noise-sensitive areas. Several noise mitigation methods will be suggested for reducing excessive noise levels.

Chapter 4 begins with a broad overview of traffic noise pollution and the legislation for controlling traffic noise limits. This chapter will focus on traffic noise analysis using a mathematical software TNM 2.5. Following many years of upgrades, this model is developed by the Federal Highway Administration in United States. Several modeling components and formulations in TNM 2.5 will be discussed. For the purpose of validating the simulated results, data and field survey in the study site is conducted and then presented in the chapter. Sound levels from traffic noise along the Sungai Dua roadway are collected and traffic volumes for different vehicle types are obtained simultaneously. Besides that, traffic composition and traffic volumes as part of the input parameter in the computer program are also presented. By means of TNM 2.5, the overall traffic noise levels are simulated for selected areas in USM campus, which are located near to Jalan Sungai Dua. Then, statistical analysis using the SPSS statistical package is done to assess model performance by considering the difference between TNM 2.5 simulated results and measured results. Further, noise level contour and barrier analysis at the study site will be included in this chapter. The FHWA noise criteria are compared to the traffic noise levels in the vicinity of USM campus.

Noise prediction on a typical oil and gas platform is performed in Chapter 5 by using NOISEPAC. The objective of the study in this chapter is to assess the in-house model NOISEPAC as an analysis tool for potential noise problems on oil and gas platforms, especially at the early stage of the design of the platform. This chapter begins with a literature review regarding noise survey in the oil and gas industry. Several noise standards in Malaysia and other regional regulation for workplace are studied. We then discuss the layout design and allocation of equipments that may generate significant noise level. Based upon the actual sound power level data, which is available in some previous research studies, the overall noise levels on offshore platform are simulated by using NOISEPAC. Some theoretical concepts on sound propagation in modeling noise levels on the offshore oil and gas platform will be also included. Noise contours generated by Matlab 6.5 will provide a visual image of sound fields on the platform. Furthermore, some noise control devices available for mitigation will be discussed in this chapter.

Conclusion and further research relevant to the theme of the thesis are discussed in Chapter 6. We hope that the noise analysis performed in this thesis will contribute towards the designing of a more friendly environment in USM and industry workplaces in the future.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Generally, noise models are designed to estimate noise levels in urban areas and working places. The models can be used to assess the degree of exposure to noise for a given or projected road, highway, railway, airport, factory or any town planning capable of generating noise annoyance (Garcia, 2001). Most of the noise models assume that noise emitted from a source attenuate logarithmically with distance away from the noise source (El-Fadel et al., 2002). With the help of computer graphic programs, the predicted noise levels can be presented by a noise map for the whole selected area.

This thesis focuses on modeling noise levels in and around the Universiti Sains Malaysia (USM) main campus in Minden and on offshore oil and gas production platforms. This chapter contains three sections. Section 2.2 will briefly review the methods that are used to predict the noise levels in industrial areas. Section 2.3 will present a review of models to simulate traffic noise levels. Lastly, Section 2.4 is a review for noise control barriers. An in-house noise model namely NOISEPAC (Hang et al., 2006) and Federal Highway Administration Traffic Noise Model (FHWA TNM) version 2.5 (Lau, 2004) are used in this thesis.

2.2 Noise Models and Related Studies

Based upon the diffused-field theory, Abdullah and Mohd Nor (2001) developed an adaptive 3D Gauss-Legendre Quadrature method. This technique is used to simulate the propagation of outdoor noise from sources with variable shapes and power distribution. The advantage of the method is that it takes into account the geometry of the defined sound sources and produces the appropriate contours conforming to the shape of the sources. The noise sources are modeled as an array of point sources which are in the form of lines, planes and 3D blocks. They recommend that curvy highway or railway interchanges be modeled as curvy line sources while process plant equipments and power station buildings should be treated as an array of 3D prism blocks. This method is suitable for noise levels modeling of large sound sources such as power plants or highways. The mathematical approach has been successfully used in a number of Environmental Impact Assessment (EIA) studies involving noise issues in Malaysia (Abdullah and Mohd Nor, 2001). For example, the effect of noise propagations from a power station on the surrounding environment is assessed in their studies. The selected study area comprises several noise sources such as gas turbines and air-cooled condensers. For the purpose of calibration, sound pressure levels at some strategies locations are collected in the study area. The simulation of adaptive 3D Gauss-Legendre Quadrature method is accepted to represent the real scenario since the overall level difference between measured and simulated results is less than $\pm 1.2\,\mathrm{dB}$ (Abdullah and Mohd Nor, 2001).

Lertsawat et al. (1999) has predicted noise emissions from the power plant by using a mathematical model. The power plant noise prediction model is developed based upon a combination of ISO 3746 (ISO, 1979), ISO9613 part I and II (ISO, 1993a; ISO, 1993b), the general equation for industrial noise prediction of Denmark (Kragh et al., 1982), the equal angle method (Jenkins et al., 1976), Colenbrander method(EEMUA, 1988) and the area surface method (Yamamoto, 1990). With the combination of different types of equations, this model is able to calculate the divergence attenuation, air absorption, reflecting obstacles attenuation, screening obstacles attenuation and ground effect attenuation. In term of facilitating those complicated equations, a noise model, namely "Sonic" is developed as a computer program using Visual Basic programming language. The prediction model is used to investigate the effective area, mitigation and prevention plans for noise pollution control in the combined cycle power plant project in Thailand (Lertsawat et al., 1999). Moreover, sound pressure level measurements are conducted in the study area by the researchers. The predicted sound pressure levels are compared with measured sound pressure levels in order to verify the accuracy of the model. The results showed that the accuracy level of the model is within 10 decibels from the measured data (Lertsawat et al., 1999). In their research, the measured sound pressure level values of upwind station are found to be lower than the predicted results. This is caused by several influences at the location of measuring stations such as directivity of noise source and environment effects on the calculation.

Due to the difficulties to obtain accurate sound power levels of each noise source in a large factory, Guasch et al. (2002) has introduced a simple inversion method. This inverse method is able to compute the acoustic power contribution of every noise source and thus decide the source that must be silenced in order to reduce the overall sound pressure levels. This method has been applied to a liquid-gas production factory. Under normal operating conditions, sound pressure levels for a large number of noise sources in the factory are measured. By using the measured data and inverse method, sound power levels at each noise source are obtained. Thus, sound pressure levels in the vicinity of sources can be calculated using any reliable sound propagation software. Both measured and simulated sound levels match well except for two reception points that showed a significant difference. This is because these two points are located below a cabin in the factory, which are not considered in the computer simulation (Guasch et al., 2002). Nevertheless, they conclude that the technique is only well applicable where the noise levels remain stationary for a long period of time at the same level.

Furthermore, a number of studies are done on the reflection and diffusion of sound. To model the reflection of sound, image source method, ray tracing technique and combination of both ray-tracing and image source method are frequently used for noise propagations where reverberation is significant (Kang, 2002). The ray tracing method is easy to implement but its accuracy is not very satisfactory, while the imagine source method can provide more accurate results but it takes a lot of computational time to model complicated shape space (Zeng, 2005). Picaut et al. (1999) proposed a theoretical model for sound propagations in long rooms with reflecting boundaries. This model is based upon two parameters, the coefficient of diffusion depending on the mean free path, and an exchange coefficient expressing wall absorption. They proved that the diffuse equation is also suitable to model the sound fields. In modeling diffuse reflections in rooms, Zeng (2005) developed an improved ray-tracing algorithm which combines the splitting coefficient model (SCM) (Embrechts, 2000) and a dynamic receiving method. Experiments have been done in real rooms with partial diffusing surfaces for the purpose of comparing the simulated and measured results.

Besides, several research is conducted on noise levels assessment without developing or using any noise simulation model (Martin et al., 2006; Park, 2003; Zannin et al., 2002). Sound field and social surveys have been done in the study area to identify whether the noise levels exceed the limit of noise regulations. These research mainly focuses on the negative impact of high noise levels in some sensitive areas such as city (Zannin et al., 2002) and Karaoke room (Park, 2003). Some mitigation technique such as installing noise control barriers and room acoustic treatments are also discussed in these studies.

2.3 Traffic Noise Simulation Model

Since 1950, traffic noise prediction models mostly were designed to predict a single vehicle sound pressure at roadside based upon constant speed experiments. The earlier road traffic noise model was given in the Handbook of acoustic Noise Control written by Anon (1952). The model is used for speeds between 56 km/hour (35 miles/hour) and 72 km/hour (45miles/hour) and the distances greater than 6 meter (20 feet) (Steele, 2001). The formulation for A-weighted sound levels that exceed the 50 percentile of time interval is given as:

$$L_{50} = 68 + 8.5\log(V) - 20\log(D_F) \quad \text{dBA} \qquad (2.1)$$

where

V = traffic volume, vehicles/hour;

D_F = the distance from traffic lane, in feet.

In 1965, Nickson (1965) and Lamure (1965) developed a model in the form of:

$$L_{50} = C_N + 10\log(V / D_F) \quad \text{dBA} \qquad (2.2)$$

where

C_N = a constant for individual noise levels.

Later, Johnson and Saunders (1968) introduced vehicle speed as a relevant factor and they proposed the following formulation:

$$L_{50} = 3.5 + 10\log(VS^3 / D_F) \quad \text{dBA} \qquad (2.3)$$

where

S = mean vehicle speed, miles/hour.

In 1966, Galloway (1969) introduced a further variable, P_H, the percentage of heavy trucks. The equation becomes:

$$L_{50} = 20 + 10\log(VS^2 / D_F) + 0.4(P_H) \quad \text{dBA} \qquad (2.4)$$

Later developments introduced more variables and changes from L_{50} to L_{10} and equivalent continuous level (L_{eq}) over a chosen period (Steele, 2001).

Recent models predict the equivalent continuous sound level (L_{eq}) under interrupted and varying flow conditions. According to the reviews of Garcia (2001) and Steele (2001), traffic noise prediction models in different countries are designed to meet the requirements of government regulations. Those prediction models are enhanced with more accurate physics and more realistic computation in actual traffic flows. Detailed information for FHWA TNM (Menge et al., 1998), which is used in this thesis, will be discussed in Section 2.3.1. Section 2.3.2 is a review of others recent traffic noise models.

2.3.1 FHWA Traffic Noise Model

The Traffic Noise Model (TNM) is developed by the Federal Highway Administration (FHWA) for predicting noise levels in the vicinity of highways and to design highway noise barriers (Menge, 1998). This model is known as a state-of-the-art computer program and developed by advance acoustics and computer technology in modeling highway traffic noise (FHWA, 2002). In year 1998, the FHWA TNM, version 1.0 was released by FHWA to replace the highway noise analysis program, Standard Method In Noise Analysis (STAMINA 2.0) (Anderson et al., 1998; Harris et al., 2000). The FHWA TNM is derived from the STAMINA 2.0 program (Bowlby et al., 1982) and has several substantial improvements. The improvements include provision for acceleration, stop signs, toll booths, input of user-defined vehicles using their reference energy mean emission level (REMEL) data, etc (Steele, 2001).

Five classes of vehicle are used in this FHWA model; they are automobiles, medium trucks, heavy trucks, buses and motorcycles. To calculate sound levels for entire traffic streams, FHWA TNM incorporates energy-averaged vehicle noise emissions for each vehicle type (Menge et al., 1998). Based on FHWA TNM technical manual (Menge et al., 1998), TNM needs three constants to compute A-weighted noise-level emissions: *A*, *B* and *C*. It also needs fourteen additional constants to convert these A-weighted noise-level emissions to 1/3rd-otave-band spectra: *D1, D2, E1, E2, F1, F2, G1, G2, H1, H2, I1, I2, J1 and J2*. Each vehicle type's total measured noise emissions take into account the whole frequency spectrum. The general REMEL equation is a function of speed and frequency for each type of vehicles (*i*) as follows:

$$\begin{aligned} L_E(s_i,f) &= 10\log[10^{(C+\Delta E_c)/10} + (0.6214 s_i^{A/10})(10^{(B+\Delta E_b)/10})] \\ &-(K1+K2s_i)+D1+D2s_i+(E1+E2s_i)\log f \\ &+(F1+F2s_i)(\log f)^2 \\ &+(G1+G2s_i)(\log f)^3 \\ &+(H1+H2s_i)(\log f)^4 \\ &+(I1+I2s_i)(\log f)^5 \\ &+(J1+J2s_i)(\log f)^6 \end{aligned} \quad \text{dBA} \qquad (2.5)$$

where

f = nominal 1/3rd-octave-band center frequency, in Hetz;

s_i = vehicle speed, in kilometer/hour;

A = the slope of tire/pavement noise portion of regression curve;

$B+\Delta E_b$ = the height of the tire/pavement noise portion of the regression curve;

$C+\Delta E_c$ = the height of the engine/exhaust noise portion of the regression equation, which is independent of vehicle speed;

D_1 to J_2 = constants of the sixth-order polynomial fit curve for the 1/3rd spectra;

K1 and *K2* = the calibration of the resulting A-weighted levels from the sixth-order polynomial fit.

Several adjustments are made to the emission level to account for traffic flow, distance and shielding in FHWA TNM (Menge et al., 1998). The following equation is the equivalent sound level over one hour time period, $L_{Aeq}(1\,\text{h})$ which involved those adjustments for different vehicle types:

$$L_{Aeq}(1\,\text{h}) = EL_i + A_{traff(i)} + A_d + A_s \quad \text{dBA} \qquad (2.6)$$

where

EL_i = the vehicle noise emission;

$A_{traff(i)}$ = the adjustment for traffic flow, the vehicle volume and speed;

A_d = the adjustment for distance between the roadway and receiver and for the length of the roadway;

A_s = the adjustments for all shielding and ground effects between the roadway and the receiver.

TNM has been updated several times and the latest version is TNM Version 2.5 (Lau et al., 2004; Ning, 2005). TNM Version 2.5 has the improved implementation to the vehicle emission level database. More comprehensive methodologies are applied in correcting the measured emission back to the source (Lau et al., 2004). The diffraction algorithm parameters are also improved in the latest version. Table 2.1 shows the FHWA TNM release versions since year 1998 until 2004.

Table 2.1: FHWA TNM versions

Year	Model
1998	TNM version 1.0;
	TNM version 1.0a;
	TNM version 1.0b.
2000	TNM version 1.1
2002	TNM version 2.0
2003	TNM version 2.1
2004	TNM version 2.5

2.3.2 Other Traffic Noise Models

There are some other noise models such as CORTN, *RLS-90, MITHRA*, *StL-86* version 1 and *ASJ Method 1993* that are used by different countries. Calculation of Road Traffic Noise (CORTN) is developed for the prediction of traffic noise in the United Kingdom Department of the Environment (Bies and Hansen, 2003). This model assumes a line source and constant speed traffic. The adjustments that apply in the model include percentage of heavy vehicle, traffic speed, gradient, road surface and propagation. The acceleration is not taken into account in CORTN (Steele, 2001). *Richtlinien fur den Larmschutz an StraBen* (*RLS-90*) (Guidelines for Noise Propagation on Streets) is a noise prediction model used in Germany (Steele, 2001). The attenuation in the noise propagation is calculated with usual ray tracing methods in *RLS-90* model. *MITHRA*, developed by a French firm, contains an extensive ray-tracing procedure. This commercial software package takes into account ground effects, diffraction, reflection, topography, building and barrier (Steele, 2001). *StL-86* version 1 is developed by the Swiss Federal Office of Environmental Protection. The model includes corrections for the reflection from building, attenuations of building and obstacles, usual distance effects and angle of road open to receiver. The Acoustic Society of Japan has developed *ASJ Method 1993* to predict a pseudo – L_{50} from free-flowing road traffic. This software contains 2 types of methods; they are A-Method and B-Method. A-Method is a direct method of calculating the equivalent sound level (L_{eq}), and deriving the pseudo-L_{50} from the results. B-Method is an empirical method which is only valid for distances that are far from the line source. Table 2.2 provides the comparison of FHWA STAMINA, FHWA TNM version 1.0, *MITHRA*, CORTN, *RLS90*, *STL-86* and *ASJ-1993* by Steele (2001).

Table 2.2: Comparison of traffic noise prediction models (sourced from Steele, 2001)

	FHWA STAMINA	FHWA TNM version 1.0	01 db *MITHRA*	CORTN	*RLS90*	*STL-86*	*ASJ-1993*
Government users	USA, Canada, Japan, Mexico	Replaces STAMINA	France, Belgium	UK, Australia, Hong Kong, New Zealand	Germany	Switzerland	Japan
Applications	Highway (L_{eq}), not architectural. Grid. Road network	Highway (L_{eq}), not architectural. Grid, excellent source base. Road networks	Highway and railways (L_{eq}), not architectural. Grid. Good propagation. Simple streams	Highways (quasi L_{10}). Point. Single traffic streams only	Highways and car parks (L_{eq}), not architectural. Point. Good propagation. Simple streams	Highways and trams, light rail (L_{eq}), not architectural. Point. Simple streams	Highway barriers
Prediction of traffic volume	No	No	Yes	No	Yes	Yes	No
Traffic condition	Constant speed, grades	Constant speed, acceleration, grades, and interruption	Constant speed, grades	Constant speed, grades	Constant speed, grades, quasi-intersections, interruptions	Constant speed, grades	Constant speed
Type	Hybrid, consistent/ inconsistent	Mathematical/ hybrid	Hybrid, consistent	Hybrid, inconsistent	Hybrid, consistent	Hybrid, inconsistent	Mathematical

(to be continued in next page)

Table 2.2: Comparison of traffic noise prediction models (sourced from Steele, 2001)

	FHWA STAMINA	FHWA TNM version 1.0	01 db *MITHRA*	CORTN	*RLS90*	*STL-86*	*ASJ-1993*
Input data	Traffic speed, flow, road and environs data. Local characteristics	Traffic type, flow, speed, whether interrupted, road and environs data. Local characteristics	Traffic type, flow, road and environs data	Heavy/light ratio, flow, speed, road and environs data	Traffic type, flow, park or road data, and environs data	Traffic type, flow, road and environs data	Traffic type, flow, speed, barrier geometry
Noise descriptor	L_{eq}/ quasi L_{10}	L_{eq}/ quasi L_{10}	L_{eq} (8-20H)	Quasi-L_{10} (18h)	L_{eq}	L_{eq}	L_{eq}, quasi-L_{50}
Type of mapping	Point -> grid	Multiple dual points -> grid	Line -> grid	Line -> point	Line -> point	Line -> point	Multiple points -> point
Source	Simple Streams	Simple Streams	Simple Streams	Single Streams	Simple Streams	Simple Streams	Simple straight Streams
Propagation	Energy type	Energy type	Ray tracing	Energy type	Energy type	Energy type	Mathematical (velocity potential)
Weighting: Source/ receiver	dBA/ dBA	1/3 octave/ dBA	octave/ dBA	dBA/ dBA	dBA/ dBA	dBA/ dBA	dBA/ dBA

(to be continued in next page)

Table 2.2: Comparison of traffic noise prediction models (sourced from Steele, 2001)

	FHWA STAMINA	FHWA TNM version 1.0	01 db *MITHRA*	CORTN	*RLS90*	*STL-86*	*ASJ-1993*
Vehicle types	Automobile/ medium trucks/ heavy trucks	Optional spectra for automobile/ medium trucks/ heavy trucks/ buses/ motorcycles	Light vehicles, heavy vehicles, and trains	Light vehicles/ heavy vehicles	Light vehicles/ heavy vehicles/ car parks	Light vehicles/ heavy vehicles/ trams and suburban trains on roadways	Light vehicles/ heavy vehicles/ heavy vehicles
Validation	Contingent; 0.58 to 1.3 dBA @ 15m to 60m	Not readily available	Not readily available	+1.4 @ 50 to 54.9 dBA (Delany): -1.2 @ 80 to 84.9 dBA. +1.7 @ facades (Saunders)	Not readily available	Not readily available	Not readily available
Major faults	No L_N, no interruptions.	No L_N, simple interruptions only.	No L_N, no interruptions, no local characteristics	No L_{eq}, L_N not rigorous, no interruptions, single traffic streams only, no local characteristics	No. L_N, no interruptions only, no local characteristics	No. L_N, no interruptions.	No L_N restricted to quasi L_{50}, no interruptions, long roadside barriers only.

Furthermore, Tansatcha et al. (2005) develop a new motorway traffic noise model based upon the measurement data from the Bangkok-Chonburi motorway in Thailand. The parameters used in the model include traffic volume, average speed of each type of vehicle and physical conditions of the roadway such as width of roadways and number of lanes. This research utilizes the equivalent sound level in 10 seconds of measurement period, L_{eq}(10s), which can cover the overall period of noise generated from vehicles passing by the noise meter. In this study, vehicles on the motorways are classified into eight types, namely, automobile, light truck, medium truck, heavy truck, semi-trailer, full trailer, bus and motorcycle. The data collection used in the analysis of the study was conducted by Phoowasawat (1999). The data is separated into two parts. The first part of data is used for the development of basic noise models for each type of vehicles on the roadways and the second part is used for analysis and development of motorway traffic noise models. The basic models are developed by using a linear regression technique in order to identify the relationship between L_{eq}(10s) and speed of each vehicle types. Then, the second part of data is used to develop the main motorway noise model based on the technique of perpendicular propagations of vehicle noise from the centerline of roadway. The prediction for equivalent sound level for each vehicle type in 1 hour is calculated by using Equation (2.7) in the model as:

$$L_{eq}(1\,\mathrm{h}),i = L_{eq}(10s),i + 10\log\left[\frac{D_0}{D}\right]^{1+\beta} + 10\log n_i - 25.563 \quad \text{dBA} \qquad (2.7)$$

where

L_{eq} (10s) = equivalent sound level in 10 seconds;

n_i = number of vehicles/hour;

D = perpendicular distance from observer to the centre line of the traffic lane;

D_0 = the reference distance (15meters);

β = ground effect adjustment.

The new model has two advantages. The first advantage is that the speed of the vehicles can be excluded from the main model. Secondly, this model provides a simple format with fewer parameters. Tansatcha et al. (2005) conclude that the motorway traffic noise model performs well in a statistical goodness-of-fit test against the field data and therefore, it can be used effectively in traffic noise prediction projects in Thailand.

2.4 Noise Control Barriers

Noise mitigation by barriers is a popular mitigation measure for environmental protection in both urban and rural areas. Currently, much research has been conducted to develop efficient noise control barriers and to assess its performance in mitigating noise pollutions. The choice of noise control methods depends on the cost, effectiveness and feasibility (Ming, 2005). To maximize the acoustic performance of a noise barrier, the mathematical prediction scheme is needed to calculate sound reduction by barriers (Li and Wong, 2005). Usually, the total reduction provided by the barrier is calculated by insertion loss (*IL*). *IL* is the difference between two sound pressure levels measured at the same point in space before and after a muffler has been installed (Bell and Bell, 1994).