The Hong Kong Polytechnic University

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A STUDY OF ROADSIDE NOISE BARRIERS IN A DENSE HIGH-RISE CITY

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Certificate of Originality

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Abstract

Due to a host of factors such as fast economic growth, limited space for habitable development and concentrated road networks, road traffic noise is recognised as one of the most severe environmental impacts affecting daily livings in dense high-rise cities. The magnitude of road traffic noise impact increases enormously in the past decades due to the ever increasing demands for more transportation. More road networks are built and more vehicles are put in actions in the cities to support the economic growth and social activities. The impact is further intensified when more housing estates are constructed in cities which leads to the sharp diminish of the buffer separation between trunk roads and residential buildings. The situations even get worse when extent of hours exposed to road traffic noise goes beyond early morning and late night.

There are different approaches and means to tackle the ever increasing magnitude of traffic noise problem in dense high-rise cities. Roadside noise barrier is one of the most commonly adopted measures. Because of the high density nature of high-rise cities, substantial roadside barriers like full enclosures, semi-enclosures or very high noise barriers are needed to provide necessary noise reduction. Many research works have been conducted in past decades for improving the assessment and evaluation of effectiveness; materials; and the design of roadside barriers. This study specifically investigates the accuracy of the current assessment and prediction tools, particularly in those cases where noise sensitive

receivers locate near the shadow boundary of the barrier.

Through theoretical and experimental evaluations, this study examines the following three aspects:

a. modify the potential barrier attenuation curve in the Calculation of Road Traffic Noise (the traffic noise assessment procedures commonly adopted in the United Kingdom, Australia and Hong Kong);
b. deterioration of noise attenuation effect of roadside barriers due to the presence of parallel roadside noise barriers; and
c. diffraction and noise attenuation characteristics of cranked barriers.

The investigations presented in the current study suggest that there are rooms for improvements in the aspects of prediction and designing of roadside barriers in dense high-rise cities.

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Nomenclature

Barrier	Non-porous walls of sufficient mass (minimum of 20kg/m2), if put between sound source and receiver, or intercepts the line-of-sight from sound source to receiver, can result in appreciable noise reduction due to the fact that sound can reach the receiver only by diffraction around the boundaries of the obstacle.
Thin barrier	The fundamental theory of barrier diffraction assumes a knife edge at the barrier top. This theory is approximately valid when the barrier thickness is smaller than the wave length.
Diffraction	The bending or spreading out of a sound wave after it intersects an aperture or a solid subject like wall.
Insertion Loss (IL)	Acoustic performance of barrier, screening structures etc. Insertion Loss (IL) is defined as $IL = 20\log\left\lvert\frac{P_{w/barrier}}{P_{w/o}}\right\rvert$ or $IL = 20\log\left\lvert\frac{P_{diff}}{P_{dir}}\right\rvert$ It sometimes also known as attenuation (att).
R_1	Direct distance from source to receiver (as if the barrier were not present)
R_2	Direct distance from image source to receiver (as if the barrier were not present)
L	Shortest distance from the source (or image source) to the receiver after diffraction from the edge of the barrier, i.e. the length of the shortest source-edge-receiver path.
N_1	Fresnel number – extra distance sound travels from the source to the receiver after diffraction by the barrier edge, normalized by half the wavelength of the incident wave, $N_1 = \frac{L - R_1}{\lambda/2} = \frac{k}{\pi}(L - R_1)$.
N_2	Fresnel number – extra distance sound travels from the image source to the receiver after

	diffraction by the barrier edge, normalized by half the wavelength of the incident wave, $N_2 = \frac{L - R_2}{\lambda / 2} = \frac{k}{\pi}(L - R_2)$.
r_s	Direct distance from source to edge of the barrier.
r_r	Direct distance from receiver to edge of the barrier.
δ	Path difference between diffracted path length and the direct path length joining the source and receiver which can be represented as $\delta = (r_s + r_r) - R_1$ or $\delta = L - R_1$ mathematically.
θ_s	The sound wave incident on edge of the barrier at angle θ_s.
θ_r	The sound wave incident on the receiver from edge of barrier at angle θ_r.
β	Exterior angle of a wedge
υ	Wedge index, $\upsilon = (\beta / \pi)$
k	Wave number, $k = 2\pi / \lambda$
λ	Wavelength of incident wave
P_{diff}	Sound pressure at receiver after barrier diffraction.
P_{dir}	Sound pressure at receiver without presence of the barrier.
$C(\mu), S(\mu)$	Fresnel Integrals expressed as $C(\mu) = \int_0^{\mu} \cos(\frac{\pi\xi^2}{2}) d\xi$, $S(\mu) = \int_0^{\mu} \sin(\frac{\pi\xi^2}{2}) d\xi$
A_D	Diffraction integral expressed as $A_D = \text{sgn}(X)[f(X) - ig(X)]$
$f(x),\ g(x)$	Fresnel integrals expressed as

$$f(x)=\left[\frac{1}{2}-S(X)\right]\cos\left(\frac{\pi X^2}{2}\right)-\left[\frac{1}{2}-C(X)\right]\sin\left(\frac{\pi X^2}{2}\right)$$

$$g(x)=\left[\frac{1}{2}-C(X)\right]\cos\left(\frac{\pi X^2}{2}\right)+\left[\frac{1}{2}-S(X)\right]\sin\left(\frac{\pi X^2}{2}\right)$$

Γ	Auxiliary Fresnel Function expressed as $\Gamma=\sqrt{\left(\frac{kr_s r_r}{\pi L}\right)}$
D	Diffraction Coefficient expressed as $P_{diff}=D(\frac{e^{ikR}}{4\pi R})$
Screening barrier	In the parallel barrier situation, the barrier separating the source and the receiver is known as screening barrier.
Reflecting barrier	In the parallel barrier situation, the barrier locating on the same side of the source with respect to screening barrier is known reflecting barrier.

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Chapter 1

Introduction

1.1 Noise is the Unwanted Sound and Causing Health Concern

Noise, defined as unwanted or excessive sound, is an undesirable by-product of today's modern ways of life. Noise can be annoying, it interferes our sleep, work, and recreations. In extreme cases, it may cause physical and psychological damage to human lives[1].

Despite advancement of today's civilization, noise has been an ancient problem in human societies. Documents recording how the Roman poets complained about the racket of iron wheels on cobblestones affecting their lives had been found. Also, in about 600 BC, the city of Sybaris in Southern Italy required tinsmiths and other 'noisy' tradesmen to locate their shops outside the city walls as a means of regulating community noise. Several centuries later, wheeled traffic from the Roman Forum was banned because of noise and congestion, and this could be one of the earliest traffic noise regulations.

High level of noise could be a serious matter. It interferes our daily activities, disturbs quality rest and distracts leisure activities. Initial findings of scientific studies have showed that high level of noise could have negative effects on human health and well-being

[1] As reported in Scientists of World Health Organisation (WHO) working out the health effects of noise pollution pointed out recently that long term exposure of high level noise could account for an alarming three per cent of fatalities from strokes and heart attacks, extracted from Aug 22 2000 issue of *New Scientists*.

which leads to problems such as hearing loss, stress, high blood pressure, sleep loss, distraction and lost productivity. As results, there are general reductions in the quality of life and the opportunities for tranquility. The reductions are in rising trend. There are also evidence showing the adverse effects of noise on communication, teaching and learning performance in schools; sleep and temper; as well as cardiovascular effects and hearing impairment.

Some findings show that the level of reception from hearing has a direct correlation with level of noise in the surrounding. Studies indicate that speech was 100% intelligible with background noise levels at 45 dB(A)L_{eq}. Above 55 dB(A)L_{eq} background noise the voice has to be raised. Such background level interferes the concentration and the raised voice becomes less intelligible. In classrooms and meeting rooms used by children, elderly people or hearing-impaired individuals (those especially sensitive to the health impacts of noise), background noise should be 10 dB(A) L_{eq} below that of the speaker.

Evidence shows that noise disturbs sleep. Noise can cause difficulty in falling asleep, reduction in deep resting sleep, increased awakenings during sleep and adverse after-effects such as fatigue and decreased performance. These effects are avoided if noise levels are kept below 30 dB(A) L_{eq} continuous noise or 45 dB(A) L_{max} indoors.

Noise also has a direct impact on human performance. Children chronically exposed to aircraft noise show impaired reading acquisition, attention and problem-solving ability. Noise can interfere with mental activities requiring attention, memory and ability to deal with complex analytical problems. Adaptation strategies, such as tuning out and ignoring noise, and the effort needed to maintain performance have been associated with high blood pressure and elevated levels of stress hormones.

People can easily be annoyed by noise. Annoyance response broadly increases with sound level, with most people being moderately annoyed at 50 dB(A) L_{eq} and seriously annoyed at 55 dB(A) L_{eq}. However, only one third of variation in annoyance is due to sound levels as there are other factors affecting the response to noise. The most annoying type of noise comes from aircraft which has the low-frequency components and is accompanied by vibration. It sometimes seriously interferes with the social and economic activity in the vicinity of airports in particular the daily lives of residents and learning activities of school children. In addition, geographic factors affect vulnerability to noise; in the Alps, for example, topography, background levels of noise and acoustic factors of the slopes will influence the effect of a given level of noise.

Noise is reported to have caused increased aggression. Loud noise increases aggressive behaviour in predisposed individuals, and levels above 80 dB(A) L_{eq} reduce helping behaviour.

Some studies also claim that loud noise caused heart disease and hypertension. There has been increasing evidence on ischaemic heart disease and hypertension points to an effect of noise at around 65 – 70 dB(A) L_{eq}. The effect is small but, since a large percentage of the population is exposed to such levels, it could be of great public health significance. Also, some reports that loud noise can cause hearing impairment, although the risk is considered negligible in the general city population for noise levels below 70 dB(A) L_{eq} over 24 hours over a period of 40 years.

1.2 Road Traffic Noise Problem Affecting Residents in Dense High-rise City

While noise emanates from many different sources, transportation noise is perhaps the most pervasive and difficult to avoid for many residents in city particularly the dense high-rise cities. Among transportation noise, road traffic noise is recognised as one of the most severe public annoyances in dense high-rise cities and is perhaps one of the most concerned environmental issues as it apparently causes great annoyance to many people living next to roads. The relevant authorities of countries and cities receive many complaints about road traffic noise and the numbers of such complaints are in rising trends. These complaints can be generally categorized in the followings, noise arising from large volume of vehicles passing by their houses or flats; single pass-by buses during late night or early morning; vehicles riding on uneven road surface or bumpers; poor driving habits such as speeding or heavy braking and poor maintenance; and others. People are demanding the relevant authorities to take action to keep road traffic noise at bay. There is no panacea to the road traffic noise problems particularly in dense high-rise cities; however, the relevant authorities should take appropriate actions to mitigate the problems.

1.2.1 Size of Road Traffic Noise Problem

There is no international standard of acceptable road traffic noise level. The relevant authorities of countries and cities define their own preferred standards, limits or criteria on the own merits. In Europe, estimation in 1996 suggested that around 20 percent of the European Union's population (or close on 80 million people) are exposed to levels over 65 dB(A), a level that scientists and health experts consider to be unacceptable. High levels of noise cause sleep disturbance, annoyance and affecting human health [1]. In England and Wales, the 1991 Building Research Establishment Survey indicated that 47% of homes heard road traffic. Among them, about 70% objected to it, nearly 80% were irritated by it and 63% considered the noise a nuisance [2]. In France, two reports were compiled in 1995 and 1998 about noise pollution caused by surface transports. It has been estimated that about 7 million French were exposed to noise levels higher than 65 dB(A) during daytime [3]. In Tokyo of Japan, an investigation of traffic noise in 2003 indicated that 19.3% and 30.1% of the assessed households in areas facing roads and truck roads respectively were subject to noise levels exceeding the respective day and / or night time Environmental Quality Standards [4]. In the New South Wales of Australia, 1.5 million residents, mainly in north of Sydney,,were found exposed to outdoor traffic noise levels between 55 and 65 dB(A) as in 1997 [5]. In Beijing of the People Republic of China, traffic noise pollution has been one of the serious environmental concerns as the traffic noise has lingered at an average level of 71 dB(A) for many years in the nineties [6]. In Hong Kong, estimations in 2000 indicated that about 1.14 million of residents are exposed to traffic noise at levels higher than 70 dB(A) L_{10}(1h) [7].

It is obvious from the above statistics that road traffic noise seriously jeopardizes the living quality of dense high-rise cities. More information shows that the non-urban areas are being more and more covered with a blanket of noise. Even worse, it is very likely that in the coming future, the traffic noise exposure period would be prolonged and excessive traffic noise would intrude from early morning to late night hours [7]. Silence is becoming a rare commodity.

1.2.2 Action Plans to Keep Road Traffic Noise at Bay

Tackling environmental noise in particular road traffic noise is among the top ranked action items in many governments. The applicability of each individual measures would very much depend on the reduction needed, the characteristic of the noise problem, the financial commitment, the social concern, the policies of each country or city.

In November 1996, the Commission of European Union published a Green Paper on Future Noise Policy (COM(96) 540) embarking on the development of a noise policy with the aim that no person should be exposed to noise levels which endangers health and quality of life [8]. In 2002, the Directive of the Commission of European Union requires that cities of population not less than 250 000 people are required to prepare a noise map by June 2007 and action plans are needed to reduce noise levels endanger human health and preserve environmental noise quality by July 2008 [9].

Hong Kong, one of the typical dense high-rise cities, also takes proactive actions. The Hong Kong SAR Government takes road traffic noise problem very seriously and has taken proactive actions to address the problems through a 4-pronged approach:

a. Prevention of traffic noise problems through planning and environmental impact assessment;
b. Legislative control of individual vehicles;
c. Abatement of noise at existing roads; and
d. Involvement of the public and other stakeholders through education, public engagement and partnership programme.

In July 2006, the Hong Kong SAR Government released a draft “Comprehensive Plan to Tackle Road Traffic Noise” [7]. On top of the above mentioned 4-pronged approach actions, the following nine enhanced measure were proposed in this plan:

a. Extend Trial of Low Noise Road Surfacing Materials;
b. Explore New Design of Low Noise Road Surfacing Materials;
c. Explore Optimum Barrier Design for Territory-wide Use;
d. Feasibility Study of Controlling Noise Emission from In-use Vehicles;
e. Review the Professional Practice Note on Road Traffic Noise;
f. Promote the Disclosure of Noise Information in Sales Brochure;

g. Improve Joints at Flyovers;

h. Explore Night-time Traffic Noise Standard; and

i. Enhance Public Engagement and Partnership

The global road traffic noise situation in many countries and cities would deteriorate in the future if development trends continue. Immediate proactive action plans are required to prevent worsening of the situation and also taking the opportunities to improve the acoustic environment.

1.3 Literature Reviews

On a positive note, there are various means to tackle road traffic noise. It is true that the applicability of each individual measures would very much depend on the financial commitment, the social concern and the policies of each country or city. From this end, it is useful to conduct literature reviews of policies and practice adopted by different countries and cities in tackling road traffic noise. The review results are useful in identifying the general trend in application of measures, the rationales behind, the technologies associated and the factors that may affect the decision or choice of measures. They also help to identify the areas or aspects that the acoustic professionals and academics could focus for further advancement and development of noise mitigation technologies. The reviews were conducted in two parts: one on policies adopted by various countries and cities and the other on practices in worldwide in using noise barriers to tackle road traffic noise.

1.3.1 A Review of Policies Adopted by Various Countries and Cities in Tackling Road Traffic Noise

Lliterature review of the means and methods on how twelve selected community, countries, states and cities deal with road traffic noise has been conducted. The policies and approaches adopted by these countries and cities are in the ensuing paragraphs.

1.3.1.1 European Union

The Commission of European Union published a Green Paper on Future Noise Policy [1] in November 1996 in which the Commission addressed noise in the environment as one of the main local environmental problems in Europe. In June 1997, the European Parliament adopted the Commission Green Paper on future noise policy, expressed its support and continued to urge that in the near future specific measures and initiatives should be laid down in a framework directive on the reduction of environmental noise (i.e. road traffic noise, railway noise, aircraft noise and industrial noise). In June 2002, The Directive 2002/49/EC [9] provided direction on assessment and management of environmental noise which forms basis for further actions in EU to tackle environmental noise. The objectives are to determine the noise exposure to environmental noise through noise mapping by common methods, inform the public on noise exposure and its effects and to adopt action plans. Strategic noise maps for major noise like railway and major roads would also be produced for presentation of data enabling public to know the noise situation of a global scale and the estimated number of dwellings, schools, hospitals etc. or people exposed to noise exceeding the limits.

Each member state shall determine its own “limit value” of noise indicators, standards or criteria and its own action plans. The Action Plan may include traffic planning; land use planning; technical measures at noise sources; selection of quieter noise sources; reduction of sound transmission like roadside barriers; and regulatory or economic measures or incentives. In a long term, the action plans would reduce noise where necessary and to preserve environmental noise quality where it is good.

Member states would need to furnish the first strategic noise mappings by 2007 and action plans to reduce noise by 2008.

A number of working groups or study teams are in place to facilitate the EU member states in tackling traffic noise at various fronts. These include HARMONOISE in developing a new common methods in assessing L_{DEN} and L_N; SILVA in studying the low noise road surfacings; RANCH in studying the health effects of Children due to road traffic noise and aircraft noise; and CALM in looking into the future policy relating to traffic, land use planning, dose-effects relationship, sources reduction, sound propagation reduction etc.

1.3.1.2 France

French adopts the following three-pronged approach for limiting noise due to road transport infrastructure:

a. the incorporation of noise consideration in constructing new roads;

b. the classification of noisy roads and the identification of areas where the soundproofing of dwellings should be enhanced; and

c. Corrective action with respect to critical situation or “black spots”.

In constructing new roads, the law requires that noise at residential uses should not exceed 60 dB(A) L_{eq}(18 hrs) for daytime and 55 dB(A) L_{eq}(6 hrs) for night-time. Protections like earth mounds or vertical barriers would be selected as protections at source for reducing road transport noise reaching the objectives [13] [14].

For existing roads, “Black Spot Restoration” programme is in place to reduce the impact on buildings with a façade exposed to more than 70 dB(A) Leq(8h – 20 h) (which are considered as “noise black spots”). The aim is to bring it down to 65 dB(A) through application of window insulation or façade protection [15].

1.3.1.3 Germany

In Germany, articles 41 to 43 of the Federal Immission Control Act in connection with the Federal Traffic Noise Protection Regulation lay down the legislative requirements to protect existing noise sensitive uses from use of new road and for roads with major alterations. Accordingly, noise at areas used exclusively or predominantly as residential areas and on small housing estates, free-field noise level at height of 2m above ground at noise sensitive uses should not exceed 59 dB(A) Leq(16 hrs)(6 – 22hrs) at daytime and 49 dB(A)

Leq(8 hrs) (22 – 6 hrs) at night-time. Noise limits for hospitals, schools and home for elderly would be more stringent (2 dB(A) lower). Noise mitigation measures have to be provided if one of the limits (even if it is daytime or night-time) is exceeded. Measures to be adopted include noise barriers and noise insulation on building as well as traffic management. Priority has to be set on mitigation measures at source and on the propagation path. All measures have to be paid by the responsible road authority. If the cost of providing noise barriers were out of proportion to the desired effect, only noise insulation on the affected houses would be provided.

As for existing residential developments affected by existing roads at level exceeding 70 Leq(16 hrs)(6 – 22hrs) at daytime and 60 dB(A) Leq(8 hrs) (22 – 6 hrs) at night-time, the Federal Ministry of Transport has implemented a noise protection programme since 1978. Noise protective measures include erection of noise barriers and provision of noise insulation at the affected buildings [16] [17] [18].

1.3.1.4 The Netherlands

The Chapter VI of the Noise Nuisance Act lays down the regulations with respect to road traffic noise and can be summarized in the following priority:

a. abatement at the sources – including the application of silent roads, restrictions to noise emission of vehicles and tyres, restrictions to use of noisy vehicles, speed reduction, and use of special planning strategies for traffic circulation and building activities.

b. Restrictions to transmission of noise to receivers – including erection of noise barriers between source and receivers, and measures to enlarge the sound absorption of the ground by way of adapted plantation.

c. Measures to protect receivers against noise – including window insulation.

In the Netherlands, noise load is expressed in L_{etm}: the 24-hr value and is defined as the maximum value of:

a. The equivalent sound level Leq dB(A) in the daytime (0700 hr – 1900 hr);

b. The equivalent sound level Leq dB(A) in the night-time (2300 hr – 0700 hr), added with a 10 dB(A) night time penalty.

The preferred limit value of every new situation (after 1986) is 50 dB(A).The executive committee at provincial level can permit a higher limit value, to be approved by the Minister of Housing, Spatial Development and Environment. The preferred limit value of every existing situation (before 1986) is 55 dB(A). An action plan is adopted to rehabilitate situations where the preferred limit value was not reached in 1986 [19].

1.3.1.5 United Kingdom

The Land Compensation Act introduced in 1973 provides mechanism to compensate those who were adversely affected by operation of all road schemes. The Noise Insulation Regulation (1975) amended in 1988 specifies that a dwelling affected by traffic noise at level higher than 68 dB(A) L10(18 hr) from use of a new road is eligible for acoustic insulation under the Land Compensation Act (1973). The Department of Transport, responsible for the motorway and trunk road system, permitted in 1992 the use of porous asphalt in urban and noise sensitive locations while banning the use of concrete surfaces for roads carrying over 75000 vehicles per day. The use of low noise road surfacing can bring moderate noise reduction only and demands for erection of barriers increase but there is no comprehensive policy for deciding when and where to use barriers [20] [21].

The Highways Agency continues to install quieter surfacing on trunk roads and estimates to have overlaid over 60% (4,022 km / 2,500 miles) of trunk roads by 2010. Also, other measures including earthen mounds, special acoustic barriers, installing double-glazing and noise insulation would be considered. In addition, there is a programme to treat noisy locations from a list presented to Parliament where they meet specific criteria [22].

1.3.1.6 United States of America

The Federal Highway Administration (FHWA) of the Department of Transportation adopts a three-pronged approach to reduce road traffic noise. This includes controlling at the source (that vehicles be quieted and use of low noise road surfacing), controlling through effective land use planning (that noise sensitive land uses near highways be avoided or restricted) and implementing highway project mitigation (that mitigation measures be undertaken on individual highway projects) [23].

The legislative power is provided through several pieces of legislations, namely, the Noise Control Act (1972) on vehicle emission, the National Environmental Policy Act (NEPA) of 1969 on Highway Project Noise Mitigation and the Federal-Aid Highway Act of 1970 mandates FHWA to develop noise standards for mitigating highway traffic noise.

The regulations requires traffic noise from highways at residency, hotels etc. should not exceed 67 L_{eq}(1hr). The regulations do not require that this to be met in every instance, but, every reasonable and feasible effort be made to provide noise mitigation when the criteria are approached or exceeded. Insulation would also be considered and applied to private residencies if and when barriers are found not feasible or are cost unreasonable high and severe noise impact [e.g. at 75 dB(A) or more, 30 dB(A) increase over existing level]. As for institutional buildings like schools, hospitals, libraries etc., both barriers and insulation would be considered but noise barrier is most commonly used [24] [25].

1.3.1.7 British Columbia, Canada

The Ministry of Transportation & Highways (MoTH) is responsible to protect residents from noise impact arising from the use of transportation facilities and a two-pronged approach is adopted. On one hand, proactive action is taken to avoid future impact through the appropriate control of land uses along existing and planned highways. On the other hand, the potential noise impact to the community brought by new or substantial upgraded controlled-access highways would be evaluated and mitigation will be carried out when warranted, cost-effective and desired by the majority of the directly affected community. The kind of mitigation measures generally includes roadside barriers, earth berm or combination of both elements constructed in the right of way of highways.

Mitigation measures would be recommended where the predicted L_{eq}(24 hr) at ground floor level of the residency is:

a. in the range of 55 to 65 dB(A) inclusive and exceed pre-project level by 10 dB(A) for pre-project level of 45 dB(A) or 3 dB(A) for pre-project level of 62 dB(A).
b. over 65 dB(A) and exceed pre-project level by 3 dB(A) or more [26].

1.3.1.8 City of Calgary, Canada

City of Calgary is committed to reducing the impact of road traffic noise in existing and future residential areas. As part of the planning process in Calgary, residential areas are examined to determine whether there is an existing or potential noise problem in outdoor rear leisure area of a residential property only. Noise levels experienced within the dwelling or building are not covered. In new subdivisions, the City works with developers to determine future traffic noise impacts to residential areas along major roads and expressways. If a potential noise impact is identified, steps are taken to reduce it. For the existing areas, City of Calgary sets priorities for construction of noise barriers subject to funding availability and individual /

community requests as well as technical and economical viability. The criteria adopted are that if the road is non-truck route, the threshold level is 60 dB(A) based on a 24-hr average. If the road is a truck route, the threshold level is 65 dB(A) based on a peak hour average [27].

1.3.1.9 New South Wales, Australia

The Road Traffic Authority (RTA) is responsible for construction, operation and maintenance of public roads in New South Wales and is also responsible to reduce noise arising from road traffic. The Environmental Planning and Assessment Act 1979 and the Environmental Planning and Assessment Regulation 2000 provide legislative framework for providing noise mitigation against road traffic noise. The NSW Environmental Protection Agency (EPA) together with the RTA and other stakeholders developed “the Environmental Criteria for Road Traffic Noise (ECRTN)”, though is not a mandatory document, provide basis for criteria and conditions to approve future road development proposals, land-use development proposals and EPA environment protection licenses. The criteria are:

a. New freeway or arterial roads in urban area, and new residential developments next to freeway or arterial roads [55 L_{eq}(0700 hr – 2200 hr) and 50 dB(A) L_{eq}(2200 hr – 0700 hr)]
b. New or “redeveloped” roads in metropolitan areas [55 L_{eq}(0700 hr – 2200 hr) and 50 dB(A) L_{eq} (2200 hr – 0700 hr)]
c. New or “redeveloped” roads in rural areas [50 L_{eq} (0700

hr – 2200 hr) and 45 dB(A) L_{eq} (2200 hr – 0700 hr)] [10]

The ECRTN adopts package of measures including traffic management, architectural acoustic treatments, quieter pavement surfaces or noise barriers without particular priority or preference [27]. The RTA also implements “Noise Abatement Program” by means of noise walls or mounds, acoustic treatments or low noise pavement to address the effects of very high road traffic noise (at least 65 dB(A) L_{eq} (0700 hr – 2200 hr) or 60 dB(A) L_{eq} (2200 hr – 0700 hr) on residences, schools, places of worship or health care institutions adjacent to existing noisy State, Federal or National roads [28].

1.3.1.10 Japan

The Basic Environmental Law (revised in 1993) and the Environmental Impact Assessment Law (in effect since 1999) are the main legislative frame works in reducing road traffic noise. The former one requires the Government to establish environmental quality Standards relating to noise. The latter one defines the procedures for conducting environmental impact assessment highways.

The Environmental Quality Standards for Noise was revised in 1998. For roads with two or more lanes and fronting residential areas, noise level at daytime and night-time at residential flats should not exceed 60 and 55 dB(A) L_{eq} respectively. Similarly, for the similar kinds of road fronting areas of mixed uses of commercial, industries and significant number of residencies, daytime and night time standards are 65 and 60 dB(A) respectively. For motorways, trunk roads etc., noise at receivers should not exceed 70 dB(A) during daytime and 65 dB(A) at night-time irrespective whether the areas in concerned are solely for residential uses or mixed uses with commercial and industries. These environmental quality standards must be achieved or maintained within 10 years after the standards are in place for areas facing roads. Measures including reducing vehicle noise emission, traffic flow control and noise barriers and enclosures [29] [30].

The Road Bureau of the Ministry of Construction and Japanese Highways Public Corporation, when undertaking construction of new highways at national, prefectural and municipal, would install sufficient and necessary noise barriers, buffer zones formed of dense trees and shrubs, earth banks and anti-noise tunnels and semi-underground structures to meet the environmental quality standards [31].

1.3.1.11 People Republic of China

The Law on Prevention and Control of Pollution from Environmental Noise promulgated in 1989 provides legislation frameworks on prevention and control of road traffic noise. It specifically requires among other measures to erect barriers where expressways, urban overhead road and light-tract lines that traverse areas [32].

GB3096 – 93 (Standard of environmental noise of urban area) lists out the noise criteria for road project proponents to comply with. When constructing new high speed roads, consideration should be given to have its alignment to avoid residential buildings, hospitals, schools etc so that center of roads should be at 100m from residential buildings and at 200m from schools. Other proactive planning efforts include erecting noise barriers to achieve the standards listed in GB3096 – 93 [70/60 (day) and 55/50 (night) for residential buildings and schools / hospitals respectively] [33] [34].

1.3.1.12 Hong Kong Special Administration Region (HKSAR) Government, People Republic of China

The Hong Kong Special Administrative Region (Hong Kong SAR) Government adopts a 4-pronged approach in tackling road traffic noise. Preventive actions would be taken at the outset when planning new roads and residential developments. The Environmental Impact Assessment Ordinance (EIAO) which was in force since April, 1998 is the major piece of legislation in tackling road traffic noise. The EIAO requires conduct of environmental impact assessment for new road project so that noise and other environmental impacts can be evaluated and appropriate mitigation measures can be recommended. Apart from recommending mitigation measures like barriers etc. when noise at nearby residents exceeds 70 dB(A)L_{10}(1hr), the road building agent would also be required to evaluate other means like road alignment options to minimize noise impact [7] [36].

Abatement programmes were implemented in late eighties and early nineties to provide noise relief to residents and students next to busy highways. These include a HK$620 million programme to provide a quieter learning environment for 475,000 children through the school insulation programme and a HK$73 million programme on quiet road resurfacing works to bring noise relief to 57,600 residents living next to high-speed roads. In year 2000, the Hong Kong SAR Government established a policy to retrofit noisy existing roads with barriers wherever technically feasible subject to availability of funds. As a result, a 10-year retrofitting barrier programme at a cost of over HK$2300 Million benefiting about 100,000 residents was put in place. Legislation is in place to avoid the import of noisy vehicles into Hong Kong. The public and other stakeholders are involved through education, engagement and partnership programme. In July 2006, the Hong Kong SAR Government took further proactive action and proposed nine enhanced measures in a draft “Comprehensive Plan to Tackle Road Traffic Noise in Hong Kong” [7].

1.3.1.13 Discussion

The twelve selected community, countries, states and cities examined here have demonstrated well-structured plans in tackling road traffic noise from various angles. Table 1.1 summarizes the means of tackling road traffic noise by the twelve selected countries, states and cities examined. These plans are either engineering base or administrative approaches. Also, tackling of the road traffic noise problems often began at the noise sources, during the propagation paths or at the receivers. Each country has its own merits in establishing its own criteria, the degree of protection necessary, the financial commitment, the affordability, the public awareness and the opportunity were the affecting factors. The adoption of measures and its priority would depend on the severity of problem and also the effectiveness of measures applied. In sum, the actions against traffic noise problems must not rely solely on the reduction of vehicle-noise-emission levels and noise barriers, but also must include other important actions such as land-use planning, sound insulation of houses etc. One common point to all countries, states and cities examined is that they all adopt noise barrier as means to reduce road traffic noise. In other words, noise barriers must offer certain level of confidents to all stake-holders as means to reduce traffic noise. It would be therefore, useful to examine the practice of applying noise barriers in these countries, states and cities where information in identifying the most appropriate approaches for advancement in developing measures for dense high-rise cities could be identified.

1.3.2 A Review of Worldwide Practice in Using Noise Barriers to Reduce Road Traffic Noise

With reference to the above literature research, noise barrier is commonly adopted as a means to reduce road traffic noise. The selected community, countries, states and cities under review have its own practice in deploying roadside noise barriers depending on its own policy, its legislative framework, its commitment to protect the citizens, its financial commitment etc. Some countries have detailed guidelines in designing and constructing roadside barriers and some countries leave it to the responsible agents to decide based on determining factors such as cost comparison and aesthetic consideration.

In France, Germany and the Netherlands, there are no published guidelines for construction of barriers. However, in France, there is a circular issued to give advice on cost of erecting barriers with regards to the number of premises to protect and severe visual intrusion of the protection works. In United Kingdom, the Highways Agency sets out the process for designing noise barriers in the “Design Manual for Roads and Bridges”. The Manual indicates that structural constraints normally limit the maximum height of simple fence type barriers to about 5 meters.

In USA, FHWA has clear guidance in applying noise barriers. In any event, noise barriers should be able to achieve at least a 5 dB(A) reduction or otherwise should not be built. Barriers cost is also a concern. Height is usually limited to 8 m because of structural and aesthetic reasons. Attempts must be made to construct noise barriers that are visually pleasing and that blend in with their surroundings and vicinity. The guidelines put emphasis on efficient and cost-effectiveness [37]. In British Columbia of Canada, barriers recommended must be able to achieve a minimum noise reduction of 5 dB(A) L_{eq}(24 hrs) over the first row of residencies abutting highways. To limit the visual impact, barriers are limited to 3m in height. Cost may be limited as well for cost-effectiveness consideration [26].

In New South Wales of Australia, the RTA’s Environmental Noise Management Manual provides guidance in analyzing an acceptable balance between barrier height and comparative cost-effectiveness. The methodology adopts consideration of the benefits in terms of noise reduction and the number of people protected and the total costs. As a general rule of thumb, noise barriers must provide an insertion loss of at least 5 dB(A) at the most affected residence. Noise barriers more than 8m high are considered visually unacceptable [10].

In Japan, Japanese Highways Public Corporation issued standards for noise barriers which define the designs, color and choice of materials. There is no requirement or restriction on barrier height but is generally limited to 8m high due to structural reasons. To reduce distant attenuation in some cases and to help to minimize reflection onto the residents at opposite, curve top, bend top or cranked barriers would be used. Edge modifiers would be added to the barriers if needed for enhancing noise attenuation. Research is focused on improving the edge modifiers [38].

In China, barriers should be limited to a maximum height of 5m according to “Design Specification of Highway Environmental Protection” [JTJ/T 006-98]. In situation where those higher barriers are needed, the higher portion should be cantilevered towards center of roads. The insertion loss of barriers should be at least 10 dB. Absorptive materials or diffused reflective panels should be considered [34, 35]. In Hong Kong SAR, the Environmental Protection Department and the Highways Department jointly issued “Guidelines for designing barriers” to assist the relevant professionals in choosing materials, avoiding common mistakes, reducing visual impacts etc. There is no height restriction or cost limitation in building barriers [39].

It is noted that roadside barrier has been used and will continue to be used as a means to reduce road traffic noise. However, there is general concern that roadside barrier could bring side effects like visual impact for vehicle drivers, passengers and residents in the vicinity as well. The general trend appears to limit roadside barriers to certain height like 5m in People Republic of China, 8m in New South Wales of Australia due to visual issue and 8m high in Japan due to structure reason. In some countries like those in North America and European countries, so as in Australia, relatively low height barrier could be effective in reducing traffic noise to the required levels as houses or residential buildings are of low-rise and medium-rise nature. Also, space is available to separate highways from housings to act as further cushion layer for noise reduction. However, for those dense high-rise cities like Beijing, Tokyo and Hong Kong, situations are quite different. Because of the dense high-rise nature of cities and relatively no extra buffer zone could be provided on both sides of highways, high barriers, curved barriers and even total noise enclosure would be needed for noise mitigation.

From an engineering point of view, higher barriers, curved barriers or full enclosure would in fact impose more difficulties in its implementation. Not only that it would need larger structure for higher barriers, curved barriers or full enclosure, it would also occupy more space, cost more, require longer time to construct and cause visual concerns. These areas would certainly need further investigation so that more accurate prediction of barrier noise reduction effectiveness and improved barrier designs could be made available for combating road traffic noise impact in dense high-rise cities.

1.4 The Objectives of the Present Research

Road traffic noise is undoubtedly one of the most pervasive noise pollution encountered by most if not all dense high-rise cities. The literature reviews reported in earlier sections show that one of the most common means for the countries, states and cities studied to tackle or to give relief to residents living next to highways or expressways is to erect roadside noise barriers. The design of noise barrier would depend very much on the need of individual project and the prevailing legislative requirements of the country, state or city. Hence, this research will study the roadside noise barriers in a high-rise city.

Because of limited habitable space in dense high-rise cities, tall residential buildings are built fairly close to the roads and hence noise mitigation measures would be required on roadside in order to maintain good acoustical environment for the residents. In a very extreme case, the provision of full enclosures is most likely to be a complete solution to mitigate road traffic noise impact. However, putting aside cost and visual impact, there are other concerns. Cities cannot allow having all major roads enclosed and it may not be feasible to cover the road junctions from the traffic safety point of view. As identified from the literature review reported in earlier sections, the countries, states and cities under studied restrict the construction of noise barriers to certain height or certain format in view of concerns mentioned above. There is imperative need to look into the accuracy of the current assessment and prediction tools, particularly in those cases where noise sensitive receivers locate near the shadow boundary of the barrier.

1.4.1 Predicting Noise Reduction Characteristic of Barrier in Further Accurate manner

It has been a common practice in many countries that prior to construction of highway or expressway projects, environmental impact assessment would be conducted for evaluation of impacts and recommendation of mitigation measures. Needless to say, noise impact assessment is one of the most significant aspects of the environmental impact assessment process. There are numbers of traffic noise prediction and assessment methods or procedures available to assist professionals, government officials and the public to look into the noise problems arising from new road networks. One of the most commonly used methods is “Calculation of Road Traffic Noise” (CRTN) published by the Department of Transport of the United Kingdom in 1989 (United Kingdom, Australia and Hong Kong adopt CRTN for traffic noise assessment). CRTN adopts Maekawa’s chart in assessing potential barrier effect as a function of Fresnel number, $N_1$where $N_1 = \frac{2\delta}{\lambda}$. Latest research study identified that predictions obtained by Maekawa’s chart deviate largely from experimental data, and from predictions obtained by analytical solutions. A critical review of CRTN’s assessment of potential barrier effect in particular at shadow boundary would be necessary.

1.4.2 Sound Diffraction Characteristic of Parallel Barrier Situation

It is another common feature in dense high-rise cities that tall residential buildings are built on both sides of heavily trafficked roads. High barriers would be needed on both sides of roads to provide noise reduction. The degradation of attenuation effect of such parallel barrier systems is a concern given that sound would reflect from one barrier to another. Notwithstanding that correction of the parallel barrier effect has been included in traffic noise prediction and assessment method or procedures like CRTN and STAMINA 2.0, it is also considered necessary to review and explore the sound diffraction characteristics of parallel barrier situation through adoption of analytical solution.

1.4.3 Sound Diffraction Characteristic of Cranked Barriers

Whilst the stakeholders, the public, the road users etc would reluctantly accept full enclosures or semi-enclosures, they would rather prefer visually less intrusive cranked or cantilever barriers as part of the dense high-rise cities. Nevertheless, the heights of the cranked or cantilever barriers would be restricted so as to minimise the visual impact. To accommodate these restrictions and to cater for large numbers of data to be handled, it is important to improve the empirical formulae available for the professional engineers and acousticians to predict in a more accurate manner the potential barrier attenuation effect or insertion loss (IL) due to cranked or cantilever barriers in particular at locations close to barrier shadow boundary.

1.4.4 Research Objectives

In dense high-rise cities, whilst increasingly more tall residential buildings are built very close to and on both sides of heavily trafficked roads, very tall roadside noise barriers or very substantial structures like noise enclosure would not be preferred due to concerns of cost, cityscape, visual etc. There is an imperative need to look into the accuracy of the current assessment and prediction tools so that measures would not be under-provided in some cases and over-provided in others. The situations include those cases where residents are located close at barrier shadow boundary and barriers are installed on both sides of road. Also, further mitigation measures or enhancement of current barrier design for better performance in noise reduction is also warranted. In this respect, investigation of ways to improving prediction and design of cranked or cantilever barriers is much needed as using of cranked or cantilever barriers in dense high-rise cities is on rising trend. These are the goals of this study. In order to achieve these goals, the following objectives are considered:

a. To examine and modify the potential barrier chart adopted by CRTN;
b. To examine and evaluate the degradation of acoustic performance for parallel noise barrier systems; &
c. To examine and evaluate the diffraction characteristics of cranked barriers.

In Chapter 2, I shall review the analytical and empirical formulae in assessing noise reduction effectiveness of barriers for developing appropriate theoretical model for the research. I shall also discuss the research methodologies based on the results of the review. In Chapter 3, I shall examine and improve the potential barrier correction chart in “Calculation of Road Traffic Noise” which is widely used in United Kingdom, New South Wales of Australia and Hong Kong. In Chapter 4, I shall examine and evaluate the deterioration of noise attenuation effect due to parallel barriers. In Chapter 5, I shall examine and evaluate the diffraction characteristics of cranked barriers. In Chapter 6, I shall discuss the study results with particular reference to Hong Kong, one of the typical dense high-rise cities and draw some conclusions. I shall also provide recommendations and pointers for future studies.

1.5 Summary

In this chapter, the following have been identified:

1. The twelve selected community, countries, states and cities studied have well-structured plans in tackling road traffic noise from various angles;
2. Roadside barriers have been used and will continue to be used to reduce road traffic noise;
3. High barriers, curved top, bend top, cranked barriers or even enclosures may be needed in dense high-rise cities like Beijing, Tokyo and Hong Kong;
4. The substantial barriers and its supporting structures induce

cost and visual concerns, more accurate prediction of barrier performance and improved barrier designs are needed;

5. The aim of the research is to look into the accuracy of the current assessment and prediction tools particularly in those cases where noise sensitive receivers locate near the shadow boundary of the barrier; and

6. The objectives of research are:

    a. To examine and improve the barrier attenuation estimation adopted by road traffic noise calculation scheme;

    b. To examine and evaluate the deterioration of attenuation effects of parallel barrier systems; and

    c. To examine and evaluate the diffraction characteristics of cranked barriers.

Community, Countries, States or Cities	Measures at source	Measures at transmission path	Measures at receivers
European Union	Member Countries required to submit Action Plan by 2007 which may include technical measures at noise sources; selection of quieter noise sources; reduction of sound transmission like roadside barriers etc.		
France	Stringent vehicle noise emission	Earth mounds, vertical barriers	Window insulation
Germany		Roadside noise barrier	Window insulation, Zoning requirement for land use
The Netherlands	Stringent vehicle noise emission, speed reduction, silent roads (concept of low noise road surfacing), withdrawal of housing function.	Noise barriers or screens	Window insulation
United Kingdom	Low noise road surfacing	Special acoustic barriers	Window insulation
United States of America	Stringent vehicle noise emission, land use planning	Roadside barriers	Window insulation
British Columbia, Canada	Land uses control along existing and planned highways	Roadside barriers, earth berm.	
Calgary, Canada	Planning control	Roadside	

	along planned highways	barriers	
New South Wales, Australia	Stringent vehicle emission, low noise road surfacing, land uses planning, traffic management.	Noise wall or mounds	Architectural acoustic treatment, building design, window insulation
Japan	Stringent vehicle emission, land use planning	Roadside barriers	Sound insulation
People Republic of China	Land use planning,	Roadside barriers	
Hong Kong SAR	Stringent vehicle noise emission, low noise road surfacing, land use planning.	Roadside barriers	Noise insulation

Table 1.1 – Summary of ways of tackling road traffic noise adopted by 12 community, countries, states and cities studied which include European Union, France, Germany, the Netherlands, United Kingdom, United States of America, British Columbia and Calgary of Canada, New South Wales of Australia, Japan, People Republic of China and Hong Kong Special Administrative Region of People Republic of China.

Chapter 2

A Review of Analytical and Empirical Formulae of Assessing Barrier's Noise Reduction Effectiveness

2.1 Introduction

Noise barriers are being used worldwide as common means to reduce road traffic noise. Different types of barriers currently in use are widely different in shapes, such as normal straight edge vertical barriers, top-bended barriers, cranked barriers, vertical barriers with lourve, barriers with multi-edges, barriers with soft-edge etc. To maximise the acoustic performance of noise barriers, it is of paramount importance to predict the sound reduction in a more accurate manner. Theoretical and experimental studies of wave diffraction by a thin plane have been a subject of interest for more than a century. The fundamental theory of barrier diffraction assumes a knife edge at the barrier top. This theory is approximately valid when the barrier thickness is smaller than the wave-length and is referred as thin barrier. For thick barriers, such as a building, approximation can be made using an equivalent thin barrier, defined by the intersection of two straight lines both just grazing the top edges of the building, one drawn from the reception point and the other drawn from the effective source position. However, this method becomes inaccurate when the thick barrier is high and the angle between the two lines is greater than 90° [40].

There has been continual interest in the past few decades in studying the attenuation of sound by a barrier. The theoretical results for the diffraction are often based on some analytical or empirical formulae. It would be useful to conduct a literature review so as to review the basic principles of sound diffracted by barriers and to identify parameters. A list of the most commonly used analytical and empirical models; and approximation equations for predicting the noise reduction performance of effectiveness of noise barriers are reported in the following paragraphs.

2.2 Analytical Solution of the Diffraction of Sound Waves

The first analytical solution for the barrier performance was developed in the late 19^{th} century by Sommerfeld. In 1896, he considered the case of a harmonic plane wave normally incident on a rigid half-plane and developed a rigorous solution for diffraction by a perfectly conducting half plane. He showed that the wave in the shadow region originates at the edge of the half plane and is composed of two main terms. The first term is the direct wave and is expressed exactly according to the principles of geometrical acoustics. The second term, which is identified as the contribution of the diffracted wave, is expressed in terms of Fresnel integrals [41].

2.2.1 The MacDonald Equation

MacDonald solved the same problem for cylindrical and spherical incident waves. The solution contains integrals that are related to an integral representation of the Hankel function. For the case of spherical wave's incident on a rigid half plane, the solution involves exponential functions instead of Hankel functions. The complete solution to the problem of sound propagation over a semi-finite barrier or rigid half plane screen shown in Figure 2.1 involves contour integration of infinite integrals. A very useful form of first order approximation for the diffracted wave pressure has been given by MacDonald. The diffracted wave pressure is given by:

$$P_{diff} = \frac{ke^{-i\pi/4}}{4\pi\sqrt{kL}}\left[\frac{\text{sgn}(\varsigma_1)e^{ikR_1}}{\sqrt{k(L+R_1)}}\Lambda(\sqrt{2N_1}) + \frac{\text{sgn}(\varsigma_1)e^{ikR_2}}{\sqrt{k(L+R_2)}}\Lambda(\sqrt{2N_2})\right] \tag{2.1}$$

where

$$\Lambda(u) = \int_{\mu}^{\pi} e^{i\pi\xi^2/2} d\xi = F_r(\infty) - F_r(\mu) \tag{2.1a}$$

$$F_r(u) = C(\mu) + iS(\mu) \tag{2.1b}$$

$$C(\mu) = \int_{0}^{\mu} \cos(\frac{\pi\xi^2}{2}) d\xi \tag{2.1c}$$

$$S(\mu) = \int_{0}^{\mu} \sin(\frac{\pi\xi^2}{2}) d\xi \tag{2.1d}$$

$$\varsigma_1 = \text{sgn}(\left|\theta_s - \theta_r\right| - \pi)\sqrt{k(L-R_1)} \tag{2.1e}$$

$$\varsigma_2 = \text{sgn}(\theta_s + \theta_r - \pi)\sqrt{k(L-R_2)} \tag{2.1f}$$

$$N_1 = \frac{L-R_1}{\lambda/2} = \frac{k}{\pi}(L-R_1) \tag{2.1g}$$

$$N_2 = \frac{L-R_2}{\lambda/2} = \frac{k}{\pi}(L-R_2) \tag{2.1h}$$

C(u) and *S(u)* are the Fresnel integrals. R_1 is the distance between source and receiver without the presence of rigid half plane while R_2 is the distance between receiver and the image source without the presence of rigid half plane. *L* is the shortest distance between source and receiver with the presence of rigid half plane.

The *sgn* function takes values of +1 or –1 depending on the sign of the argument. The Fresnel integrals are standard functions for which numerical subordinates are widely available so that the diffracted field is easy to calculate. The approximation holds for kR_1 >>1, i.e. either the source and receiver; or the receiver alone are distant away from edge of the barrier. The result shown here can be directly extended to three dimensions. If the source is visible from the receiver point another term is required in the expression for the total sound field to represent the direct, and any reflected waves [47].

2.2.2 The Hadden and Pierce Equation

An accurate solution for the pressure diffracted by a semi-infinite plane screen, which can be also applied to a semi-infinite wedge shown in Figure 2.2, has been given by Hadden and Pierce. In this case the diffracted field is the sum of four terms which correspond to the sound paths between the source, its image in the barrier, the receiver and its image in the barrier. For the wedge shaped barrier with 4 sound paths shown in Figure 2.3, the diffracted wave pressure is given by:

$$P_{diff} = \sum_{n=1}^{4} V(\zeta_n) \qquad (2.2)$$

For each path the diffracted field $V(\zeta_n)$ is given by:

$$V(\zeta_n) = -\frac{1}{4\pi^2} A_n \frac{e^{ikL}}{L} F(\zeta_n) \qquad (2.2a)$$

where L is the shortest length of the sound path over the barrier,

$$A(\zeta_n) = (\upsilon/2)(-\beta - \pi + \zeta_n) + \pi U(\pi - \zeta_n) \tag{2.2b}$$

$$F(\zeta_n) = \int_0^\infty \frac{kL}{kL + i\zeta}\left(1 + \frac{i}{kL + i\zeta}\right) q_n e^{-\zeta} d\zeta \tag{2.2c}$$

$$q_n = \frac{1}{|A_n|} \tan^{-1}\left[\tan|A_n| \tanh(\upsilon X_n)\right] \tag{2.2d}$$

$$\sinh X_n = \sqrt{\left(\frac{\zeta i}{\alpha 2} - \frac{\zeta}{4kL}\right)} \tag{2.2e}$$

$$\alpha = \frac{k r_s r_r}{L} \tag{2.2f}$$

Also, υ is the wedge index represented by $\upsilon = (\beta/\pi)$ and U is the Heaviside step function which is 1 for positive argument and zero for zero or negative arguments. The ζ_n are given by

$$\zeta_1 = |\theta_s - \theta_r| \tag{2.2g}$$

$$\zeta_2 = 2\beta - |\theta_s - \theta_r| \tag{2.2h}$$

$$\zeta_3 = \theta_s + \theta_r \tag{2.2i}$$

$$\zeta_4 = 2\beta - |\theta_s + \theta_r| \tag{2.2k}$$

This is an accurate representation of the sound field, which has been shown to agree well with experiment. Since reflections of the source and receiver in the faces of the barrier are considered the effects of having barrier surfaces of finite impedance can be calculated by incorporating appropriate reflection coefficient(s) for the paths from the image sources [42, 42, 47].

2.2.3 The Solution by Pierce

For a semi-infinite long half plane thin vertical barrier locating on fully absorptive ground (see Figure 2.4), according to Keller's geometrical theory of diffraction, the sound field of diffraction in the shadow zone can be written as [42, 43]:

$$P_{diff} = D(\frac{e^{ikR}}{4\pi R}) \qquad (2.3)$$

where *D* is the diffraction coefficient, *k* is the wave number and *R* is the distance from source to receiver without the presence of the thin vertical barrier. Expressions of *D* have been given by many researchers. Solution by Pierce is shown below:

$$P_{diff} = (\frac{e^{ikL}}{4\pi L})(\frac{e^{i\pi/4}}{\sqrt{2}})\sum\left(\frac{\sin\upsilon\pi}{(1-\cos\upsilon\pi(\theta_s \pm \theta_r)}\right)A_D\left[\Gamma \mathrm{M}_\upsilon(\theta_s \pm \theta_r)\right] \qquad (2.4)$$

where *L* is the total length of the sound ray path, the angles, θ_s & θ_r, are defined as respective angles subtended by ray paths from source with the barrier and to receiver with the barrier, and again $\upsilon = (\beta/\pi)$), is the wedge index. The function A_D, diffraction integral is given by

$$A_D = \mathrm{sgn}(X)\left[f(X) - ig(X)\right] \qquad (2.4a)$$

The diffraction integral, with the auxiliary Fresnel functions,

$$\Gamma = \sqrt{\left(\frac{kr_s r_r}{\pi L}\right)} \qquad (2.4b)$$

and

$$\mathrm{M}_\upsilon(\theta_s \pm \theta_r) = \frac{(\cos\upsilon\pi - \cos\upsilon\pi(\theta_s \pm \theta_r)}{(\upsilon\sqrt{(1-\cos\upsilon\pi\cos\upsilon\pi(\theta_s \pm \theta_r))}} \qquad (2.4c)$$

Also, the auxiliary Fresnel integrals *f(X)* and *g(X)* are given as:

$$f(x)=\left[\frac{1}{2}-S(X)\right]\cos\left(\frac{\pi X^2}{2}\right)-\left[\frac{1}{2}-C(X)\right]\sin\left(\frac{\pi X^2}{2}\right) \qquad (2.4d)$$

$$g(x)=\left[\frac{1}{2}-C(X)\right]\cos\left(\frac{\pi X^2}{2}\right)+\left[\frac{1}{2}-S(X)\right]\sin\left(\frac{\pi X^2}{2}\right) \qquad (2.4e)$$

and the Fresnel integrals *C(X)* and *S(X)* are those used in Macdonald Equation in the above section.

In the case of a thin barrier or screen with either the source or receiver located at a distance a few wavelengths from the edge of the barrier or screen, such that the wedge index, ν = ½ and the length ratio $r_s r_r / L^2 \rightarrow 0$ but $(k r_s r_r / L)$ remains finite. In such case, the diffraction terms can be grouped to a compact formula as follows:

$$P_{diff} = (\frac{(1+i)}{2}(\frac{e^{ikL}}{4\pi L})[A_D(X_+)+A_D(X_-)] \qquad (2.4f)$$

where

$$X_+ = X(\theta_r+\theta_s) \qquad (2.4g)$$

$$X_- = X(\theta_r-\theta_s) \qquad (2.4h)$$

$$X(\Phi) = -2\sqrt{\left(\frac{2kr_s r_r}{\lambda L}\right)}\cos\left(\frac{\Phi}{2}\right) \qquad (2.4i)$$

2.3 Approximate Analytical Solution for a Thin Barrier

2.3.1 The Fresnel and Kirchhoff Approximation

The theory of diffraction was originally developed in optics and it was later applied to all diffraction phenomena in acoustics. A sound wave from a point source S propagated through an opening in infinity wide and thin wall with P as receiving point (see Figure 2.5). When the opening is limited to $x_1 – x_2$ and $y_1 – y_2$ on the rectangular coordinate x, y on the wall surface, the sound field at P can be expressed by

$$U_{(p)} = B\int_{x_1}^{x_2} dx \int_{y_1}^{y_2} dy \bullet e^{ikf(x,y)} \tag{2.5}$$

where *k* is the wave number and is represented by $k = 2\pi/\lambda$, *f(x,y)* is a contribution function of the coordinate of the opening and the positions of S and P. B is the function of the geometries of S, P and the wall opening and also wave length λ, but it is here treated as a constant, assuming that the dimension of the opening are small compared to distances of both S and P from the wall.

With numerical calculation and necessary conversions of variables from *x* to *u* and *y* to *v* according to the Kirchhoff diffraction theory, the equation becomes:

$$U_{(p)} = -iA\int_{u_1}^{u_2} e^{\left(i\frac{\pi}{2}u^2\right)} du \int_{\upsilon_1}^{\upsilon_2} e^{\left(i\frac{\pi}{2}\upsilon^2\right)} d\upsilon \tag{2.5a}$$

where *A* is the constant converted from B and the integral

$$\int_{0}^{u_1} \exp(i\frac{\pi}{2}u^2)du - C(u_1) + iS(u_1) \tag{2.5b}$$

and the Fresnel’s integrals are those used in Macdonald Equation in the above section.

Defining a term, diffraction factor [DF] as ratio of sound filed with barriers to that of no barrier, one can determine that of the half-infinite thin screen as:

$$[DF] = \frac{-i}{2}(1+i)\left\langle\left(\frac{1}{2}\bullet C(\upsilon_1)\right) + i\left(\frac{1}{2}\bullet S(\upsilon_1)\right)\right\rangle \qquad (2.5e)$$

The Insertion Loss (IL) of half infinite thin barrier [48] can be defined further as.

$$IL = -10\log\left|[DF]\right|^2 = -10\log\frac{1}{2}\left\langle\left(\frac{1}{2}\bullet C(\upsilon_1)\right)^2 + \left(\frac{1}{2}\bullet S(\upsilon_1)\right)^2\right\rangle$$

(2.5 f)

Study conducted by Li & Wong [47] indicates that the Fresnel and Kirchhoff approximation always over-estimates the attenuation of the thin barriers.

2.4 Empirical Formulae for a Thin Barrier

Many analytical and approximation equations for predicting barrier diffraction characteristics or noise reduction performance of barriers (usually known as Insertion Loss (IL)) are in fact semi-empirical and are based on the application of ray-tracing and geometrical acoustics procedures. They are to some extent difficult to be used in day to day engineering calculation. Some simplifications without compromising the accuracy are preferred. In this respect, the most influential early study was that of Maekawa and his work was later further elaborated by Kurze and Anderson. Techniques were developed for predicting the insertion loss of reflecting, sharp edged and semi-infinite thin barriers based on the path difference between diffracted path length and the direct path length joining the source and receiver which can be represented as $\delta = (r_s + r_r) - R_1$ or $\delta = L - R_1$ mathematically. For this expression, r_s and r_r is the path length from source to edge of the semi-infinite thin barrier and from edge to receiver respectively while *L* is shortest path joining the source and receiver over the barrier.

2.4.1 Maekawa's Chart

Maekawa used a spherically spreading pulsed tone of short duration and measured the diffraction with a thin rigid barrier in a test room. He measured the sound pressure level in the shadow zone for a variety of frequencies and locations of source and receiver and described the attenuation of a screen using an empirical approach based on two important parameters which were the path difference δ shown in the above section and the wave length of the sound, λ. These two parameters were combined into the Fresnel number, N_1 associated with the source to give $N_1 = \frac{2\delta}{\lambda}$. Maekawa's measurements included data the receivers located in both the shadow zone and illuminated zone. In the shadow zone, receivers were screened from source by the semi-infinite thin barrier while receivers in the illuminated zone could see the source. For this, a negative value of N_1 (i.e. $N_1 < 1$) would be used to indicate that the receiver is located in the illuminated zone. Since the receiver in the illuminated zone could see the source, the attenuation quickly drops to zero according to Maekawa's chart. For those receivers at the shadow boundary (i.e. $N_1 = 0$), the attenuation is 5 dB. At this point the source is just visible over the top of the barrier.

Maekawa's chart is one of the most established methods for predicting the noise reduction effectiveness of noise barriers or insertion loss (IL) behind noise barriers. This approach predicts the amplitude of the attenuation only and no wave interference effects will be predicted [44, 47].

2.4.2 Kurze and Anderson Formula

Kurze and Anderson [45] derived empirical formulae for the sound attenuation by a thin rigid barrier, utilizing various theoretical and experimental results. The experimental data were taken from the work of Maekawa and Rathe while theoretical results were taken from Keller's theory of diffraction. Kurze and Anderson further extended their evaluation of the effect of a barrier parallel to an incoherent line source based on sound emanating from a few points on the line source. The resulting empirical formulae have been extensively used in the noise control engineering community:

$$IL = 5 + \log \frac{\sqrt{2\pi N_1}}{\tanh \sqrt{2\pi N_1}} \qquad (2.6)$$

where IL is the Insertion Loss and N_1 is the Fresnel Number. The main advantage of the formulae derived by Kurze & Anderson is that this is simple to be applied and the predictions are accurate for the use in noise control community.

2.4.3 Modified Equations by Yamamoto and Takagi

On the basis of Maekawa's original chart, Yamamoto and Takagi [50] developed 4 different types of approximate expressions. The first was an expression that describes the whole chart with only one numerical formula:

$$IL = \begin{cases} 10\log[1+G(N_1((N_1+0.3)] & for \quad N_1 > -0.3 \\ 0 & for \quad N_1 < -0.3 \end{cases} \qquad (2.7a)$$

$$G(N_1) = 3.621\{\tan\left(\frac{N_1 - 5\times10^{-3}}{1.45\times10^{-2}}\right) + \frac{\pi}{2}\} + 6.165\{1 - e^{-0.205(N_1+0.3)}\} + 2.354$$

(2.7b)

where N_1 is the Fresnel Number and the coefficients 3.621, 6.165 etc were developed based on the original chart using the least squares methods.

The formula appears to be complicated with the $G(N_1)$. To reduce the difficulty, Yamamoto and Takagi further developed three more series of expressions:

$$IL = \{ \begin{matrix} 10\log N_1 + 13 & for & N_1 > 1 \\ 5 + 8N_1 \big/ |N_1|^{0.55+0.143|N_1|} & for & -0.3 < N_1 < 1 \\ 0 & for & N_1 < -0.3 \end{matrix} \qquad (2.7c)$$

$$IL = \{ \begin{matrix} 10\log N_1 + 13 & for & N_1 > 1 \\ 5 \pm 8|N_1|^{0.438} & for & -0.3 < N_1 < 1 \\ 0 & for & N_1 < -0.3 \end{matrix} \qquad (2.7d)$$

$$IL = \{ \begin{matrix} 10\log N_1 + 13 & for & N_1 > 1 \\ 5 \pm 9.07674 \times \sinh^{-1}|N_1|^{0.485} & for & -0.3 < N_1 < 1 \\ 0 & for & N_1 < -0.3 \end{matrix} \qquad (2.7e)$$

Any one of the above expressions gives good agreement with the data obtained from the Maekawa chart with a maximum difference of less than 0.5 dB in the first expression and is no more than 0.3 dB in other expressions. These 4 sets of empirical formulae can be readily used for assessing acoustic performance of thin barrier in any situation.

2.4.4 Improvement of Maekawa's Method by Lam; and Muradali and Fyfe

Lam [48] improved Maekawa's method by summing the complex pressures instead of the energies traveling along each of the diffraction paths around finite length barriers for predicting noise reduction effectiveness of finite length noise barriers. Muradali and Fyfe [51] further extended Lam's research by using the Kurze and Anderson formulation as well as Pierce's solution in combination with Lam's summation procedure with successful results. Muradali and Fyfe also applied the approach in calculating IL of parallel barrier situations.

2.4.5 Modification to Maekawa's Chart by Menounou

Recently, Menounou [46] studied Maekawa's chart and particularly noted that in some cases, Maekawa's curve gives predictions that deviate largely from experimental data and analytical solutions when the source or receiver is very close to or at the barrier surface, or when the receiver is very close to or at the shadow boundary. Menounou studied the problem extensively by comparing Maekawa's chart with MacDonald equation and experimental data. Menounou found that the experimental data agree in good manner with MacDonald equation.

Menounou explained the phenomenon that Maekawa's chart uses a single parameter, the Fresnel Number. The full analytical equation, however, requires knowledge of several parameters including the location of sound source, receiver, the frequency of the incident wave etc. It is clear that Maekawa’s chart includes approximations. In other words, there could be multiple source-receiver locations with the same Fresnel number used in Maekawa’s chart that may experience different insertion loss.

Menounou further considered that the discrepancy should be attributed to the existence of an image source in the mirror position of the observation point. Discarding the image source contribution would probably lead to lower pressure at the receiver point and hence possibly a higher insertion loss may be obtained. Based on this argument, Menounou modified Maekawa’s chart from a single curve with one parameter to a family of curves with two Fresnel numbers. The first Fresnel number, N_1 is the conventional Fresnel number and is associated with the relative position of the source to the barrier and the receiver. The second Fresnel number, N_2 is defined similarly to the first Fresnel number but refers to image source.

Menounou also modified the Kurze and Anderson formula. Menounou considered the plane, cylindrical and spherical incident waves in her works. She combined the simplicity of use with the accuracy of sophisticated diffraction theories and delivered an improved Kurze and Anderson formula that allows a better estimation of the barrier attenuation by including the effect of the image source on the total field. The Kurze and Anderson formula improved by

Menonou is given by

$$IL = IL_s + IL_b + IL_{sb} + IL_{sp} = IL_c + IL_{sp} \qquad (2.8)$$

Where

$$IL_s = 20\log\frac{\sqrt{2\pi N_1}}{\tanh\sqrt{2\pi N_1}} - 1 \qquad)$$

$$IL_b = 20\log\left[1+\tanh\left(0.6\log\frac{N_2}{N_1}\right)\right] \qquad) \qquad (2.8a)$$

$$IL_{sb} = (6\tanh\sqrt{N_2} - 2 - IL)(1-\tanh\sqrt{10N_1}) \qquad)$$

$$IL_{sp} = \begin{cases} 3dB & \text{for plane waves} \\ -10\log\dfrac{1}{\left(\dfrac{L}{R_1}\right)+1} & \text{for cylindrica l waves} \\ -10\log\dfrac{1}{\left(\dfrac{L}{R_1}\right)^2+\left(\dfrac{L}{R_1}\right)} & \text{for spherical waves} \end{cases} \qquad (2.8b)$$

(

$$N_1 = 2\frac{L-R_1}{\lambda}, \quad N = 2\frac{L-R_2}{\lambda}, \quad \frac{L}{R_1} \qquad (2.8c)$$

The first term of *IL* is a function of N_1, which is a measure of the relative position of the receiver from the source. The second term depends on the ratio of N_1 and N_2. It is a measure of the proximity of either the source or the receiver from the half plane. The third term is only significant when N_1 is small. It is a measure of the proximity of the receiver to the shadow boundary. The last term is a function of the ratio L / R_1, which is used to account for the diffraction effect due to spherical incident waves. Again, both formulae appear to give sensible predictions of the attenuation of the thin screen in most practical cases of interest. The proposed formula contains elementary functions, involves simple calculations, and provides a reasonably accurate description of the new graph. It should be noted that the study and modification works of Maekawa's chart by Menounou were confined to the shadow zone region and did not extend to include any part at the illuminated zone region. The Maekawa's chart modified by Menonou with $N_2 = N_1$; and N_2 = 1, 2, 5, 10, 25, 50, 100, 250 & 500 is shown in Figure 2.6.

2.5 Discussion

Full analytical solution including Macdonald equation, Hadden & Pierce equation and the solution by Pierce offer very accurate prediction of barrier attenuation effects in particular those with complex barrier geometries. However, in daily assessment like conducting traffic noise impact assessment, the full analytical solutions would be seen as time consuming, complicate and not flexible particularly in the situation when large numbers of assessment points have to be addressed. While approximation analytical solution like Fresnel and Kirchhoff approximation would likely over-estimate the attenuation of thin barriers, it is therefore likely that empirical formulae are very frequently used in noise control engineering community. The most influential are Maekawa's Chart and Kurze & Anderson formula as the predictions of insertion loss of thin barriers are simplified in using the Fresnel number.

Two road traffic noise prediction schemes commonly used by professionals, administrators and practitioners adopt Maekawa's chart and Kurze & Anderson formula for predicting attenuation effects of barriers. They are the "Calculation of Road Traffic Noise" (CRTN)

[11] and STAMNIA 2.0. The CTRN issued by Department of Transport in 1998 of United Kingdom, which is widely used in United Kingdom, Australia and Hong Kong, adopts Maekawa's work in the assessment of potential barrier effect as a function of path difference. In the United States of America, traffic noise predictions had been performed using the Federal Highway Administration (FHWA) approved STAMINA 2.0 highway noise prediction modes, derived from the FHWA Highway Traffic Noise Prediction Model. The barrier calculations within STAMINA are based on the Kurze and Anderson formula [52].

Recently, Menounou refined Maekawa's chart and also Kurze and Anderson formula to provide a more accurate prediction of attenuation of thin barriers taking into account the presence of image source. The more accurate prediction would be useful in improving the assessment of attenuation effects of barriers in the daily assessment of road traffic noise impact.

2.6 Research Methodologies

2.6.1 To Examine and Modify the Potential Barrier Chart adopted by CRTN

For the purpose of study, Menounou's works in modifying Maekawa's Chart would be followed. Menounou replaced the single curve in Maekawa's chart by a family of curves. Each curve corresponds to a different Fresnel Number N_2 (based on path difference between image source and receiver) and provides Insertion Loss versus the commonly used Fresnel Number N_1 (based on path difference between source and receiver). The family of curves provide increased accuracy in prediction of Insertion Loss on one hand and maintains the simplicity of using empirical formula with accuracy of sophisticated full analytical solution [46].

CRTN is the approved methodology in prediction traffic noise in some countries and cities like United Kingdom, Australia and Hong Kong. A barrier attenuation curve based on Maekawa's works is included in CRTN for assessing potential barrier effect at particular receivers. Further works would be done with a view to modifying the CRTN's potential barrier attenuation curve on the basis of Menounou's works. Case studies would be conducted to evaluate the potential implication of the modified CRTN's potential barrier attenuation curve to situations in Hong Kong.

2.6.2 To Examine and Evaluate the Deterioration of Noise Reduction Effectiveness of Parallel Noise Barrier Systems

For the purpose of study, the noise attenuation effects at receivers behind barriers would be investigated in the situations with and without the presence of another barrier (usually known as reflecting barrier) on the other side of the road. The effects of acoustic performance with and without parallel barrier situations would be investigated and evaluated so as to develop a theoretical model. The previous work by Li & Kwok [74, 75] for the prediction of the noise reduction effectiveness of hard parallel noise barriers placed in urban environment, which basically adopt the solution for thin barrier by Pierce, would be followed in developing the theoretical model. Case studies of some typical parallel barrier situations would be conducted using the theoretical model and correction adopted in CRTN. The results delivered by using of theoretical model and correction adopted in CRTN would be compared so as to identify any potential implication of assessment of noise barrier performance of parallel barrier systems in Hong Kong.

2.6.3 To Examine and Evaluate the Diffraction Characteristics of Cranked Barriers

For the purpose of study, the effect of single, double and triple sound diffraction characteristics due to various edges of cranked or cantilever barriers would be looked into. The solution by Pierce on sound diffraction characteristics around corners and over wide barriers would be used basically coupling with the works by Salomons on sound diffraction characteristic of multi-edge of barriers and wedges would be adopted to develop the theoretical ray model [42, 87]. The theoretical ray model would be validated through experimental model and numerical modelling. Then, the theoretical ray model would be used to investigate the potential improvement to the current general day to day applications.

2.7 Summary

In this chapter a list of the most commonly used analytical, approximation and empirical models for predicting the noise reduction performance of effectiveness of noise barriers have been reviewed as follows:

1. Full analytical solutions, approximation and empirical formulae for predicting Insertion Loss (IL) of infinite length barriers are available;
2. Full analytical solutions may be too time consuming, complex and not flexible for day to day application;
3. The empirical formulae like Maekawa's chart and Kurze and Anderson formula are the most established methods for predicting IL behind noise barriers in the engineering community; and
4. Menounou modified Maekawa's chart with inclusion of Fresnel Number for image source into family of curves which improve predictions for receivers close to shadow boundary or close to barrier.

Also, the research methodologies have been established based on the results of literature reviews.

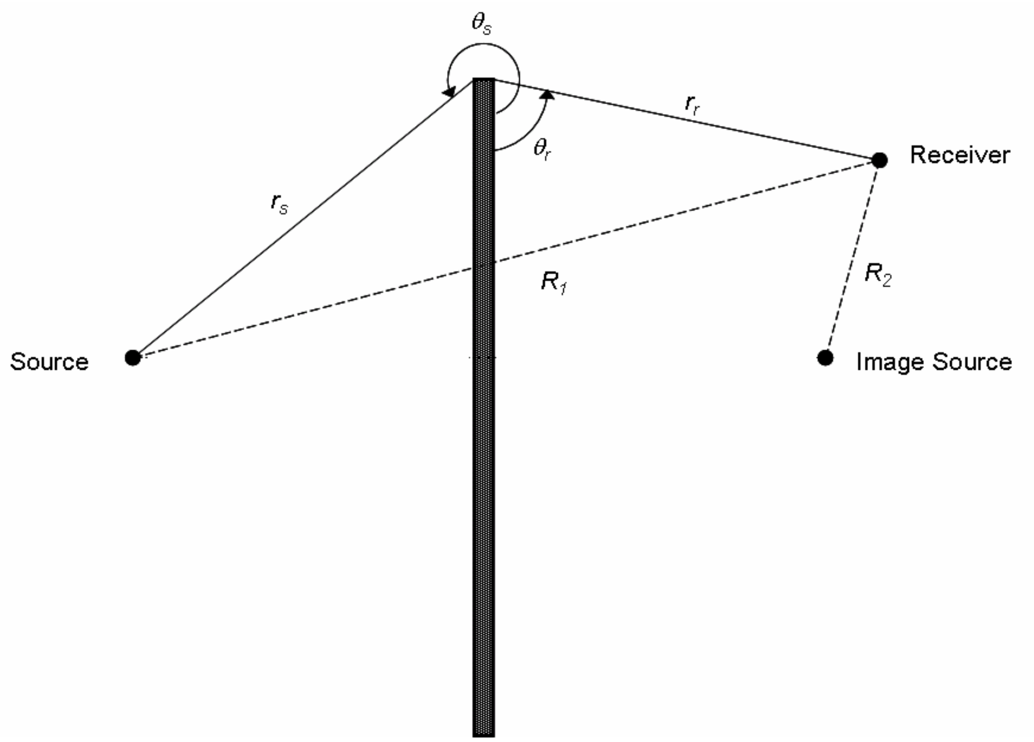


Figure 2.1 – The geometry of source and receiver in the vicinity of thin vertical barrier in the case of solution by MacDonald

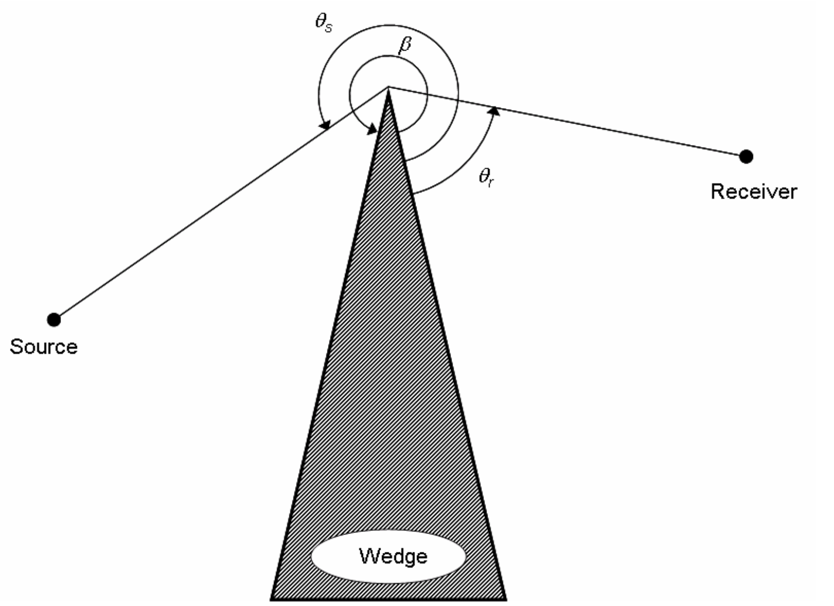


Figure 2.2 – The geometry of source and receiver in the vicinity of a wedge in the case of solution by Hadden and Pierce

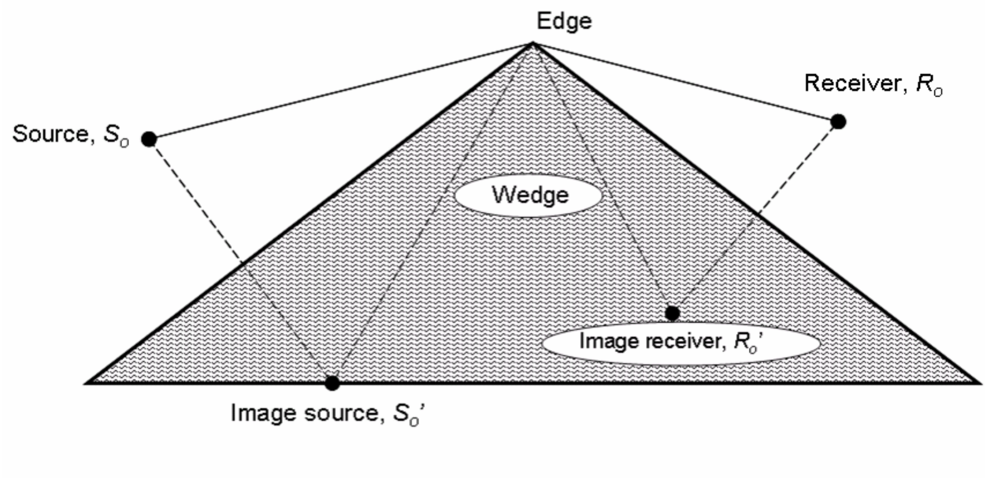


Figure 2.3 – Diagram showing the source, image source, receiver and image receiver in the case of solution by Hadden and Pierce

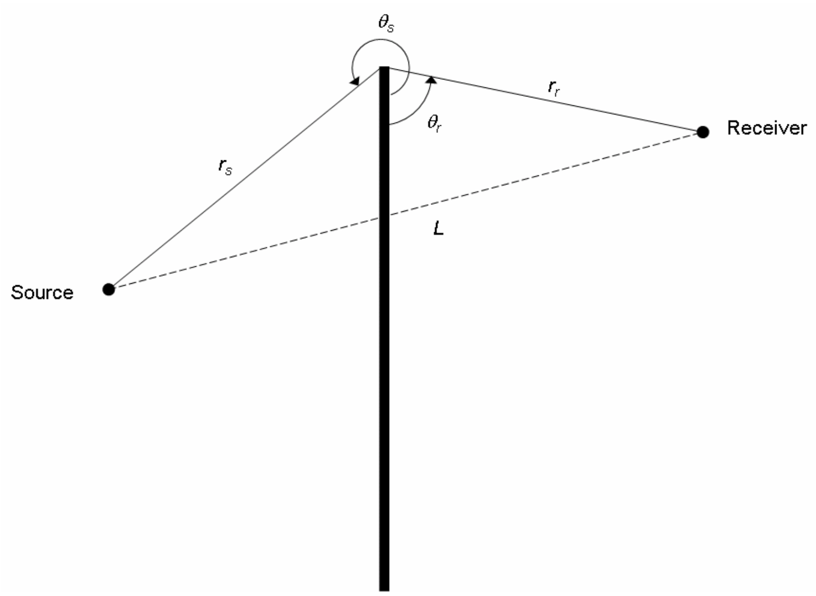


Figure 2.4 – The geometry of source and receiver in the vicinity of thin vertical barrier in the case of solution by Pierce

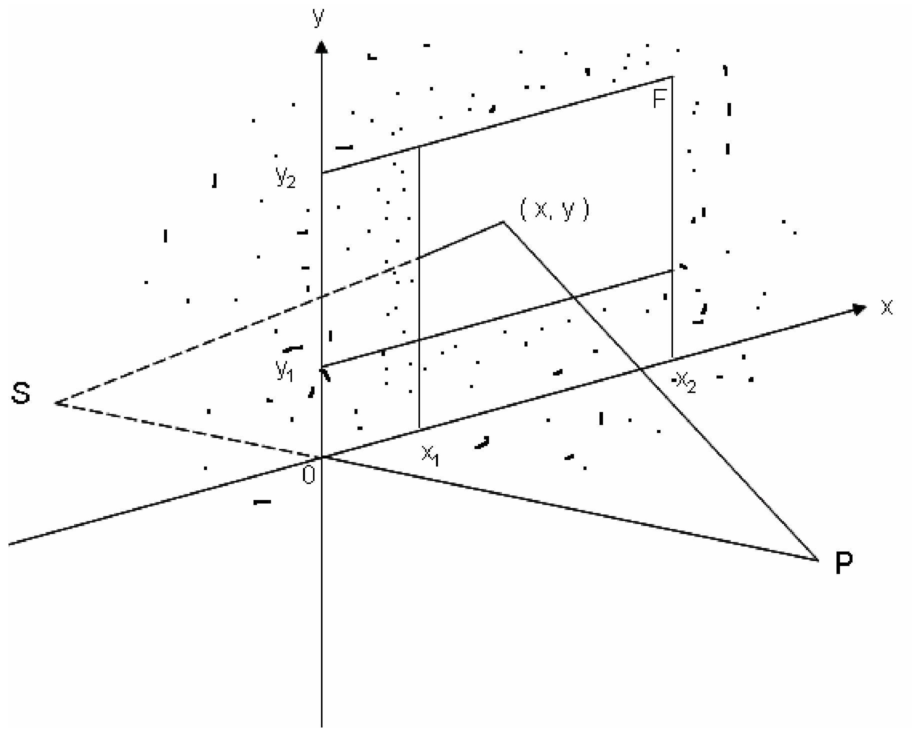


Figure 2.5 – The geometry of an infinite plane x-y. a point source S and a receiver P considered in Fresnel and Kirchhoff approximation

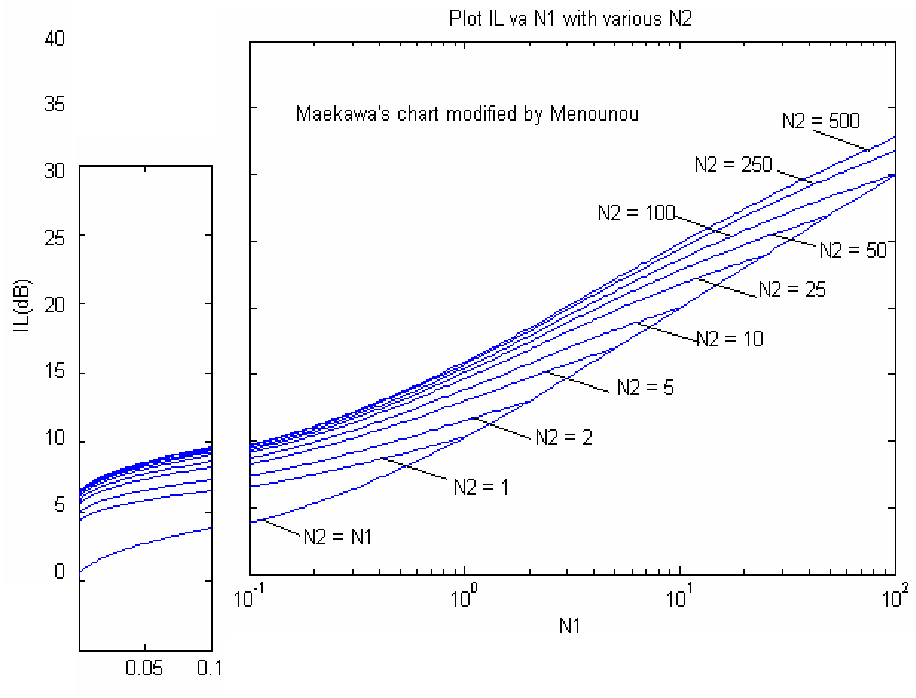


Figure 2.6 – Maekawa's Chart modified by Menounou for $N_2 = N_1$; N_2 = 1, 2, 5, 10, 25, 50, 100, 250 & 500

Chapter 3

The Modification of Potential Barrier Correction Chart in the "Calculation of Road Traffic Noise" (CRTN)

3.1 Introduction

Tackling road traffic noise is one of the paramount important agenda item in governments or administrations at federal, regional and municipal levels. Efforts are being taken through various means and fronts. Many governments or administrations would take early actions at planning stage to avoid heavily trafficked roads putting close to residential estates. It is a common practice in many countries that prior to construction of highway or expressway projects, noise impact assessment would be conducted for the evaluation of traffic noise impacts and recommendation of mitigation measures. There are numbers of traffic noise prediction and assessment methods, procedures or schemes available to assist professionals, government officials and the public to examine the noise problems arising from new road networks. From the literature review conducted in Chapter 1, the "Calculation of Road Traffic Noise" (CRTN) [11] published by the Department of Transport of the United Kingdom in 1988 is one of the most commonly used traffic noise prediction or assessment methodology. Government officials, acoustic professionals and practitioners in the United Kingdom, Australia and Hong Kong adopt the CRTN for traffic noise assessment [73].

3.2 The Calculation of Road Traffic Noise (CRTN)

The CRTN was developed by Delany, Harland, Hood and Scholes for the Department of Environment of the United Kingdom and was first published in 1975 [53, 54, 55]. It contained procedures for both predicting and measuring road traffic noise, and was intended to be used primarily as the method for calculating entitlement to sound insulation treatment of residential properties under the Noise Insulation Regulations 1975 of the Land Compensation Act 1973 [21]. In addition, it was also referred to in the Manual of Environmental Appraisal of road schemes issued by Department of Environment of the United Kingdom, and has general application in highway design and land use planning. In July 1988, the Department of Transport of the United Kingdom published revision for the CRTN which more accurate predictions for a much wider range of circumstances than the original version were included. It has also been substantially rewritten and restructured with the intention to removing all possible ambiguity and mis-interpretation.

In the CRTN, there are two major parts in calculating road traffic noise. The first part is the calculation of the 'basic L_{10} levels', defined as the noise level at a reference point 10 metres from the nearside carriageway. The basic L_{10} level is based on the traffic flow, the traffic speed, % heavy commercial vehicle, road surface condition and the road gradient. The second part is to apply correction to the basic L_{10} level as appropriate for a specific site for the effects of distance from the road, nature of the ground surface (soft or hard), intervening obstructions like barriers, reflection effects etc

In applying the CRTN for the prediction of road traffic noise, one would need to know detail information like the alignment of roads in concern, the road surfacing materials, the volume of traffic using the road and their speeds, its geometrical relationship with the residential developments in the vicinity, whether there are intervening structures in between etc. To provide a simplified prediction tool and at the same time without compromising the accuracy of the prediction results, calculations based on full analytical equations would be avoided. This simplification also applies to the calculation of potential barrier attenuation due to presence of roadside barriers.

3.3 The Potential Barrier Correction adopted in the CRTN

The CRTN considers the barrier screening effect of intervening obstruction such as buildings, walls, purpose-built noise barriers etc. The basic calculation for the noise attenuation by a barrier refers to a barrier parallel to the road and shielding the whole of the length of the road from the reception point. In general, the screening effect depends on the relative positions of the source position, the receiver location and the diffraction edge of the intervening obstruction.

At the time when developing the CRTN, there were numbers of full analytical solutions for obtaining screening effect (with or without ground effect) available for compiling the potential barrier correction chart. Delany et al however considered that, these full analytical solutions were complex even discarding ground-reflection effects influence for both screened and unscreened noise levels and time consuming for day-to-day predictions. As such, an empirical approach worked out by Maekawa was adopted to develop the potential barrier correction for the CRTN [53].

Whilst the CRTN intends to provide procedures for assessing traffic noise impact, there is a need to focus on some generalized cases for the ease of calculation but without compromising the assessment results. Therefore, the objective at that time when establishing the CRTN was to specify the screening to be expected at any point due to an infinitely long barrier erected parallel to a straight and level road. To materialize this, it is necessary to make some assumptions in order to keep the prediction technique simple, in particular, that ground effects can be ignored when estimating the shielding of long noise barriers. From field data collected, this appears a valid approximation for most situations of practical importance.

In the absence of any mathematical formula representing Maekawa's chart at that time, Delany considered appropriate to have polynomial approximations to Maekawa's chart through least-squares methods with x = $\log(2\delta/\lambda)$ as the independent variables and dB reduction as dependent variables [53]. δ is path difference between the sound path from source to reception point through edge of the barrier and by direct path; and λ is the wavelength of sound. In the shadow zone, a 7^{th} order polynomial was found necessary while a 5^{th} order polynomial would be sufficient for illuminated zone. The polynomial coefficients, range of validity, and standard error of the estimation of dB reduction in graphical results are in Table 3.1. Kurze and Anderson published the mathematical equation to simulate Maekawa's chart in 1970 which was in parallel to Delany's study. Comparison of the polynomial expression with Kurze and Anderson

Equation or formula indicates very close resemblance [45].

As traffic noise would be regarded as a line source, it was found necessary to have adjustment in certain form. A series of closely spaced single stationary pure-tone point sources using a typical octave-band vehicle-noise spectrum were used in the field analysis to verify the barrier attenuation for a range of barrier heights and source / receiver separations (in excess of 3 dB(A) / double distance associated with cylindrical spreading). The analysis included applying standing A-weighting to the theoretical calculation using Maekawa's chart (the equivalent polynomial expressions) and the screening effects were normalized reasonably accurately in terms of path difference δ in meters. Again, a 7th order polynomial was found necessary while a 5th order polynomial would be sufficient for illuminated zone. Delany et al included the barrier attenuation correction as a chart in the CRTN for evaluation of the potential barrier correction (Figure 3.1) [11, 53].

This potential barrier chart developed by Delany et al was similar to that of the Maekawa's chart but a specific type of source spectrum was assumed so the frequency distribution was automatically included in the chart. This barrier attenuation correction chart was very handy for use as what users needed to know were the geometry relationship between the site, the road and the intervening obstruction. Apart from the barrier attenuation correction chart, the CRTN also includes polynomial expressions for potential barrier correction in both shadow and illuminated zones and dB(A) reduction values for path differences calculated to the nearest 0.01 meters. The availability of these simple polynomial expressions would greatly facilitate the evaluation of screening effects due to a wide range of noise barriers.

As stipulated in the CRTN, the noise source is assumed to lie at 3.5m from the edge of the nearside kerb of the road and 0.5m above the ground. The noise level L_{10} at the observation position is calculated following the procedures in the CRTN but discarding the effect of barrier. Then, the Chart in Figure 3.1 is used to obtain a correction due to the barrier attenuation and the value is then subtracted from the predicted basic L_{10} level. It should be noted that the barrier correction is sensitive to the value of δ and as a result, reliable corrections can best be achieved by calculation of δ from the geometry of the situation rather than by scale drawing.

3.4 Critical Examination of the Potential Barrier Correction adopted in the CRTN

The CRTN provides correction of barrier attenuation due to presence of intervening obstruction like thin barriers. The basic principle of noise attenuation adopted is Maekawa's chart. Instead of calculating the attenuation, frequency by frequency, the correction is an A-weighted attenuation. No allowance is made for differences between spectra, and like most of the CRTN procedure, the simplification appears to have been made statistically [73].

Maekawa's work was well established for predicting attenuation effect (or Insertion Loss (IL)) of sound behind rigid, thin and semi-infinite barriers. Maekawa conducted tests using a spherical spreading pulsed tone of short duration in an anechoic chamber. The exhaustive experimental works and the comprehensive set of data were published as a chart containing a single curve that provides IL versus a single parameter known as Fresnel Number (N_1). The set of data included the receiver in both the shadow and the illuminated zones [44, 45, 46, 47].

In Maekawa's measurements, both experimental data in the shadow zone and the illuminated zone were obtained. For illuminated zone, a negative value of N_1 was used to signify that the receiver is located in the illumination zone. According to Maekawa's chart, the attenuation is 5 dB for N_1 = 0. At this situation the source is just visible over the top of the barrier. For N_1 < 0 the receiver is in the illuminated zone and the attenuation quickly drops to zero.

In 1970, Kurze and Anderson [45] provided a mathematical description of Maekawa's chart as follows:

where N_1 is the Fresnel Number

$$IL = 5 + \log \frac{\sqrt{2\pi N_1}}{\tanh \sqrt{2\pi N_1}} \tag{3.1}$$

The Maekawa's chart and the corresponding Kurze and Anderson formula are extensively used within the noise control engineering community. The main advantage is their simplicity without compromising the accuracy of the predictions. However, both Maekawa's chart and Kurze and Anderson formula predict only the amplitude of the attenuation and no wave interference effects will be predicted [45].

3.4.1 Menounou's Recent Works in Modifying Maekawa's Chart

Recently, Menounou [46] studied Maekawa's chart and particularly noted that in some cases, Maekawa's chart gives predictions that deviate largely from experimental data and analytical solutions when the source or receiver is very close to or at the barrier surface, or when the receiver is very close to or at the shadow boundary. Details about Menounou's modifications of Maekawa's chart and Kurze & Anderson formula have been provided in Chapter 2 and hence would not be repeated here. Menounou's modifications of Maekawa's chart and Kurze and Anderson formula appear to give sensible predictions of the attenuation of the thin screen in most practical cases of interest and provide reasonably accurate predictions. With these findings, there is a need to review the Potential Barrier Correction Chart of the CRTN so that more accurate prediction of potential barrier correction can be incorporated.

3.5 The Re-construction of the Potential Barrier Correction Chart in the CRTN

To achieve a meaningful review of the potential barrier correction chart of the CRTN, it is necessary to establish the way how the potential barrier correction chart was developed or constructed at the time when the CRTN was developed. Although report of National

Physical Laboratory [53] provides information how Delany et al developed the barrier attenuation chart adopted in the CRTN, no further details regarding the typical octave-band vehicle-noise spectrum can be found. In this respect, further literature searches would be necessary. Delany et al remarked that the attenuation correction chart in the CRTN was developed based on A-weighted vehicle noise spectrum with reference to Maekawa's chart (which was from pure-tone point sound without ground-plane) and compared with the relationship between the assumed source location and the unobstructed distance attenuation. The process assumed some transfer function between attenuations due to the presence of barrier and distant separation in unobstructed situation. Delany et al considered that there was more than one way of making such a transfer. One of the transfer functions considered by Delany is from Scholes.

Scholes, one of the authors who developed the CRTN, conducted extensive studies of barrier attenuations on traffic noise by comparing theoretical prediction based on Maekawa's chart with the actual site measurements. Scholes et al [58, 59] conducted measurements to obtain the experimental results for a source (loudspeaker) at 0.7m high at two distances, 10m & 25m from barriers; for 4 barrier heights, i.e. 1.8m, 3m, 3.7m and 4.9m; for four receiver distances, i.e. 15m, 30m, 60m and 120m, for 5 receiver heights at each distance, i.e. 15.m, 3m, 6m, 9m and 12m and for the six octave bands centered on 125Hz to 4Khz. Scholes assumed spectrum shown in Figure 3.2 which was measured at 4m from the edge of the nearest carriageway of a six-lane motorway and it referred to the peaks of the traffic noise. The reductions of traffic noise peaks were calculated from the measured reductions by modifying the received spectra, with and without the barrier, to take into account the differences between the spectra, at the barrier position, of the loudspeaker source used for the measurements and of motorway noise peaks. These modified spectra were each combined to give the screens and unscreened levels in dB(A) and the reductions were given between these two sets of levels. The attenuations were calculated in the similar manner except that, by definition, the unscreened levels were based only on the spectrum of motorway noise peaks at the top of the barrier, and distance.

The theoretical values the spectrum shown due to motorway noise source was reduced in accordance with the theoretical values of barrier performance for each receiver position, using Maekawa's chart. The differences between the A-weighted totals of the screened and unscreened spectra at each position gives the theoretical values in dB(A) and on this basis, Scholes et al developed a design curve in Figure 3.3 to predict attenuation of noise barriers [58].

Scholes was also concerned with the comparison of noise Peak and L_{10}. His works showed that for unscreened reception position, L_{10} exceeded the average of the peaks by 0.1 dB(A) on average. For partially screened reception points, L_{10} exceeded the average of the peaks by 0.6 dB(A) on average and by 0.5 dB(A) for the fully screened situations. In essence, Scholes considered the differences between L_{10} and the average peak level ranged from 0 to

1 dB(A). Thus, the both screened and unscreened dense motorway traffic, L_{10} is practically the same as the average peak level and, hence the design curve in Figure 3.3 could be used for L_{10} [58].

Figure 3.4 compares the Potential Barrier Correction Chart of the CRTN with the design curve by Scholes indicates that two curves are similar for a path difference is 0.03m and smaller. Beyond that, Scholes' design curve exhibits higher attenuation up to path difference of 3m.

Attempts had been tried modifying the spectrum of Scholes' design curve to come up with new attenuation curve and the end results appear to be exactly the same as the potential barrier correction curve in the CRTN (as shown in Figure 3.5). It is appropriate to argue that the revised spectrum can be used in conjunction with Maekawa's Chart to re-construct the potential barrier correction curve in the CRTN.

Taking similar argument, one can employ the same revised spectrum to calculate a new set of potential barrier correction chart in the CRTN based on Menounou's new set of equations in modifying Maekawa's chart to obtain a more accurate and improved calculation of barrier IL.

3.6 A New Chart as Modification to the Potential Barrier Correction Chart in the CRTN

Following the same procedures in re-constructing the potential barrier attenuation chart in the CRTN, a new chart based on Menounou's improvement of Maekawa's chart (or Kurze and Anderson Equation improved by Menounou) can be constructed. The single potential barrier attenuation chart in the CRTN gives IL value at particular path difference. The new chart is a family of curves and each curve corresponds to a different "path difference" due to image source and the receiver point and provides insertion loss (IL) for a particular path difference between real source and the receiver point. As discussed above, Menounou refined Kurze and Anderson formula leading to:

$$IL = IL_c + IL_{sp} \qquad (3.2)$$

The discussions about IL_c and IL_{sp} can be found in Chapter 2. As IL_{sp} varies with the ratio of L/R_1, it would be difficult to have a family of curves combining IL_c & IL_{sp}. Whilst traffic noise could be categorized as line source in terms of characteristic, therefore, calculation of IL_{sp} for simulating curves for the CRTN (or traffic noise) would base on cylindrical waves. When examining IL_{sp} in details, one can determine the upper and lower bound to simplify the development of family of curves. For the lower bound, L would be equal to R_1 (i.e. receiver on shadow boundary) and IL_{sp} becomes 3dB. As the largest path difference used in the potential barrier attenuation chart in the CRTN is 3m, this could be used to establish as the upper limit of the case under study. In other words, in any event, one can set that $L - R_1$ will not be larger than 3m. It is useful to know that under the CRTN, source would be located at 0.5m above ground and 3.5m from the nearside kerb of the road. The smallest R_1 would exist when barrier located right at the road curb and the receiver locates immediately right behind the barrier and is 0.5m high. For this configuration, IL_{sp} becomes 4.56 dB. For a more realistic approach, barriers would usually be erected at 1m from the other side of road curb and receiver would be at least 1m from barriers. Therefore, with this configuration, IL_{sp} becomes 4.06 dB. With the argument, one can assume that IL_{sp} lies between 3 and 4 dB. For a conservative calculation of IL, one may just assume IL_{sp} is 3 dB.

Based on the above analysis, one can construct the family curve of IL against path difference in the similar form as the potential barrier attenuation chart in the CRTN when incorporating the 3 dB (as IL_{sp}) in promulgating the family of IL_c curves. Figures 3.6 & 3.7 show the IL curves based on this conservative approach. Once the geometric relationship between the road and the receivers is available, the overall IL can easily be calculated based on the family of curves.

3.7 The Application of the modified Barrier Correction Chart in Dense High-rise Cities

To illustrate the applicability of the family of IL curves derived for the CRTN based on Menounou's improved Kurze and Anderson's formula (or equivalent to improved Maekawa's chart), the following hypothetical scenarios are used.

3.7.1 The First Case Study

Assuming that a 3m high barrier locates at 1m from the road curb and receivers locate at 5m, 10m, 25m, and 50m of the other side of this 3m high barrier. The elevations of the receivers are at 1m, 4m, 7m, 10m etc. (3m interval) to represent receivers at different heights of residential building as long as they are within the shadow zone of the 3m barrier. IL at each receiver point is calculated using the potential barrier attenuation chart in the CRTN and the new family of IL curves developed following the discussions in the previous sections. For independent checking, IL values at each receiver point would be calculated using solution by Pierce [42]. The calculation would further be extended to points along shadow boundary. The configuration of road traffic, barrier and receivers are shown in Figure 3.8 and the IL values calculated using potential barrier attenuation chart in the CRTN, the new family of IL curves and solution by Pierce are shown in Table 3.2.

3.7.2 The Second Case Study

The second case is similar to the first case except that the barrier is 5m high instead of 3m high. The configuration of road traffic, barrier and receivers are shown in Figure 3.9 and the IL values calculated using potential barrier attenuation chart in the CRTN, the new family of IL curves and Pierce Equation are shown in Table 3.3.

3.7.3 The Results of Case Studies

With respect to Tables 3.2 & 3.3, one can easily identify that the potential barrier attenuation curve adopted in the CRTN tends to have under-estimated the IL by as high as 2.3 dB(A). The most noticeable situation is at the region close to shadow boundary. The IL at shadow boundary is about more than 1 dB(A) higher than the 5 dB(A) from the potential barrier attenuation curve from the CRTN.

3.8 Summary

In the present chapter the following works have been done:

1. Based on Menounou's recent modification of Maekawa's Chart, the potential barrier chart adopted by the CRTN is modified;
2. The new chart is a family of curves and each curve corresponds to a different "path difference" due to image source and the receiver point and provides insertion loss (IL) for a particular path difference between real source and the receiver point; and
3. Two case studies conducted and found that the original potential barrier chart adopted by the CRTN tends to under-estimate IL as high as 2.3 dB(A) in most region and by more than 1dB(A) in region closes to shadow boundary.

Term	**Coefficient**	
	Shadow Zone	**Illuminated Zone**
X^0	+14.55	+ 0.06
X^1	+ 7.58	- 0.109
X^2	+ 2.557	+ 0.815
X^3	+ 0. 762	- 0.479
X^4	+ 0.1820	- 0.3284
X^5	- 0.1412	- 0.04583
X^6	- 0.11237	-
X^7	- 0.019954	-
Range of Validity	$-3 \leq x \leq +1.2$	$-4 \leq x \leq 0$
Standard Error	0.58 dB(A)	0.12 dB(A)

Table 3.1 - The polynomial coefficients, range of validity, and standard error of dB reduction considered by Delany et al in the polynomial approximations to Maekawa's chart through least-squares methods with $x = \log(2\delta/\lambda)$ as the independent variables

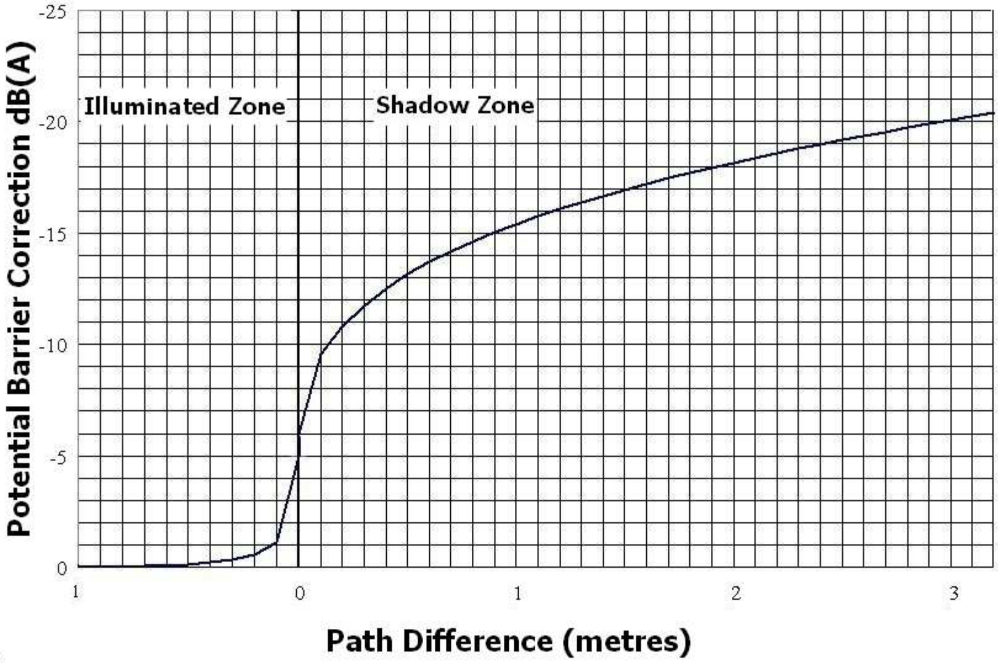


Figure 3.1 - barrier attenuation correction developed by Delany et al and adopted in the CRTN for evaluation of the potential barrier correction

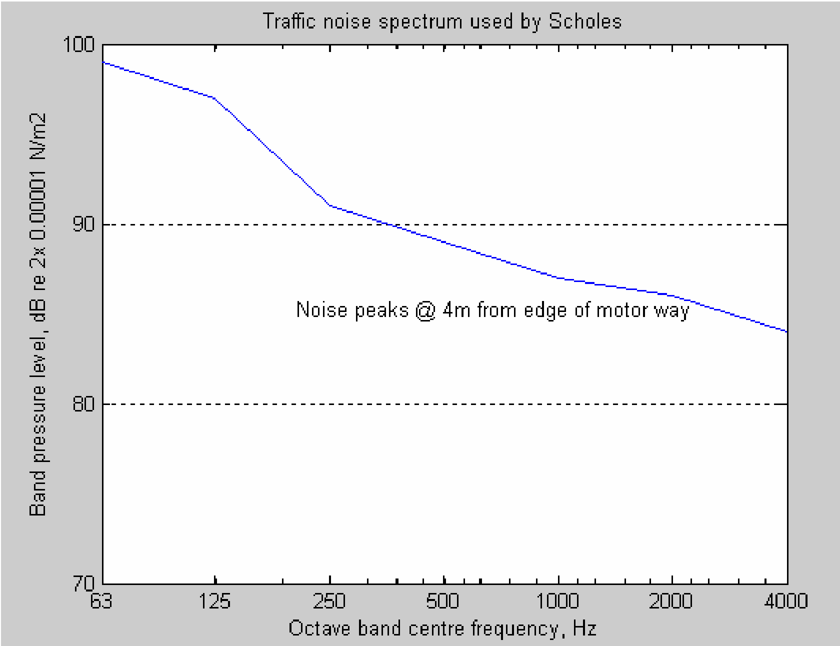


Figure 3.2 - Traffic noise spectrum used by Scholes

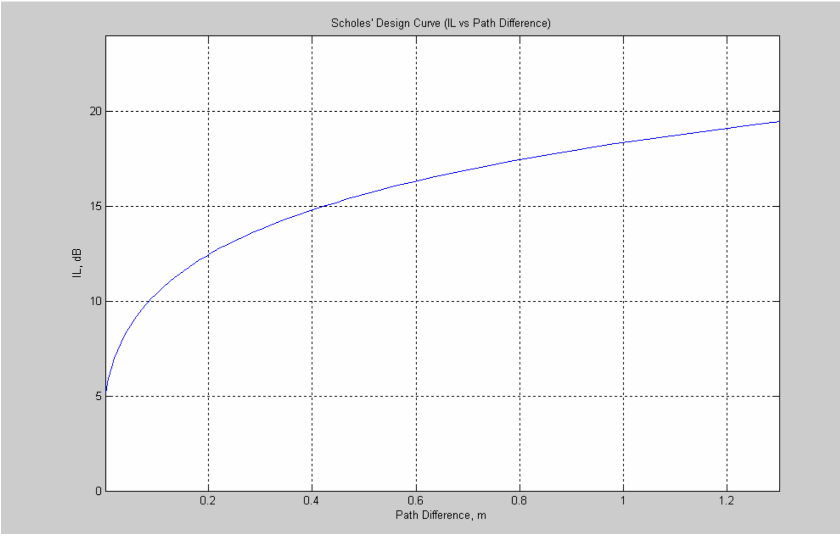


Figure 3.3 – Scholes' design curve for prediction of Insertion Loss (IL) of barriers

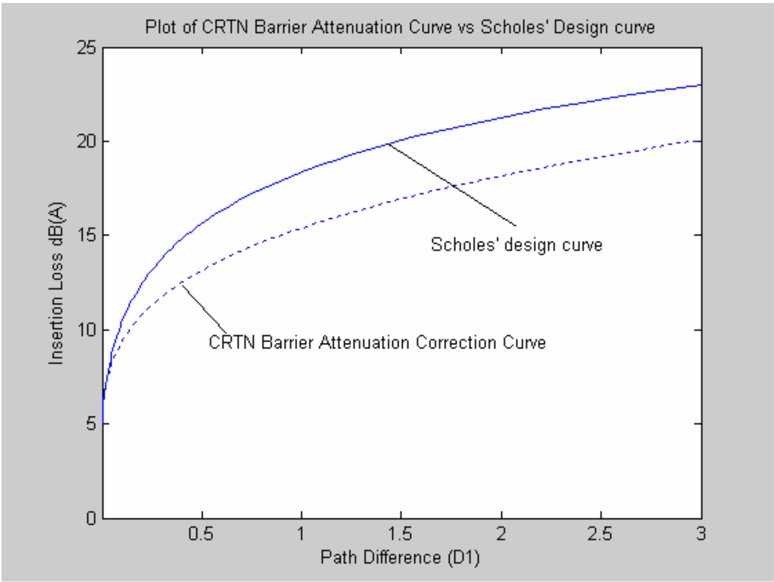


Figure 3.4 - Comparison between attenuation barrier correction charts in the CRTN with Scholes' Design curve

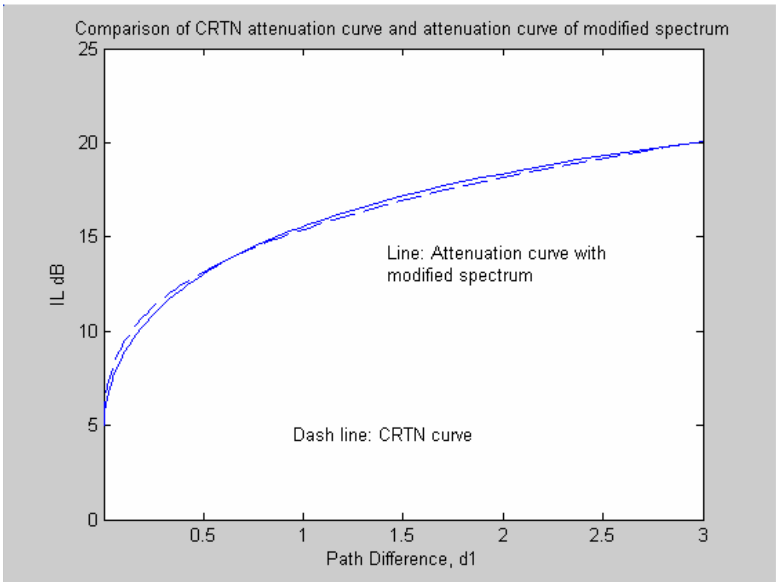


Figure 3.5 - Comparison between potential barrier correction chart in the CRTN with attenuation curve developed by modifying Scholes' traffic noise spectrum

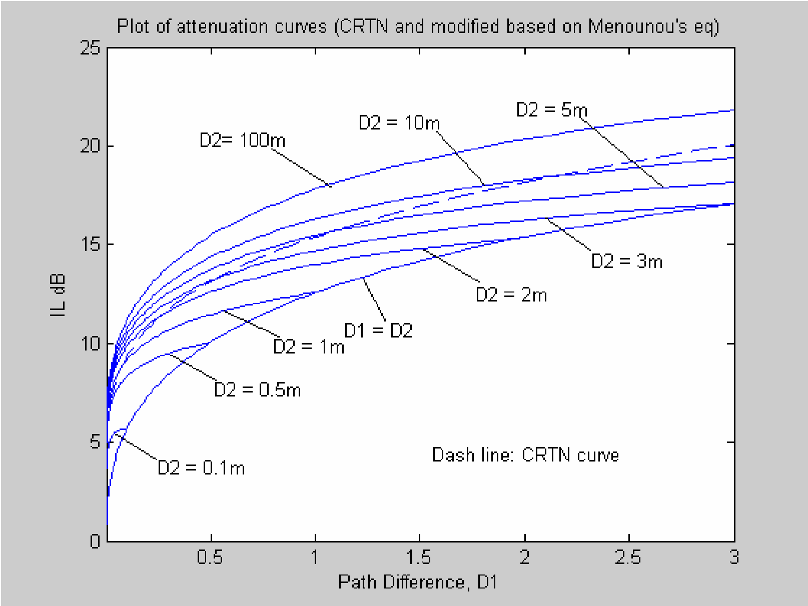


Figure 3.6 - A new set of family of attenuation (or insertion loss) curves developed based on Menounou's work taking into account the image source for the use in the CRTN. Scale of path difference between real source and receiver is in linear. Dotted line shows the potential barrier attenuation chart in the CRTN.

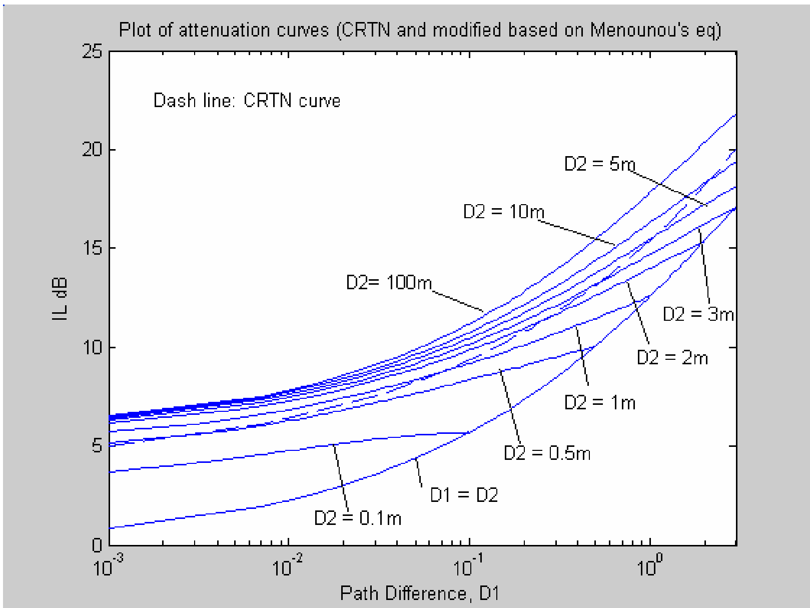


Figure 3.7 - A new set of family of attenuation (or insertion loss) curves developed based on Menounou's work taking into account the image source for the use in the CRTN. Scale of path difference between real source and receiver is in logarithm. Dotted line shows the potential barrier attenuation chart in the CRTN.

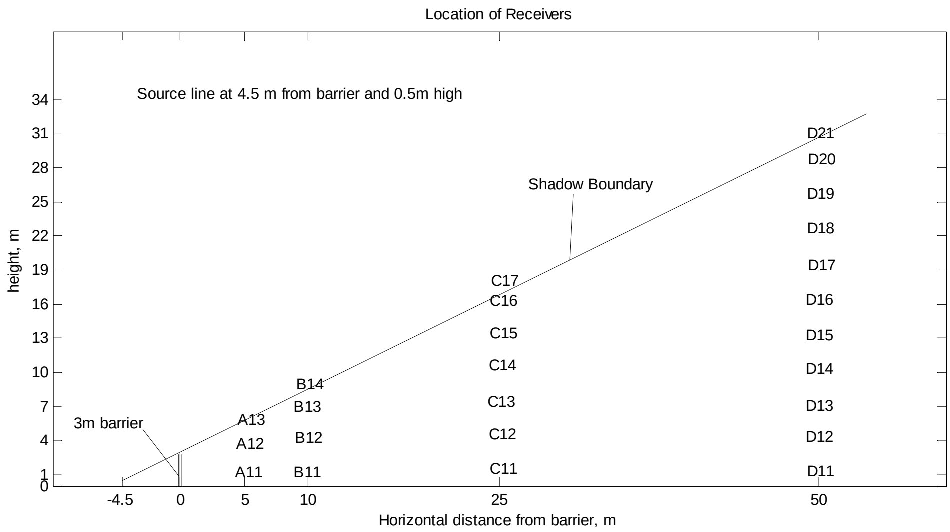


Figure 3.8 - Positions of noise source and receivers adopted in the first case study

Receiver Locations	IL from the CRTN Attenuation Curve, dB(A)	IL from the modified Correction Curve, dB(A)	IL from Pierce Equation, dB(A)
A11	15.5	16.1	16.1
A12	9.7	11.6	11.5
A13	5	6.9	6
B11	14.8	15.7	15.6
B12	11.6	13.4	13.4
B13	7.5	9.8	9.8
B14	5	6.1	5
C11	14.3	15.2	15.2
C12	12.9	14.4	14.4
C13	11.4	13.2	13.2
C14	9.7	11.6	11.6
C15	7.7	9.9	10
C17	5	6.1	5.8
D11	14.1	15.3	15.3
D12	13.4	14.6	14.7
D13	12.7	14.1	14.2
D14	11.9	13.3	13.3
D15	11	12.8	12.8
D16	10.1	12.2	12.3
D17	9.2	11.4	11.5
D18	8.2	10.3	10.4
D19	7.1	9.2	9.4

D20	5.6	7.5	7.6
D21	5	6	5.7

Table 3.2 - Values of Insertion Loss (IL) calculated using different charts and equation in the first case study

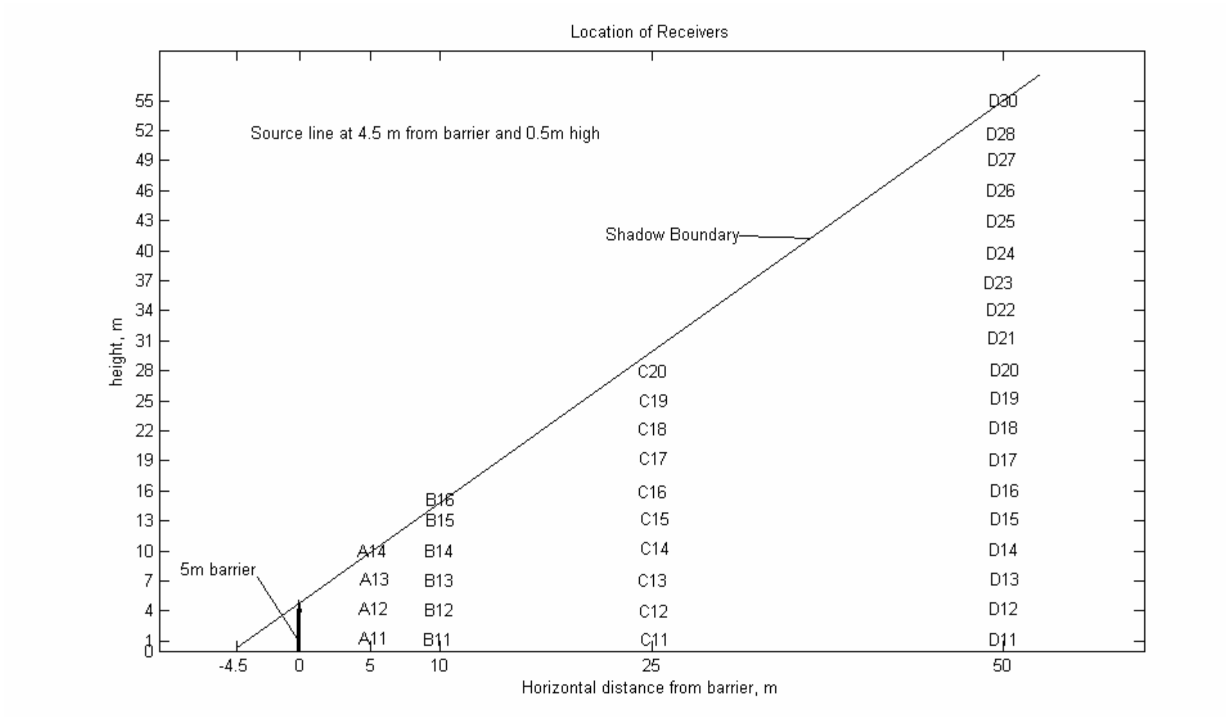


Figure 3.9 - Positions of noise source and receivers adopted in the second case study

Receiver Locations	IL from the CRTN Attenuation Curve, dB(A)	IL from the modified Correction Curve, dB(A)	IL from Pierce Equation, dB(A)
A13	11.2	12.6	12.6
A14	5	5.9	6.5
B13	14	15.1	15.1
B15	7.4	9.6	9.6
B16	5	6.3	6.5
C14	14.9	15.7	15.7
C17	10.7	12.6	12.6
C20	5.7	7.5	7.5
D14	16.6	16.9	16.9
D17	14.3	15.2	15.4
D20	12.2	13.6	13.6
D23	9.9	11.8	11.9
D26	7.5	9.8	9.9
D30	5	6.3	6.4

Table 3.3 - Values of Insertion Loss (IL) calculated using different charts and equation on representative receivers in the second case study

Chapter 4

An Evaluation and Investigation of Deterioration of Noise Reduction Characteristics due to Parallel Barriers in High-rise Cities

4.1 Introduction

It is common in dense high-rise cities that tall residential buildings are built on both sides of heavily trafficked roads. Barriers are constructed on both sides to alleviate road traffic noise impacts on the residents living in these high-rises buildings. The adoption of parallel barriers of both sides of heavily trafficked roads undoubtedly causes concern of multiple reflections due to presence of barriers on the opposite side of roads. These multiple reflected sound rays may travel to receivers directly or diffracted at top edges of the parallel barriers. This phenomenon, which leads to the degradation in noise reduction effectiveness of barrier, has been well recognized and studied by various researchers like Hutchins and Chew [76, 77, 78, 79]. Recently, Li & Kwok [75] developed a ray model based on image source approach to assess acoustic performance of parallel barriers in high rise cities.

The effect of parallel barriers has also been taken into consideration in road traffic noise prediction procedures like the CRTN issued by Department of Transport, United Kingdom in 1998 and “FHWA Highway barrier Design handbook” by “Federal Highway Administration” (FHWA) since mid 80s. A correction factor has been included in the CRTN for this purpose. Also, the FHWA advises that for parallel barriers, if the distance between the two barriers is kept at least 10 times their average height (i.e. a 10:1 width-to-height (w/h) ratio), the degradation in noise reduction effectiveness would be an imperceptible one. The traffic noise manual states that if a roadway width to wall height ratio between 10:1 and 20:1, the degradation should be between 0 and 3 dB, and if this ratio is less than 10:1 the degradation should be 3 dB or greater. To some extent, the noise reflection problem could be resolved by applying absorptive materials but this could induce aesthetic concerns [11, 84].

Despite these widespread interests, there are relatively few studies that consider the degradation effect of parallel barriers in an urban environment in greater details. The objective of the study is to look into the reflection and diffraction characteristics of parallel barriers with no ground reflection. The findings would be compared with the prediction practice used in the CRTN. The results would provide pointers for further and more in-depth study of this particular issue to facilitate potential modification of the CTRN procedures if any.

4.2 Formulation of the Problem

The study of the problem bases on the setting of 2 semi-infinite long thin barriers which are placed perpendicular to ground and separated in fixed separate distance all along. One of the barriers is called screening barrier while the other reflecting barrier. The noise source locates at a point between these 2 parallel barriers while receiver is behind the screening barrier. To facilitate and simplify the analysis, a rectangular co-ordinate system is chosen so that receiver and sources are located at the same vertical plane. For the purpose of the study, the real and image sources are included for consideration. Figure 4.1 shows a schematic diagram of the problem considered in this case and the system used in the analysis. The setting of parallel barriers (Barriers A & B) is that the real source S_1 locates at $X = X_1$ and X_2 from Barrier A (the screening barrier) & Barrier B (the reflecting barrier) respectively. Due to the presence of Barrier B, there are a number of image sources namely S_2, S_3, S_4, S_5 ……& S_n. Each of these image sources would produce sound rays as a result of multi-reflections of Barriers A & B and these sound rays could travel to the receiver sides. Depending on the locations of receivers, the sound rays from image sources could reach the receivers directly or through diffraction at top of Barrier A. For simplicity, the ground would be assumed as a non-reflecting one throughout this study.

Receivers could be located in various regions. The areas which of great interest are Regions A & B where receivers are in shadow region of the real source S_1. Sound rays due to presence of 2 parallel barriers would reach receivers in Region A through diffraction at top of Barrier A. In the case of receivers in Region B, the sound rays reflected from Barrier B etc could reach the receivers directly and through diffraction at top of Barrier A. In both cases, the barrier attenuation effect of Barrier A could be degraded substantially.

A host of parameters of parallel barriers would be considered in the analysis. One of these parameters, apart from heights of Barriers A & B and distance of receiver, is the distance X of sources (real and image) from Barrier A. Such distances could be represented as follows:

$X = X_2 + (n - 1)(X_1 + X_2)$ for n is even in number; &

$X = X_1 + (n - 1)(X_1 + X_2)$ for n is odd in number.

4.3 Theoretical Ray Model

The solution for thin barrier by Pierce would be adopted as the theoretical ray model for assessing the attenuation effect of parallel barriers. The validity of adopting the solution by Pierce in assessing the attenuation effect of parallel barriers has been confirmed by Li & Kwok [75] for the prediction of the insertion loss of hard parallel noise barriers which are placed in an urban environment would be adopted. Similar approach has also been used by Li & Tang [74] in studying the barrier effects in the proximity of tall buildings. The details of the solution for thin barrier by Pierce have been provided in Chapter 2 and hence would not be repeated here.

4.3.1 Region A

While sound rays due to presence of Barrier B could reach the receivers through diffraction at top of Barrier A, the total sound pressure at receiver would be the sum of all these diffracted sound rays plus the sound ray from real source S_1 diffracted at top of Barrier A. Mathematically, the total sound pressure could be represented as

$$\sum_{i=1}^{n} P_{diff} = P_{diff\,1} + P_{diff\,2} + P_{diff\,3} + P_{diff\,4} + P_{diff\,5} + + \ldots\ldots\ldots + P_{diffn} \quad (4.1)$$

In general expression, Insertion Loss (*IL*) can be expressed as

$$IL = 20\log\left|\frac{P_{diff}}{P_{dir}}\right| \tag{4.2}$$

Therefore, we can write IL of parallel barriers for Receiver R as

$$IL = 20\log\left|\frac{\sum_{i=1}^{n} P_{diff}}{P_{dir}}\right| \quad \text{or,}$$

$$IL = 20\log\left|\frac{P_{diff1}}{P_{dir}}\right|(1+\left|\frac{P_{diff2}}{P_{diff1}}\right|+\left|\frac{P_{diff3}}{P_{diff1}}\right|+\left|\frac{P_{diff4}}{P_{diff1}}\right|+ \quad .... \quad +\left|\frac{P_{diffn}}{P_{diff1}}\right| \quad) \tag{4.3}$$

Further manipulation changes the equation to:

$$IL = 20\log\left|\frac{P_{diff1}}{P_{dir}}\right| + 20\log(1+\left|\frac{P_{diff2}}{P_{diff1}}\right|+\left|\frac{P_{diff3}}{P_{diff1}}\right|+\left|\frac{P_{diff4}}{P_{diff1}}\right|+\cdots\left|\frac{P_{diffn}}{P_{diff1}}\right|) \tag{4.4}$$

The first part of equation (4.4) is the *IL* due to diffraction at the top of Barrier A alone. The second part of equation (4.4) is the effect of reflection rays due to presence of Barrier B and diffracted at top of Barrier A to Receiver. For all possible barrier configurations of X_1 and X_2, this second part could be interpreted as deterioration of noise reduction effectiveness of Barrier A due to presence of Barrier B.

4.3.2 Region B

The situation is similar to that of in Region A except that receivers in Region B would have direct line of sight with sound rays from the image sources in addition to the sound rays diffracted at the top of Barrier A. This would unavoidably cause substantial deterioration of noise reduction effectiveness of Barrier A than those in the Region A.

As such, two sets of sound rays from various sources (real and image sources) could be established. One set is due to those sound rays diffracted at top of Barrier A and could be represented mathematically as follows:

$$\sum_{i=1}^{n} P_{diff} = P_{diff1} + P_{diff2} + P_{diff3} + P_{diff4} + P_{diff5} + + \ldots\ldots\ldots + P_{diffn} \qquad (4.5)$$

The other set is due to the direct exposure from image sources and could be represented as:

$$\sum_{i=1}^{n} P_{dir} = P_{dir1} + P_{dir2} + P_{dir3} + P_{dir4} + P_{dir5} + \ldots\ldots + P_{dirn} \qquad (4.6)$$

Again, following that *IL* can be expressed as $IL = 20\log\left|\frac{P_{diff}}{P_{dir}}\right|$, IL for Receiver R can be represented as

$$IL = 20\log\left|\frac{\sum_{i=1}^{n} P_{diff\_i} + \sum_{i=1}^{n} P_{dir\_i}}{P_{dir}}\right|$$

or,

$$IL = 20\log\left|\frac{P_{diff1}}{P_{dir}}\right|(1+\left|\frac{P_{diff2}}{P_{diff1}}\right|+\left|\frac{P_{diff3}}{P_{diff1}}\right|+\ldots\ldots\left|\frac{P_{diffn}}{P_{diff1}}\right|+\left|\frac{P_{dir1}}{P_{diff1}}\right|+\left|\frac{P_{dir2}}{P_{diff1}}\right|+\ldots\ldots\left|\frac{P_{dirn}}{P_{diff1}}\right|)$$

or,

$$IL = 20\log\left|\frac{P_{diff1}}{P_{dir}}\right| +$$

$$20\log(1+\left|\frac{P_{diff2}}{P_{diff1}}\right|+\left|\frac{P_{diff3}}{P_{diff1}}\right|+\cdots\left|\frac{P_{diffn}}{P_{diff1}}\right|+\left|\frac{P_{dir1}}{P_{diff1}}\right|+\left|\frac{P_{dir2}}{P_{diff1}}\right|+\ldots\ldots\left|\frac{P_{dirn}}{P_{diff1}}\right|)$$

(4.7)

Again, the second part of equation (4.7) could be interpreted as deterioration of noise reduction performance of Barrier A due to presence of Barrier B.

4.3.3 Diffraction at the Top of Barrier A

For a semi-infinite long half plane thin vertical barrier locating on fully absorptive ground (see Figure 4.2), the sound field of diffraction ray in the shadow zone can be written as, according to Keller's geometrical theory of diffraction [85]:

$$P_{diff} = D(\frac{e^{ikR}}{4\pi R}) \tag{4.8}$$

where D is the diffraction coefficient, k is the wave number; R is the distance from source to receiver without the presence of the thin vertical barrier. Expressions of D have been given by many researchers. In this ray model, the solution by Pierce shown below is adopted [42]. Details of the solution of Pierce have been provided in Chapter 2 and hence would not be repeated here. For easy reference, the pressure of the diffracted sound wave would be represented as:

$$P_{diff} = (\frac{(1+i)}{2}(\frac{e^{ikL}}{4\pi L})\left[A_D(X_+) + A_D(X_-)\right] \tag{4.9}$$

where

$$A_D = \text{sgn}(X)\left[f(X) - ig(X)\right] \tag{4.9a}$$

$$f(x) = \left[\frac{1}{2} - S(X)\right]\cos\left(\frac{\pi X^2}{2}\right) - \left[\frac{1}{2} - C(X)\right]\sin\left(\frac{\pi X^2}{2}\right) \tag{4.9b}$$

$$g(x) = \left[\frac{1}{2} - C(X)\right]\cos\left(\frac{\pi X^2}{2}\right) + \left[\frac{1}{2} - S(X)\right]\sin\left(\frac{\pi X^2}{2}\right) \tag{4.9c}$$

$$X_+ = X(\theta_r + \theta_s) \tag{4.9d}$$

$$X_- = X(\theta_r - \theta_s) \tag{4.9e}$$

$$X(\Phi) = -2\sqrt{\left(\frac{2kr_s r_r}{\lambda L}\right)}\cos\left(\frac{\Phi}{2}\right) \tag{4.9f}$$

4.3.4 Direct Exposure to Sound Rays

The direct exposure sound wave could be represented as follows:

$$P_{diff} = D\left(\frac{e^{ikR}}{4\pi R}\right) \quad \text{where } D = 1 \tag{4.10}$$

4.4 Case Studies

To enable studying of the characteristics of multiple reflections due to the presence of Barrier B at various separating distances of 2 parallel barriers (Barriers A & B), the following cases adopting the ray model described above have been looked into. The parallel barriers are thin and infinite long 0.5m high vertical barrier. The source locates at (0.35m, 0.05m) at one side of Barrier A while receivers locate on the other side. The distance from source to top of Barrier A is 0.57m. For simulating the situation of parallel barriers, Barrier B which is another thin and infinite long 0.5m high vertical barrier locates at the same distance of 0.35m from source but on the other side of Barrier A. The distance progressively increases by a multiple of 0.35m so that a series of parallel barrier situation can be simulated. All surfaces of barriers are considered to be acoustically hard while ground is assumed as absorptive. Figure 4.3 shows the configuration of the case while Table 4.1 summarizes the positions of receivers in different case studies.

The theoretical ray model is applied to the four cases under study. The locations of Barrier B for the 4 cases are basically set following the same principle. For cases A & C, Barrier B would be placed at 8 different locations ($X_i = X_o$, 2 X_o, 3 X_o, 4 X_o, 6 X_o, 8 X_o, 11 X_o & 15 X_o) from source. For cases B & D, Barrier B would be set at 3 more locations (X_i = 20 X_o, 26 X_o & 33 X_o) in addition to those for cases A & C. The settings of Barrier B at different locations enable evaluation of how separation between Barriers A & B would affect the noise reduction performance of Barrier A for receivers in Region A & B.

By adopting the theoretical ray model discussed above, IL of each test of the 4 cases under study is generated. Figures 4.4 to 4.5 show the plots of IL against Frequency for receivers in Region A and B.

As discussed in equations (4.4) & (4.7), IL can be represented by two terms: the IL due to diffraction of Barrier A of real source and receiver alone and the deterioration effects due to the reflecting rays at the presence of Barrier B. To illustrate how the presence of Barrier B would affect the noise reduction effectiveness of Barrier A alone, IL of Barrier A alone (i.e. on real source and receiver) in each test of the 4 cases under study are also generated and compare with the IL generated from the theoretical ray model. Figures 4.6 & 4.7 show the Insertion Loss (IL) for receivers in Regions A & B. From the plots, the degradation of IL would decrease when separation between Barriers A & B increases.

To enable further analysis, the calculation of IL are also carried out in terms of amplitude only (i.e. incoherent summation of the contribution of all ray paths) as described by Maekawa et al and LI et al [44, 47]. On this basis, the IL of parallel barriers shown in Figure 4.1 is then given by:

$$IL = 10\log\left(10^{-\left|\frac{IL_1}{10}\right|} + 10^{-\left|\frac{IL_2}{10}\right|} + 10^{-\left|\frac{IL_3}{10}\right|} + 10^{-\left|\frac{IL_4}{10}\right|} + \ldots\ldots + 10^{-\left|\frac{IL_i}{10}\right|}\right) \tag{4.11}$$

Sensitivity tests conducted show that the broad band analysis resembles closely with the approach based on amplitude only. For simplicity, further evaluation of the deterioration of noise reduction effectiveness due to reflecting rays at Barrier B would follow the amplitude only approach. Also, as A-weighted level is more frequently used in our daily application of assessing road traffic noise, the IL in A-weighted level are generated for all 4 cases under study.

Figures 4.8 to 4.11 show the comparisons of IL of Barrier A alone with the calculation of IL using approach based on amplitude only for the 4 cases under study. Such comparisons also include that of the A-weighted level. The deteriorations of IL with presence of Barrier B for the 4 cases under study are shown in Table 4.2.

From Figures 4.8 to 4.11 and Table 4.2, it is noted that the deterioration of noise reduction effectiveness of Barrier A alone drops with increase of separation between Barriers A & B. When 2 parallel barriers are separated from real source by equal distance, the deterioration in the 4 cases under study are the greatest. When 2 parallel barriers are separated in large distance, the deterioration diminishes drastically and becomes insignificant. For scenarios A & B in which receivers located deep in the shadow zone region of Barrier

A (the screening barrier), deteriorations could be as high as 4 dB(A) (for r_r/r_s = 0.5547) and 7.8 dB(A) (for r_r/r_s = 2.113) (where r_r and r_s are the path lengths from receiver to top of the screening barrier and that from source to top of the screening barrier respectively). The deterioration is much higher for receivers further from Barrier A (remaining at same height from ground). Similar effects have been identified by Herman at el in 2002 in which he concluded, through actual site measurement, that reflections from parallel barriers have caused the overall increase in noise levels perceived by the distant receivers [83]. For scenarios C & D in which receivers located close to shadow boundary of Barrier A (the screening barrier) in which receivers would have direct line of sight to the reflecting ray from reflecting barrier. The deteriorations could be as high as 8 dB(A) (for r_r/r_s = 0.685) and 16 dB(A) (for r_r/r_s = 2.2804). Again, the deterioration is much higher for receivers further from Barrier A (remaining at same height from ground).

To allow further advancement of analysis, the corrections of IL (dB(A)) are plotted against different barrier configuration in terms of X_i/X_0 for the 4 cases under study on the basis of Table 4.2. The plots are in Figures 4.12 & 4.13.

The plots in Figures 4.12 & 4.13 show the trend of deterioration of noise reduction effectiveness of Barrier A alone with respect to receivers in regions A & B due to the presence of reflection rays at barrier B in the parallel barrier situation under study. The trends, however, do not enable development of formulae or equations for general uses. It is useful to note that the 4 cases under study have the similar parallel barrier configurations and location of source. The differences between the 4 cases are the locations of receivers. On this perspective, it is useful to take into account the distance between receiver and top of Barrier A into the analysis. In other words, it is useful to compare the 4 cases in a normalized manner. For the purpose of study, the barrier configurations in the 4 cases are normalized to the distance between receiver and top of Barrier A. Mathematically, the term $[(X_i/X_o)/r_r]$ is employed (where X_i & X_o are distance from source Barrier A and Barrier B respectively; and r_r is the distance from top of Barrier A to receiver). The corrections of IL (dB(A)) are further plotted against different barrier configuration normalized with receiver distance in terms of $[(X_i/X_o)/r_r]$ for the 4 cases under study. The plots are in Figures 4.14 & 4.15.

Although the trends shown in Figures 4.14 & 4.15 resemble closely to those in Figures 4.12 & 4.13, these provide opportunity for comparison of the IL Corrections in 4 cases after normalizations. For this purpose, the normalized plots for cases A & B in Region A are plotted together for exploration of possible development of useful formulae or equations for generalized use. Similar plots are conducted for cases C & D in Region B. As the results of the current case studies are very limited, it is inappropriate for deployment of such purpose and hence a dimension parameter of $(Xi/Xo)r_r$ is employed for such purpose. It is obvious from Figure 4.16 that there is a pattern of IL correction [dB(A)] for receivers in Region A & B in the 4 cases under study. This provides pointer for developing a dimensionless parameter in the further study in future.

4.5 Comparison with the CRTN

CRTN discusses the combined screening and reflection effects of parallel barriers of prediction of road traffic noise [11]. A correction for reflections could be calculated by using the following formula:

$$\text{Correction} = [1.5 + (\Delta_2 - \Delta_3)\{1 + \Delta_5 (\Delta_1 - 1)\}]\, \Delta_4 \qquad (4.12)$$

where

Δ_1 depends on relative height of the barriers and the height of receiver;

Δ_2 is a function of receiver height;

Δ_3 is the horizontal distance between receiver and the screening barrier (i.e. Barrier A in the study);

Δ_4 is a function of horizontal distance between 2 parallel barriers; and

Δ_5 is a function of the angle of the reflecting barrier (i.e. Barrier B in the study) to the vertical.

To evaluate the practicability of the ray model in actual situations, 2 cases shown below in Table 4.3 are studied separately using the ray model and the relative procedures contained in the CRTN for comparison. In these 2 cases, Barriers A & B are of 5m high. Source is located at 0.5m high and 3.5m from Barrier A. Barrier B is set a distance X_i from source.

Results from calculation using ray model and the relevant section of the CRTN are shown in Table 4.4 for comparison. Plot of IL Correction [dB(A)] vs Barrier Configuration / Receiver Distance are also shown in Figure 4.17.

It is noted from Table 4.4 and Figure 4.17 that there are differences between calculations from the ray model and the CRTN. For barrier separation is less than 30m, calculations from the CRTN in both cases E & F show that deterioration of noise reduction effectiveness of the screening barrier (Barrier A) alone are constants which are 1.9 dB(A) and 4.09 dB(A) for case E and F respectively. For barrier separation more than 30m, the difference are approximately 1 to 1.2 dB(A) for both cases E & F. It is useful to note that in the CRTN, when all parameters like barrier heights, distance between receiver and source to that of Barrier A remain unchanged, the factor that would affect the horizontal distance between 2 parallel barriers which is represented by Δ_4. Accordingly, Δ_4 is constant for distance between parallel barriers is less than 30m and hence the calculated IL correction in both cases E & F. There is no information in the CRTN indicating why Δ_4 is constant for distance between parallel barriers is less than 30m. However, it is useful to note that in actual situation, the width of a dual 3-lane road with hard shoulder would be 30m approximately. Although this is not indicated, it appears that parallel barriers were only assumed for trunk roads or expressway of dual 3-lane. For high-rise metropolitan cities like Hong Kong, barriers are commonly found erected at the central median of trunk roads or expressway for noise mitigation. This may not be the situations considered when the CRTN was developed.

As identified in the above case study, there is a concern in the adequacy of the CRTN in calculating deterioration of noise reduction effectiveness of parallel barrier system. Further study would be worth to review the CRTN in the context of parallel barriers in particular in the aspect of separation between parallel barriers is less than 30m.

4.6 Summary

In this Chapter the following works have been done:

1. Theoretical model based on recent works of LI & Kwok was developed for assessing deterioration of noise attenuation effect due to parallel barriers;
2. Initial investigations indicates that deterioration of noise attenuation depends on the distant separations between the screening and reflecting barriers, the larger the separations, the less deterioration; and
3. The current correction used in the CRTN for parallel barriers starts with 30m separations between screening and reflecting barriers which may not cover the situations in dense high-rise city like Hong Kong.

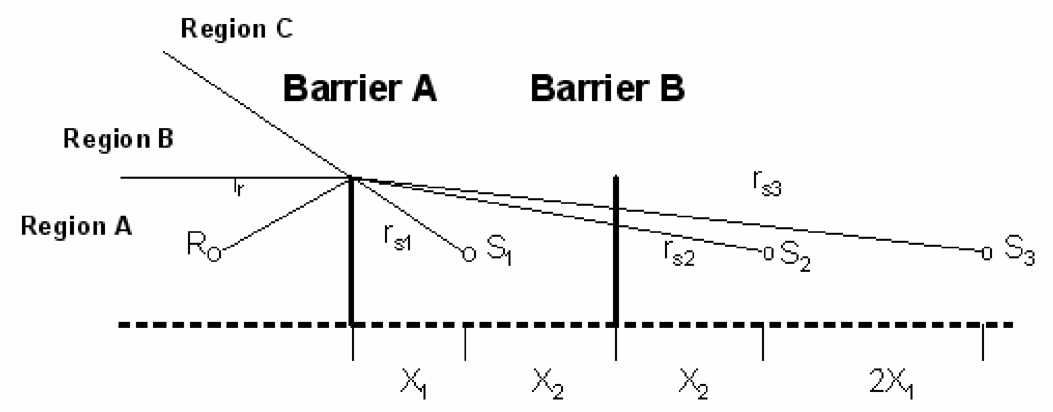


Figure 4.1 – Configuration of parallel barrier under study

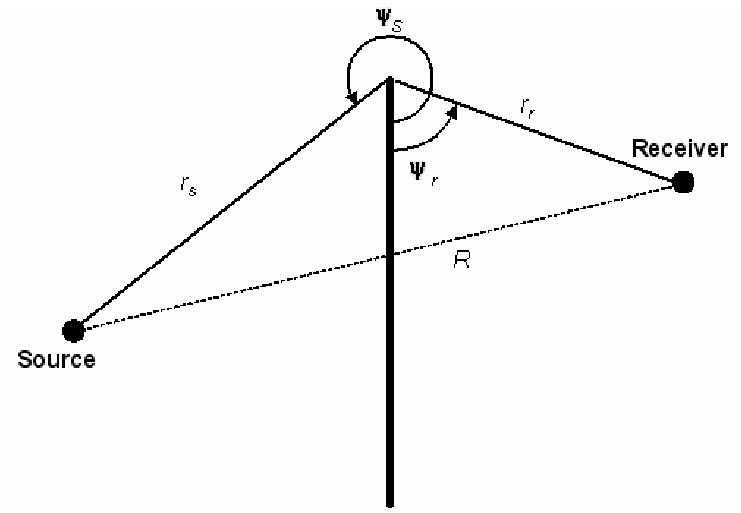


Figure 4.2 – The geometry of source and receiver in the vicinity of thin vertical barrier

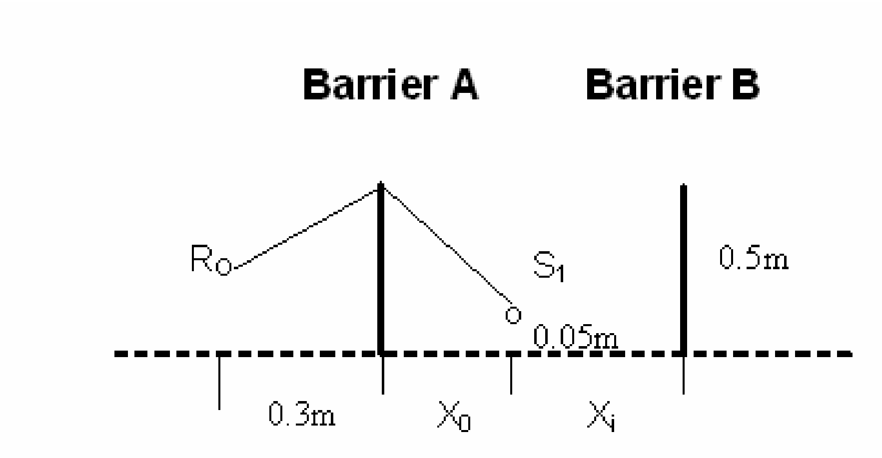
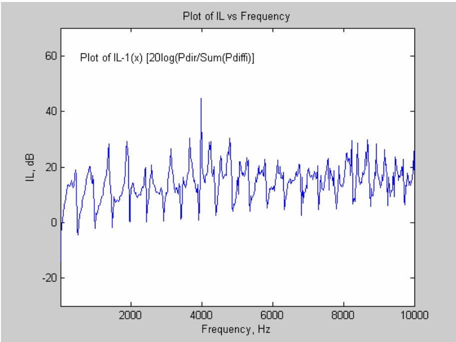
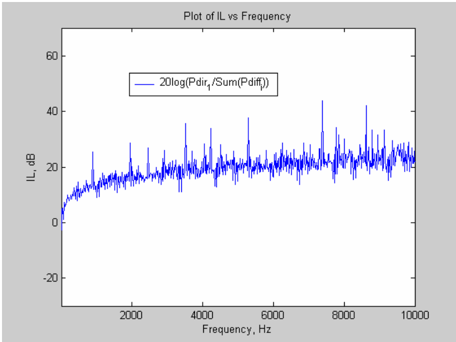


Figure 4.3 – Configuration of parallel barriers in the case studies

Case	**Position of Receivers relative to Barrier A**	**Receiver distance from top of Barrier A**	**Remarks**
A	0.4m high 0.3m away	0.3162m	Receiver in Region A, Ratio of r_r/r_s = 0.5547
B	0.4m high 1.2m away	1.2042m	Receiver in Region A, Ratio of r_r/r_s = 2.113
C	0.75m high 0.3m away	0.3905m	Receiver in Region B, Ratio of r_r/r_s = 0.685
D	1m high 1.2m away	1.3m	Receiver in Region B, Ratio of r_r/r_s = 2.2804

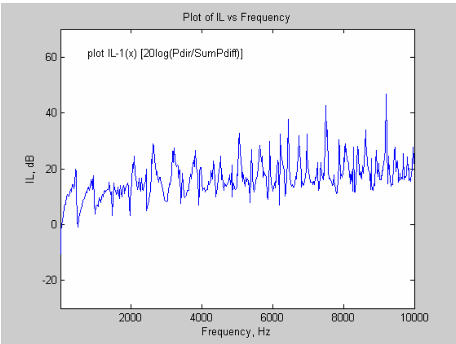
Table 4.1 - the positions of receivers in different case studies

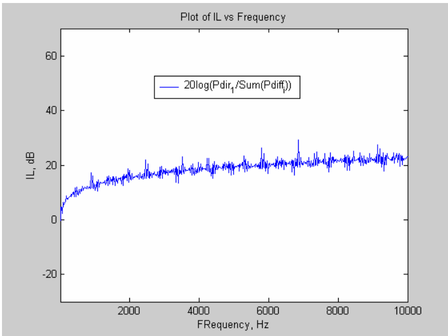




Case A: $X_i = X_0$

Case A: $X_i = 15X_0$

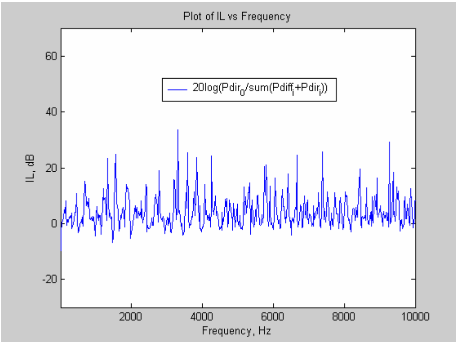




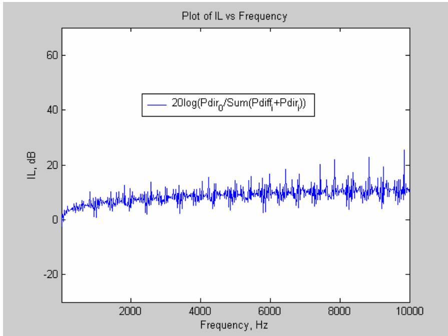
Case B: $X_i = X_0$

Case B: $X_i = 15X_0$

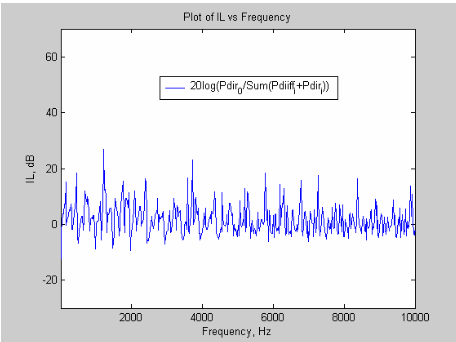
Figure 4.4 – Plot of IL vs Frequency for Receivers in Region A



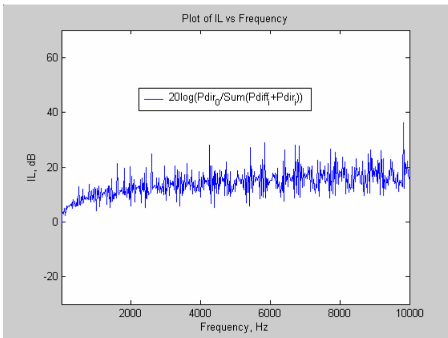
Case C: $X_i = 2X_0$



Case C: - $X_i = 15X_0$

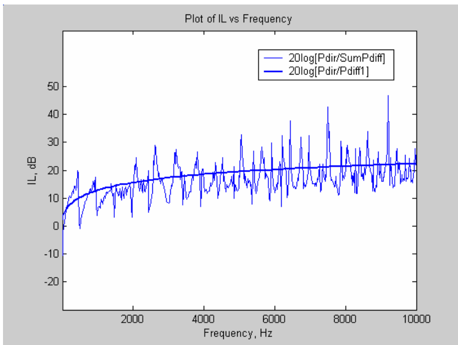


Case D: $X_i = 2X_0$

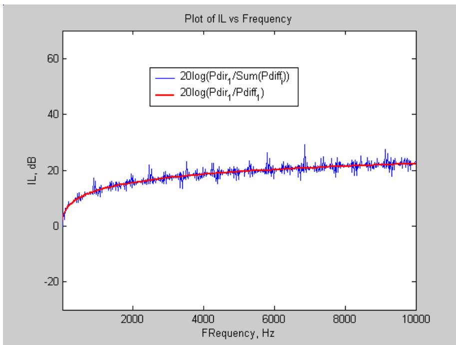


Case D: $X_i = 33X_0$

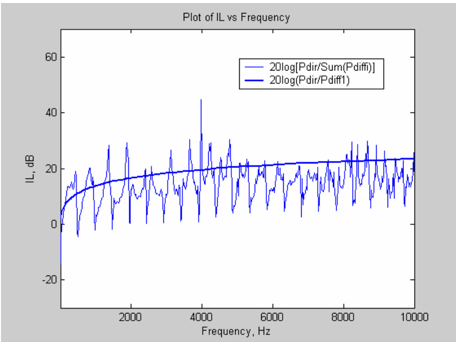
Figure 4.5 – Plot of IL vs Frequency for Receivers in Region B



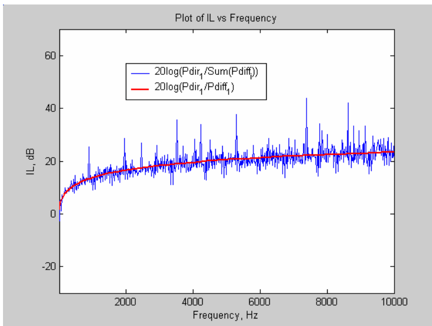
Case A: $X_i = X_0$



Case A: $X_i = 15X_0$

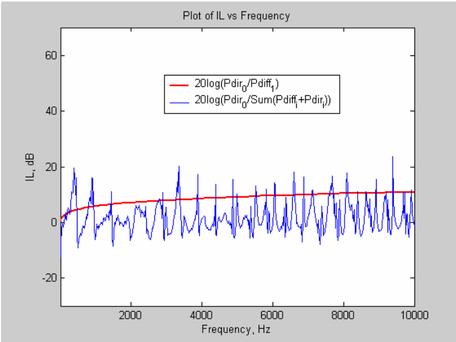


Case B: $X_i = X_0$

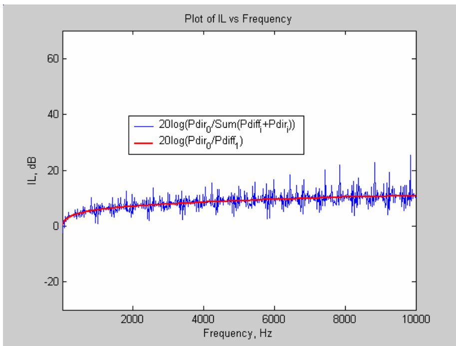


Case B: $X_i = 15X_0$

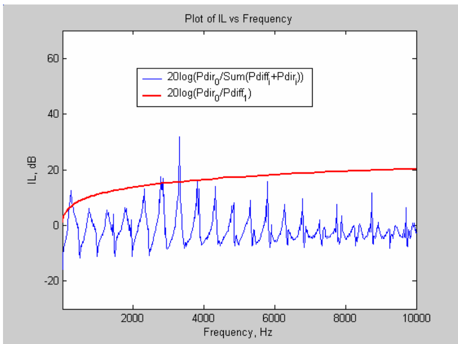
Figure 4.6 – Comparison of IL of Barrier A alone and with the presence of Barrier B for Receivers in Region A



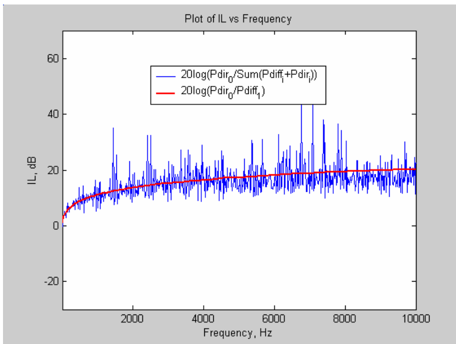
Case C: $X_i = X_0$



Case C: $X_i = 15X_0$

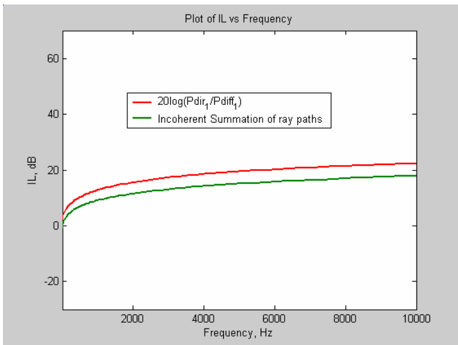


Case D: $X_i = X_0$

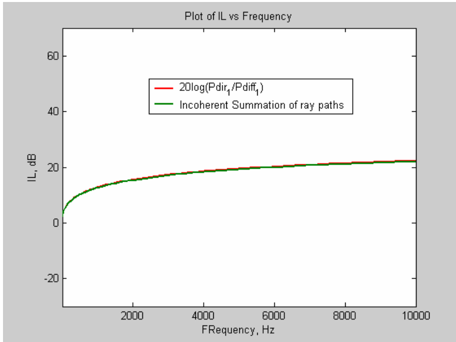


Case D: $X_i = 33X_0$

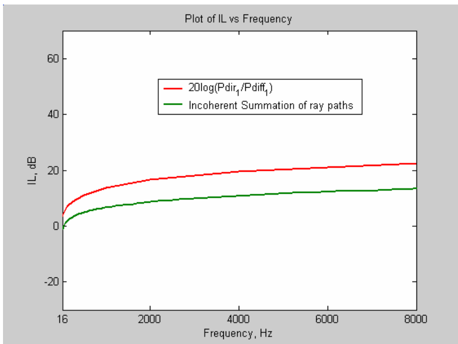
Figure 4.7 - Comparison of IL of Barrier A alone and with the presence of Barrier B for Receivers in Region B



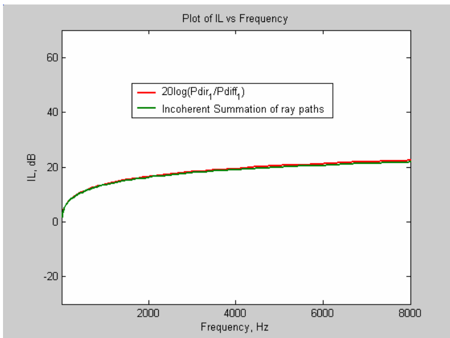
Case A: $X_i = X_0$



Case A: $X_i = 15X_0$

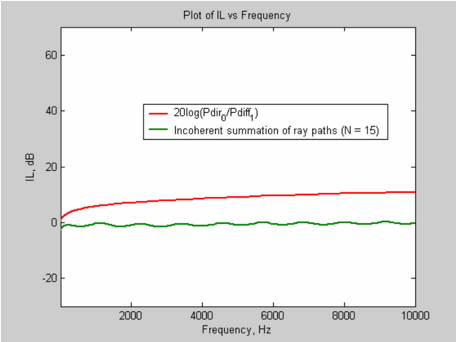


Case B: $X_i = X_0$

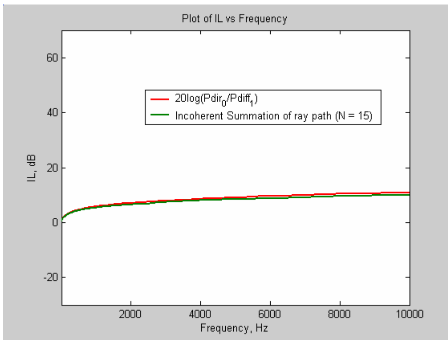


Case B: $X_i = 33X_0$

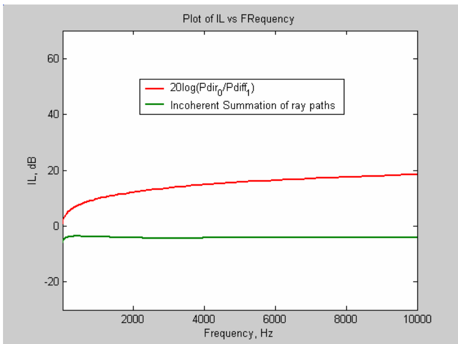
Figure 4.8 - Comparison of IL of Barrier A alone and IL using amplitude approach for Receivers in Region A



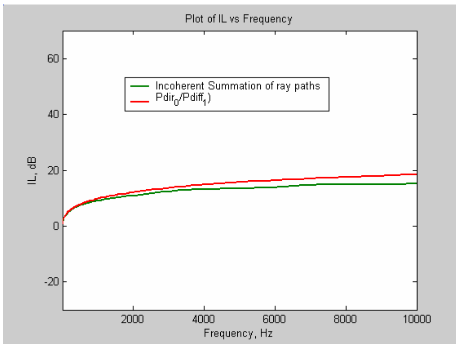
Case C: $X_i = X_0$



Case C: $X_i = 15X_0$

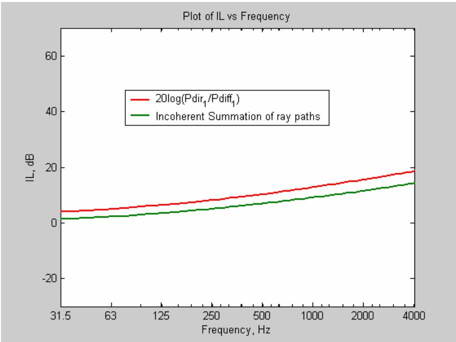


Case D: $X_i = X_0$

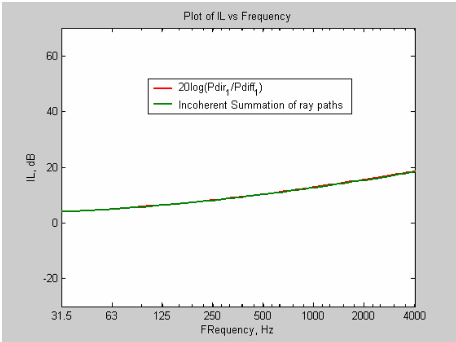


Case D: $X_i = 33X_0$

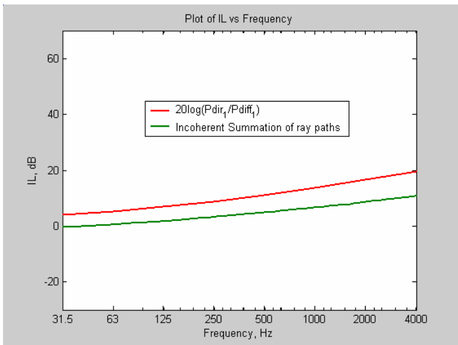
Figure 4.9 - Comparison of IL of Barrier A alone and IL using amplitude approach for Receivers in Region B



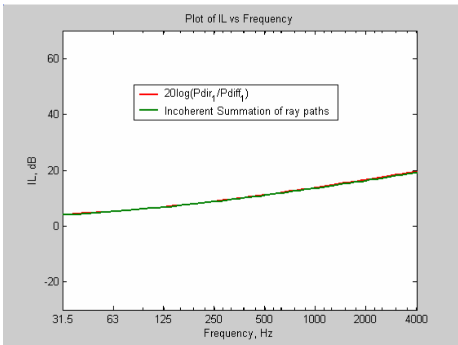
Case A: $X_i = X_0$



Case A: $X_i = 15X_0$

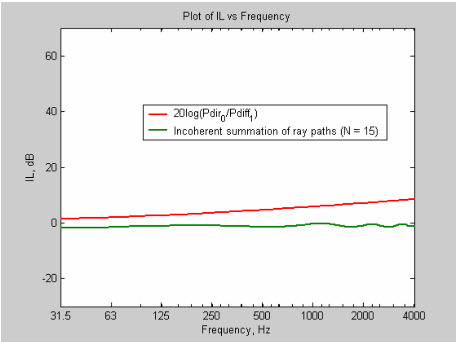


Case B: $X_i = X_0$

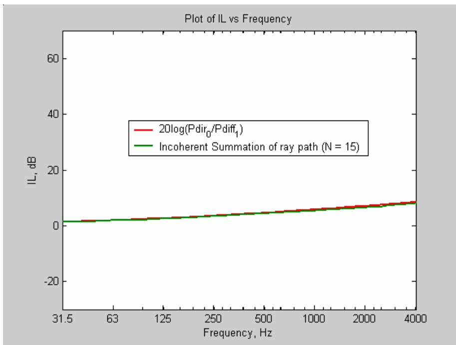


Case B: $X_i = 33X_0$

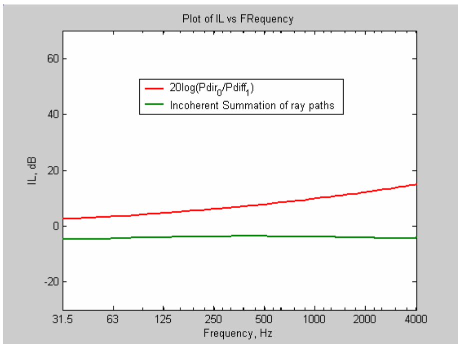
Figure 4.10 - Comparison of IL of Barrier A alone and IL using amplitude approach for Receivers in Region A (in octave band)



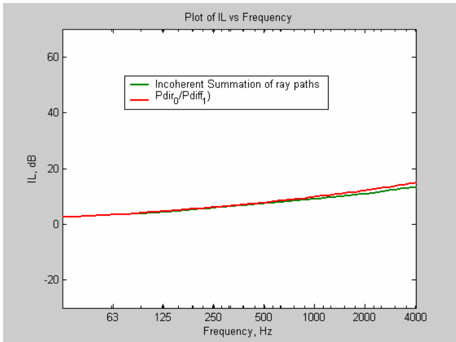
Case C: $X_i = X_0$



Case C: $X_i = 15X_0$



Case D: $X_i = X_0$

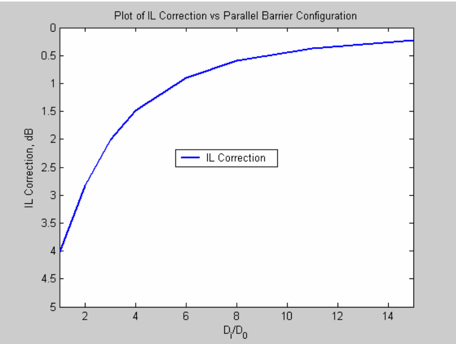


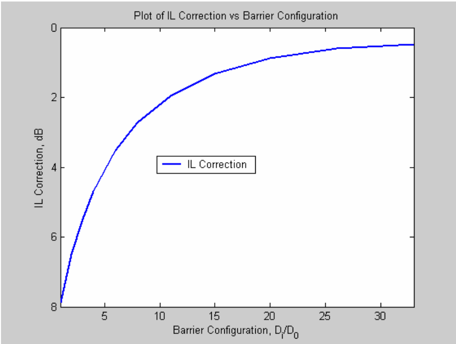
Case D: $X_i = 33X_0$

Figure 4.11 - Comparison of IL of Barrier A alone and IL using amplitude approach for Receivers in Region B (in octave band)

Test	X_i / X_o	Deterioration of IL due to presence of parallel barrier			
		Scenario A	**Scenario B**	**Scenario C**	**Scenario D**
1	1	-4.0	-7.7	-8.0	-16.5
2	2	-2.9	-6.5	-5.6	-12.5
3	3	-2.0	-5.5	-4.2	-11.4
4	4	-1.5	-4.7	-3.2	-10.5
5	6	-0.9	-3.5	-2.0	-8.2
6	8	-0.6	-2.7	-1.3	-6.7
7	11	-0.4	-2.0	-0.8	-4.5
8	15	-0.2	-1.3	-0.5	-3.7
9	20	NA	0.9	NA	-2.6
10	26	NA	-0.6	NA	-1.9
11	33	NA	-0.5	NA	-1.3

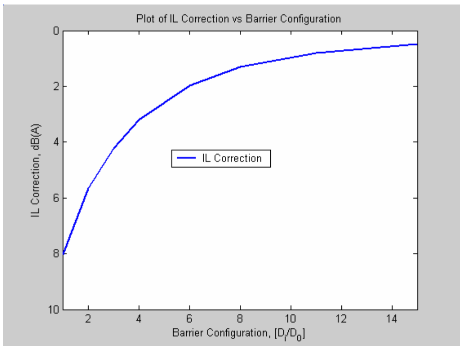
Table 4.2 – Deterioration of IL due to presence of parallel barriers for 4 cases under study

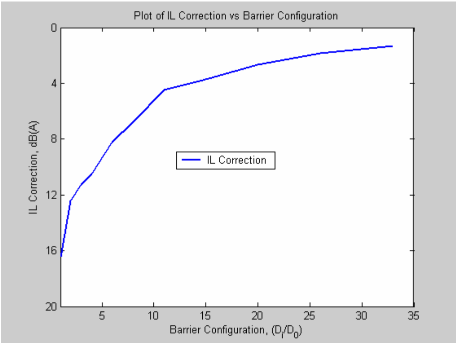




Case A: IL Correction dB(A) vs X_i/X_o Case B: IL Correction dB(A) vs X_i/X_o

Figure 4.12 – Plot of IL Correction against Barrier Configuration (case A & B) in Region A

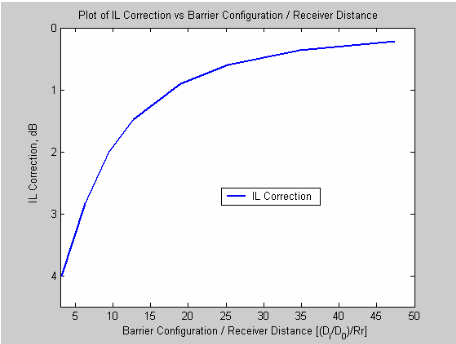




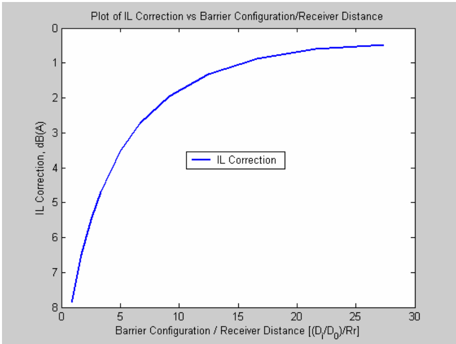
Case C: IL Correction dB(A) vs X_i/X_o

Case D: IL Correction dB(A) vs X_i/X_o

Figure 4.13 – Plot of IL Correction against Barrier Configuration (cases C & D) in Region B

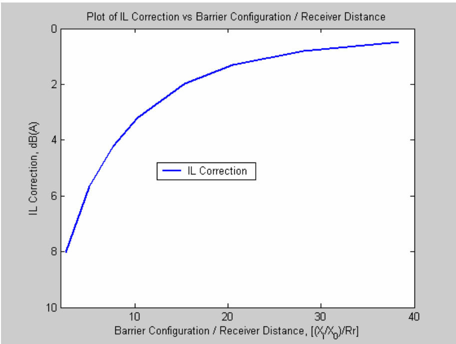


Case A: IL Correction dB(A) vs $[X_i/X_o /r_r]$

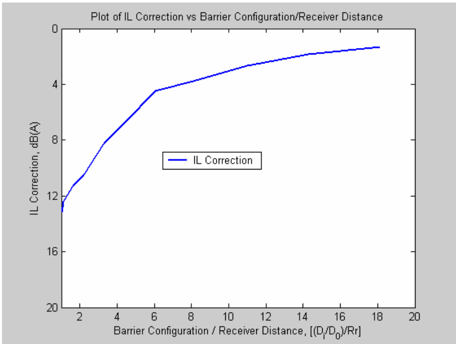


Case B: IL Correction dB(A) vs $[X_i/X_o /r_r]$

Figure 4.14 – Plot of IL Correction against Barrier Configuration normalized with Receiver Distance (Case A & B) in Region A

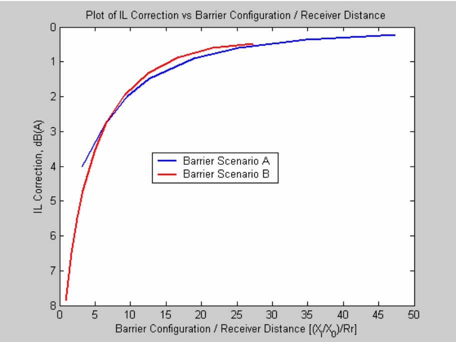


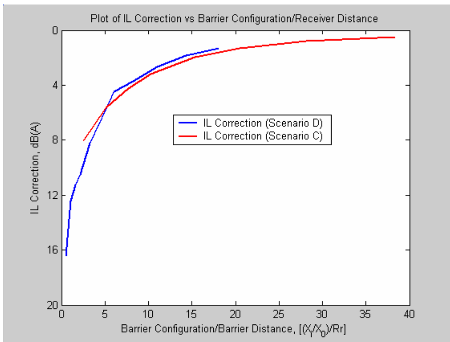
Case C: IL Correction dB(A) vs $[X_i/X_o /r_r]$



Case D: IL Correction dB(A) vs $[X_i/X_o /r_r]$

Figure 4.15 – Plot of IL Correction against Barrier Configuration normalized with Receiver Distance (Cases C & case D) in Region B





Cases A & B – Comparison after normalization

Case C & D – Comparison after normalization

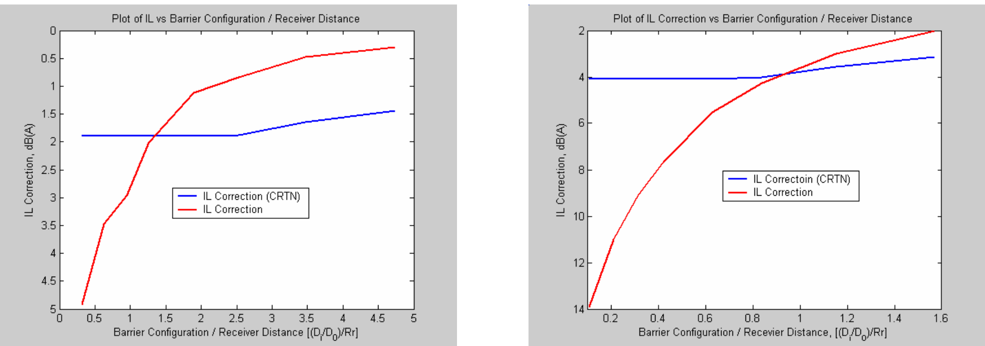
Figure 4.16 – Plot of IL Correction [dB(A)] after normalization of Barrier Configuration and Receiver Distance (for 4 cases)

Case	Position of Receivers relative to Barrier A	Receiver distance from top of Barrier A	Remarks
E	4m high 3m away	3.162m	Receiver in Region A, Ratio of r_r/r_s = 0.5547; X_i is set at X_i/X_0 = 1, 2, 3, 4, 6, 8, 11 & 15
F	7.5m high 3m away	3.905m	Receiver in Region B, Ratio of r_r/r_s = 0.685; X_i is set at X_i/X_0 = 1, 2, 3, 4, 6, 8, 11 & 15

Table 4.3 - the positions of receivers in the 2 cases under study

Test	Separation between barriers, m	Deterioration of attenuation characteristics IL due to presence of parallel barrier, dB(A)			
		Scenario E		Scenario F	
		Theoretical Ray Model	CRTN	Theoretical Ray Model	CRTN
1	7	4.9	1.9	13.9	4.1
2	10.5	3.5	1.9	11.0	4.1
3	14	3.0	1.9	9.1	4.1
4	17.5	2.0	1.9	7.7	4.1
5	24.5	1.1	1.9	5.5	4.1
6	31.5	0.9	1.9	4.3	4.0
7	42	0.5	1.7	3.0	3.6
8	56	0.3	1.4	2.0	3.1

Table 4.4 - Comparison of results from theoretical ray model and the CRTN in the 2 cases under study



Case E – Comparison of results from theoretical ray model & the CRTN

Case F – Comparison of results from theoretical ray model & the CRTN

Figure 4.17 – Plot of IL Correction [dB(A)] after normalization of Barrier Configuration and Receiver Distance (for cases E & F)

Chapter 5

An Investigation of Diffraction Characteristics of Cranked Barriers in High-rise Cities

5.1 Introduction

Cranked barriers have been commonly used in recent years to mitigate road traffic noise in dense high-rise cities. In many situations, the use of a cranked barrier is favoured instead of the relatively high or substantial noise barriers for noise mitigation as it can improve the shielding efficiency at a reduced barrier height and resulted in less cost and less visually intrusive. The basic feature and principle of adopting cranked barrier is that an enlarged shadow zone would be produced due to the bent at the top of the cranked barrier. The noise reduction effectiveness, usually know as Insertion Loss (IL) of cranked barriers is commonly assumed to be the same as that of normal vertical barriers of equivalent heights, however, its diffraction characteristics has not been duly investigated. There is a need to look into the diffraction characteristic of cranked barriers through a more systematic and analytical manner.

Only recently, researchers started to the diffraction patterns and characteristics of cranked barriers. Jin [88] predicted the noise reduction performance of a partially inclined barrier by summating the multiple diffractions at top and corner points of the partially inclined barrier at which convex and concave edges are formed. Kouyouminjan and Pathek's diffraction theory was adopted to construct diffraction coefficients for both convex and concave edges. Kin [89] expanded the study further to include computation of diffractions by multiple wedges and polygonal-like shapes barriers involving both convex and concave edges where edges may or may not be inter-connected. This study found that the performance of polygonal-like shapes is likely dominated by diffraction associated with the shortest propagation path. They also found that the partially inclined barrier increases the shadow zone as compared to simple vertical barrier of equivalent height, however, it does not necessarily increase the performance at all heights. Li & Wong [90] investigated the sound diffraction by a cranked barrier due to a single source using the boundary integral formulation on the basis of image source method and approximate boundary conditions. The method was then extended to consider the case of sound diffraction by a finite length cranked barrier. Notwithstanding all these, the diffraction characteristics of cranked barriers in dense high-rise cities in greater details are yet to be investigated.

5.2 Theoretical Ray Model

For a semi-infinite long half plane thin vertical barrier locating on fully absorptive ground (Figure 5.1), according to Keller's geometrical theory of diffraction, the sound field of diffraction in the shadow zone can be written as [85]:

$$P_{diff} = D(\frac{e^{ikR}}{4\pi R}) \tag{5.1}$$

where *D* is the diffraction coefficient, *k* is the wave number; *R* is the distance from source to receiver without the presence of the thin vertical barrier. The term is also known as the direct field. Expressions of D have been given by many researchers. In this theoretical ray model, the solution by Pierce [42] would be adopted. Details of the solution by Pierce have been provided in Chapter 2 and hence would not be repeated here. For easy reference, the pressure of the diffracted sound wave would be represented as:

$$P_{diff} = (\frac{e^{ikL}}{4\pi L})(\frac{e^{i\pi/4}}{\sqrt{2}})\sum\left(\frac{\sin\upsilon\pi}{(1-\cos\upsilon\pi(\theta_s \pm \theta_r)}\right)A_D\left[\Gamma M_\upsilon(\theta_s \pm \theta_r)\right] \tag{5.2}$$

where *L* is the total length of the sound ray path, the angles, θ_s & θ_r,, are defined as respective angles subtended by sound paths from source with the barrier and to receiver with the barrier, and $\upsilon = (\beta/\pi)$, is the wedge index. The function A_D is given by

$$A_D = \mathrm{sgn}(X)\left[f(X) - ig(X)\right] \tag{5.2a}$$

The diffraction integral, with the auxiliary Fresnel functions,

$$\Gamma = \sqrt{\left(\frac{kr_s r_r}{\pi L}\right)} \tag{5.2b}$$

and

$$M_\upsilon(\theta_s \pm \theta_r) = \frac{(\cos\upsilon\pi - \cos\upsilon\pi(\theta_s \pm \theta_r)}{(\upsilon\sqrt{(1-\cos\upsilon\pi\cos\upsilon\pi(\theta_s \pm \theta_r))}} \tag{5.2c}$$

Also, the auxiliary Fresnel integrals *f(X)* and *g(X)* are given as:

$$f(x) = \left[\frac{1}{2} - S(X)\right]\cos\left(\frac{\pi X^2}{2}\right) - \left[\frac{1}{2} - C(X)\right]\sin\left(\frac{\pi X^2}{2}\right) \tag{2.4d}$$

$$g(x) = \left[\frac{1}{2} - C(X)\right]\cos\left(\frac{\pi X^2}{2}\right) + \left[\frac{1}{2} - S(X)\right]\sin\left(\frac{\pi X^2}{2}\right) \tag{2.4e}$$

and the Fresnel integrals *C(X)* and *S(X)* are

$$C(\mu)=\int_0^{\mu}\cos(\frac{\pi\xi^2}{2})d\xi \tag{2.4f}$$

$$S(\mu)=\int_0^{\mu}\sin(\frac{\pi\xi^2}{2})d\xi \tag{2.4g}$$

In the case of a thin barrier or screen with either the source or receiver located at a distance a few wavelengths from the edge of the barrier or screen, such that the wedge index, ν = ½ and the length ratio $r_s r_r$ / $L^2 \rightarrow 0$ but ($kr_s r_r$ / L) remains finite. In such case, the diffraction terms can be grouped to a compact formula as follows:

$$P_{diff}=(\frac{(1+i)}{2}(\frac{e^{ikL}}{4\pi L})\left[A_D(X_+)+A_D(X_-)\right] \tag{5.3}$$

where

$$X_+=X(\theta_r+\theta_s) \tag{5.3 a}$$

$$X_-=X(\theta_r-\theta_s) \tag{5.3 b}$$

$$X(\Phi)=-2\sqrt{\left(\frac{2kr_s r_r}{\lambda L}\right)\cos\left(\frac{\Phi}{2}\right)} \tag{5.3 c}$$

In the case of cranked barriers shown in Figure 5.2, the diffracted rays include those of single diffraction (at edge 2), double diffractions (at edge 1-2 & edge 2-3) and triple diffractions (at edge 1-2-3) and so on.

For single diffraction ray S-2-R, equation (5.3) would be adopted as this could be considered as a thin barrier case. With respect to the double diffraction rays (i.e. S-1-2-R & S-2-3-R) and triple diffraction ray (S-1-2-3-R), Salomon's method of diffraction coefficient would be adopted. According to Salomon [92], the total diffraction coefficient is written as a product of a partial diffraction coefficients $Di = D$:

$$D = \left(\frac{1}{2}\right)^{\mathrm{M}} \prod_{i=1}^{N} D_i \tag{5.4}$$

where M is the number of double edge, i.e. the number of pairs of neighbouring wedges with a common side place, the factors $\left(\frac{1}{2}\right)$ is included to eliminate double counting of the reflection at a common plane between two wedges. For diffraction by two single wedges, the factor of $\left(\frac{1}{2}\right)$ is excluded. Π is the product of diffraction coefficient from *i* to *N* and *N* is number of edge of diffraction.

For double diffraction ray S-2-3-R in which convex interior angle is involved, equation (5.3) would be used. For the case if a concave interior angle is involved like double diffraction ray S-1-2-R, equation (5.2) would be adopted.

Similar to the simple vertical barrier, the noise reduction effectiveness can be expressed as Insertion Loss (IL) and represented as:

$$\mathrm{IL} = 20\log\left(\left|\frac{P_{\mathrm{w/o}}}{P_{\mathrm{w}}}\right|\right) \tag{5.5}$$

where P_{w} and $P_{\mathrm{w/o}}$ is the total sound field with and without the presence of the thin cranked barrier. The total sound field represents the coherent summation of the single diffraction rays, double diffraction rays, and triple diffraction rays and so on. However, the attenuation of the ray increases with the number of diffractions.

In the case where a cranked barrier located on reflecting ground is used to mitigate road traffic noise, the attenuation would be changed from the above discussion. Consider the situation shown in Figure 5.3, the total sound field in shadow zone would be:

$$P_T = P_1 + P_2 + P_3 + P_4 \qquad (5.6)$$

where

P_1 = the total diffraction sound fields due to S_1 & R_1

P_2 = the total diffraction sound fields due to S_2 & R_1

P_3 = the total diffraction sound fields due to S_1 & R_2

P_4 = the total diffraction sound fields due to S_2 & R_2

Similarly, total diffraction sound fields represent the coherent summation of the single diffraction rays and double diffraction rays. The same approach of determining sound field of single and double diffraction (shown above) will be used.

If the ground has a finite impedance (such as grass or a porous road surface) then the pressure corresponding to rays reflected from these surfaces will need to be multiplied by the appropriate spherical wave reflection coefficient(s) to allow for the change in phase and amplitude of the wave on the reflection, as follows:

$$P_T = P_1 + Q_S P_2 + Q_R P_3 + Q_S Q_R P_4 \qquad (5.7)$$

where Q_S and Q_R are the spherical wave reflection coefficients at the source and receiver side, respectively. The spherical wave reflection coefficients depend on the acoustical characteristic of the ground and the source/receiver geometry. The insertion loss (IL) is defined as:

$$\mathrm{IL} = 20\log\left(\left|\frac{P_g}{P_b}\right|\right) \tag{5.8}$$

where P_g the total pressure field with the present of ground and P_b is the total pressure field with the barrier and ground present.

With the configuration of cranked barrier shown in Figure 5.2, the side where receivers locate could further be demarcated into 3 zones (namely Zone I, II & III as shown in Figure 5.4) in which diffraction characteristics would be different due to presence of single, double and triple diffraction rays. Zone II & III would be of greatest interest in this study. Following the above, the ray paths in each zone can be defined as follow:

a. Zone I – all single, double and triple diffraction plus the direct ray would occur as this is in the illuminated zone.
b. Zone II – all single, double and triple diffraction would occur; and
c. Zone III – only the double and triple diffractions would occur;

5.3 Comparison with Experimental Model

To validate the theoretical ray model, indoor experiments were conducted in an anechoic chamber of size 6 x 6 x 4-m (high) to investigate the acoustic performance of infinite length cranked barriers. The cut-off frequency of the anechoic chamber was 75 Hz.. A thin wooden board of 2.4m long and 1.2 m high was used to simulate infinite long vertical barrier. This wooden board was vanished to provide smooth hard surface for parts of the experiments. A steel sheet of 2.44 m long 0.8 m wide (0.5m + 0.3m inclined part subtended at 50° to the vertical) was customized to form a cr anked side of cranked barrier. It was clamped to the top of the wooden board vertical barrier to model a thin edge cranked barrier and the cranked barrier was set to incline to the left hand side. The source was fixed at a location at the right side of the cranked barrier at a horizontal distance of 0.31 from vertical surface of the cranked barrier. The receiver was located at the left side of the cranked barrier at a horizontal distance of 0.69 m from the cranked barrier. The source and receiver were kept near to cranked barrier for the purpose of simulating infinite cranked barrier for the experiments. The first test (known as Test A) involved source at 1.295m high and receiver at 1.208m high (all above ground). This simulated a zone II receiver. In the second test (known as Test B), source was shifted to 0.523m high above ground but the receiver position remained unchanged. The second test was also for a zone II receiver but with change of source height. Then, the receiver was shifted to 0.813m above ground but the source position remained unchanged so as to form the third test (known as Test C). The third test simulated a zone III receiver. In the indoor experiments, the cranked barriers, the source and the receiver were set on the wire-mesh of the anechoic chamber for no ground reflection situation. The general configuration of the indoor experiments of investigating acoustic performance of infinite length cranked barrier and the positions of source and receiver are shown in Fig. 5.5. Photos 5.1 & 5.2 shows the actual set-up of indoor experiments inside the anechoic chamber.

A Tannoy driver with a tube of 3 cm internal diameter and 1m long was used as a point source in the experiments. The sound source was connected to a Maximum Length Sequence Systems Analyzer (MLSSA) with an MLS card installed in a PC. The analyzer was connected to a B&K 2713 power amplifier. The MLSSA system was used both as the signal generator for the source and as the signal-processing analyzer. A BSWA TECH MK224 ½ –in condenser microphone and a BSWA TECH MA201 preamplifier were used together as the receiver. Both source and receiver were placed at a fixed position by means of a stand and clamps.

It is worth mentioning that the principal aim of the indoor experiments was to provide useful experimental data for the validation of the theoretical model. They were not intended to be proper scale model experiments. Hence, no attempt was made to conduct measurements for wide ranges of source and receivers.

Errors tend to occur when conducting experiments. However, they are considered to be small which do not affect the degree of accuracy of the indoor experiments. When conducting indoor experiments, the following errors may arise:

- The perpendicular alignment of the cranked barrier;
- Whether the source and receiver were kept in the same perpendicular plane which was to the cranked barrier and ground;
- The reflection of noise due to the experimental apparatus such as stand, clamps etc.

In order to minimize the first error, a leveling meter rule was used to measure whether the cranked barrier was aligned perpendicular to the ground. For the second error, careful inspections using measurement equipment were conducted before each measurement. To prevent from the final error, the apparatus chosen for the experiments should be as small as possible in size in comparison to the two wooden boards and microphone. Hence, we could assume that reflection of noise is minimal.

The comparison between the predictions using the theoretical ray model and the results from the indoor experiments are shown in Figure 5.6. The results from three indoor experimental tests show reasonably good agreement with the theoretical predictions.

5.4 Numerical Validation

The ray model derived has been used for the computation of sound fields of a thin and infinite long acoustically hard cranked barrier situated on top an acoustically hard ground surface. A two dimensional Boundary Element Method (BEM) is also used to predict the acoustic sound fields of this configuration. The predictions according to the BEM formulation provide benchmarking results for the validation of the theoretical ray model derived. The cranked barrier is of 0.4m high with the cranked barrier at 0.2 m long subtended at 45° from the vertical (Figure 5.7). Th e source locates at (1m, 0.077m) while receivers are located at a distance of 0.2m from barrier and at various heights of 0.1m, 0.3m 0.6m, 0.7m and 0.762m (at shadow boundary). All surfaces are considered to be acoustically hard. Fig 5.8 shows the comparisons of the predicted insertion loss of the cranked barriers with the receivers at the heights described above. It is noted that the predictions from the theoretical ray model agree in reasonable good manner with the predictions from BEM.

5.5 The Effect of Single, Double and Triple Diffraction

It is noted that the attenuation of the diffraction ray increases with the number of diffractions. In other words, the more diffraction, the less contribution of sound transfer of the diffraction rays. To avoid unnecessary computation time of the theoretical ray model and at the same time without compromise the accurate performance, it is prudent to investigate the extent of contribution effect due to single, double and triple diffraction rays. For the sensitivity tests, several scenarios of using all diffraction ray paths; single diffraction ray path only; single plus double diffraction ray paths and triple diffraction ray path only for Zone II & III are looked into. The cranked barrier configuration shown in Figure 5.7 was adopted for testing. Receiver heights were adjusted so that zones II & III situations were simulated. The results are listed in the comparisons shown below.

5.5.1 Zone III

From above, only the ray path exhibiting double diffraction at Edge 2 and Edge 3 and ray path exhibiting triple diffraction at Edge 1, Edge 2 and Edge 3 would exist. Receiver at 0.1m high was used for analysis. Predictions of the following scenarios were conducted:

a. with all double and triple diffraction rays;

b. with all double diffraction rays only; and

c. with all triple diffraction rays only

The results were compared in Figure 5.9. Accordingly, rays with double diffraction are the major and significant contribution of sound transfer while that of triple diffraction can be ignored.

5.5.2 Zone II

As discussed above, ray paths of single, double and triple diffraction would occur. Receiver at 0.3m high was used for analysis. Predictions of the following scenarios were conducted:

a. with all single, double and triple diffraction rays;

b. with all single and double diffraction rays only;

c. with all single diffraction rays only;

d. with all double diffraction rays only; and

e. with all triple diffraction rays only;

The results were compared in Figure 5.10. Accordingly, rays with triple diffraction can be ignored. Using either rays with exhibiting single diffraction or that of double diffraction alone cannot reproduce the same results which indicates that in this zone II, all rays except that with triple diffraction would need to be used in calculating the diffraction effect.

Sensitivity tests conducted above indicate that only the single and double diffraction rays would contribute to sound transfer. On this basis, the only single and double diffraction rays would be taken into account in the study of diffraction characteristics of cranked barrier.

5.6 Potential Improvement to Current General Application

5.6.1 Prediction of Sound Fields of Cranked Barriers

In the daily practice of predicting noise reduction effectiveness of cranked barriers, an approach of predicting the sound field of an alternative vertical barrier of equivalent height would usually be adopted for simplicity reason. No prior study has conducted to evaluate the appropriateness of such approach. To investigate the diffraction patterns and characteristics of cranked barriers and those of the vertical barrier of equivalent heights, scenarios of two vertical barriers of equivalent heights shown in Figure 5.11 were investigated. The cranked barrier configuration shown in Figure 5.7, the source position of (1m, 0.077m) and receiver locate at positions of (0.1m, 0.3m, 0.6m and 0.726m) high and 0.2m away from barrier would again be adopted for investigation. Prediction of Insertion Loss (IL) for cranked barrier would follow the ray model developed while solution by Pierce on diffraction of thin barriers would be adopted for both 1st and 2nd alternative vertical barriers [equations (5.2) & (5.3)]. Again, the investigation would focus in Zone II and Zone III as these are the areas that the practitioners would be most interested.

5.6.1.1 Zone III

The receivers in Zone III would be deep in the shadow zone and the situation would be represented by receiver located at 0.1m high. The plots of IL against Frequency are shown in Figure 5.12. It is observed that higher IL value is obtained from the ray model as compared with those from solution by Pierce applied at 2 alternatives vertical barriers.

The difference is relatively small for frequency up to 2500Hz but increases as large as 5 dB towards frequency ranging from 7500 to 15000 Hz. Also, IL values obtained in 2^{nd} alternative vertical barrier are higher than that from 1^{st} alternative vertical barrier by about 2 dB. From the above, the adoption of alternative vertical barrier (in 2 forms) would likely under-predicted the IL values. While the IL values of receivers deep in shadow zone are relatively large in magnitude (like 15 – 20 dB), under-prediction of 2-5 dB may not affect the end results significantly.

5.6.1.2 Zone II

The receivers in Zone II are those are relatively not deep in shadow zone and those are close to shadow boundary. The former one would be represented by receiver located at 0.3m high while the latter one by receiver at 0.6m. The plots of IL against Frequency are shown in Figures 5.13 & 5.14. For receiver at 0.3m high, IL values for cranked barriers are higher than that for 2^{nd} alternative vertical barrier at frequency up to 3000Hz and 1^{st} alternative vertical barrier at frequency up to 4000Hz. The differences are up to 4 dB and 6 dB for two cases respectively. For frequency at 6000Hz and higher, the IL values of 2^{nd} alternative vertical barrier are higher than that of cranked barrier and could be as high as 5 dB at 16000Hz onward. For 2^{nd} alternative vertical barrier, IL values at 10000Hz onward higher are higher than that of cranked barrier by up to 3 dB (at 18000Hz). Again, IL values obtained in 2^{nd} alternative vertical barrier are higher than that from 1^{st} alternative vertical barrier by about 2 dB. From the above, the adoption of alternative vertical barrier (in 2 forms) would likely under-predicted the IL values for frequency up to 4000Hz but over-predicted at higher frequency. While road traffic noise would usually be assessed in A-weighted for frequency up to 4000Hz, the adoption of alternative vertical barrier for prediction would tend to give under-estimation.

For receiver at 0.6m high, the plot of IL against Frequency for cranked barrier resembles closely to that of 2nd alternative vertical barrier except that it exhibits a wave form rather than line form. The wave form is due to the presence of interferences of sound rays between single and double diffractions. The IL curve appears to fluctuate in bigger magnitude at frequency up to 5000Hz as compared with those at higher frequency but the magnitude remains to be 1-2 dB. Again, IL values of 2nd alternative vertical barrier are higher than that from 1st alternative vertical barrier and the magnitude is about 3 dB at higher frequency. From the above, adoption of 1st alternative vertical barrier for prediction would give a good and reasonable estimation. However, adopting 2nd alternative vertical barrier would likely provide an over-estimation.

5.6.1.3 Shadow Boundary

Receiver at 0.726m sits on the shadow boundary line. The plot of IL against Frequency is shown in Figure 7.15. By and large, the plot of IL against Frequency of cranked barrier agrees in good manner with those for 1st and 2nd alternative vertical barriers except the IL curve of cranked barrier fluctuates within 1 dB at Frequency up to 2500. Also, IL values of both alternative vertical barriers agree very closely. From, adoption of either alternative vertical barrier for predicting noise reduction performance of cranked barrier is generally in order.

According to the above investigations, the adoption of alternative vertical barrier for predicting the noise reduction effectiveness of cranked barrier may not be appropriate approach. For a rough estimation of IL values for receivers at and close to shadow boundary, predicting using solution by Pierce on 1^{st} alternative vertical barrier could give reasonable results. However, for receivers in shadow zone and those down deep in shadow zone, the estimation would tend to under-estimated. From the investigations, approach using 2^{nd} alternative vertical would give over-estimation.

5.6.2 Optimum Design of Cranked Barriers

As cranked barriers are relatively new version of barriers as compared to vertical barriers, semi-enclosures and enclosures, guidelines promulgated by various authorities including Highways Department and Environmental Protection Department of Hong Kong SAR Government, Highway Agency of United Kingdom, Federal Highway Authority (FHWA) have not included the designs of cranked barriers. Also, no particular investigation has been conducted on the diffraction characteristics of cranked barriers and hence designing cranked barriers seem to base on some general practice or as a result of consideration of other issues or engineering matters. For instance, the overall height of the cranked barriers is sometimes considered as a constraint or limiting factor in designing the cranked barriers as to some extent, higher barriers would usually being along more serious visual impact. That could explain why in some cases, the angles subtended by the cranked plank to the vertical or to the horizontal is not standard but is varied so as to give the same overall height. Figure 5.16 shows the design of 3 cranked barriers in one of the road projects in Hong Kong. It is noted that if the angle subtended by cranked plank to the vertical (or to the horizontal) changes, the diffraction pattern and characteristics would be affected as angles of diffraction edge to receiver and source also change. While the use of a cranked barrier can improve the shielding efficiency at a reduced barrier height, it is prudent to investigate how the angle subtended by the cranked plank to the vertical or horizontal would affect the efficiency as originally planned.

Whilst the use of cranked barriers aims at improving the shielding efficiency at a reduced barrier height, it would be useful to look into the following aspects in optimising the design of cranked barriers:

a. the size of shadow zone created by cranked barriers; and

b. whether noise reduction effectiveness at particular receivers could be maximised.

For the purpose of studying, the investigation would base on the configurations of cranked barrier shown in Figure 5.17. In simple term, the cranked barriers under investigation would have same vertical height and equal length of cranked plank; however, different angles would be subtended by the cranked plank to horizontal.

Source S locates at fixed position at right hand side of cranked barrier and Receivers (represented by R_i in which i denoted different angles subtended to horizontal) would be assigned on a vertical plane drawn at a fixed distance to right hand side of cranked barrier. The positions of R_i would be determined by drawing a straight line (i.e. shadow boundary line) from Source S connecting the tip of the cranked plank and then to the vertical plane. It is noticed that at different subtended angle Φ, the height of Receiver (represented by H_Φ) would change. By drawing the shadow boundary lines at different angle Φ, locations of different Receivers R_i can then be set. By comparing H_Φ of these Receivers R_i, one can then compare the size of shadow zone produced by the cranked barriers. It is further noticed that the highest receiver height H_Φ is obtained when the straight line (i.e. shadow boundary line) touches the tip of the cranked plank at 90°. This also implies when the shadow boundary line touches the cranked plank at 90°, the particular cranked barrier configuration p roduces the largest shadow zone among Receivers at same vertical plane.

To investigate whether noise reduction effectiveness due to cranked barriers could be maximized through optimisation process, the IL at different Receivers, R_i locating on the same vertical plane due to different cranked barriers (i.e. different angles subtended by cranked plank to the horizontal) should be compared. On this, different cranked barrier configurations shown in Figure 5.18 are studied. The cranked barrier is of 0.4m high with the cranked barrier at 0.2 m long subtended at Φ to the horizontal. The source locates at (1m, 0.077m) while receivers are located on a vertical plane at a distance of 0.2m from cranked barrier. All surfaces are considered to be acoustically hard but ground is of perfect absorptive situation. Mathematical manipulation indicates that when Φ = 61°, the shadow boundary line connecting Source S to Receivers R_i intersecting the tip of the cranked plank at 90°.

The investigation looks into the cases of Φ = 0°, 30°, 45°, 60°, 61° and 90°. As shown in Figure 5.18, with Source S assigned at 1.0m away and at 0.077m high, Receivers are located at vertical plane at 0.2m on the other side of cranked barrier. The Receiver height H_Φ in the investigation are 0.3m, 0.5616m[2], 0.6909m[3], 0.7046m[4], 0.726m[5] and 0.7386m[6]. The Receiver at 0.3m high is chosen as this would be located well or deep in the shadow zone and would provide good comparison among various cases. For the case of Φ = 61°, the receiver height would be 0.7423m which is the highest among the receivers under investigation. This receiver would be at the shadow boundary of case of Φ = 61° but would be in illuminated zone of other cases. As such, this receiver would not be used for

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[2] In the case of cranked plank subtended to horizontal at 0°, the straight shadow boundary line is drawn connecting Source S and the vertical plane intersecting the tip of the cranked plank; the receiver locates at 0.5616m high.

[3] Similar to [4], the receiver height is 0.6090m high when cranked plank subtended to horizontal at 30°.

[4] Similar to [4], the receiver height is 0.7046m high when cranked plank subtended to horizontal at 90°.

[5] Similar to [4], the receiver height is 0.726m high when cranked plank subtended to horizontal at 45°.

[6] Similar to [4], the receiver height is 0.7386m high when cranked plank subtended to horizontal at 60°.

comparison. Also, it is noticed that for one particular Receiver, if it locates at the shadow boundary of a particular barrier configuration, it would possibly be in illuminated zone of barrier configuration. For simplicity, for those Receivers locating in illuminated zone of any barrier configuration, prediction of IL values would not be conducted. Prediction of IL of these Receivers would be predicted using the ray model developed. For the case of Φ = 90°, solution by Pierce would be used.

The plots of IL against Frequency for 6 Receivers under investigation are shown in Figures 5.19(a) to 5.19(f). One general observation is that the IL values obtained for the cases of Φ = 60° & 61° are very similar. For simplicity, one can consider that their IL values are the same. Other observations are:

(a) Receiver at 0.3m high – from Figure 5.19(a), the largest IL value obtained is the case of Φ = 30°. For the case of Φ = 30°, IL values at frequency below 5000Hz are the second largest. For the case of Φ = 90°, IL values at frequency above 5000Hz are the second largest. For the case of Φ = 60° (or 61°), IL values are inferior as compared with other cases. This Receiver is well or deep in shadow zone; the differences of IL values would not have any particular significant effect in the daily prediction purpose.

(b) Receiver at 0.5616m high – from Figure 5.19(b), the largest IL value obtained is the case of Φ = 60° (or 61°). It is also noticed that the next higher IL value is for the case of Φ = 90°, then followed by the case of Φ = 45° & 30°. This Receiver is still in relatively good position in the shadow zone with large IL values; the differences of IL values in different cases would not have any particular significant effect in the daily prediction purpose.

(c) Receiver at 0.6909m high – from Figure 5.19(c), again the largest IL value obtained is the case of Φ = 60° (or 61°). The next higher IL value is for the case of Φ = 45°, then followed by the case of Φ = 90° & 30°. This Receiver is at the shadow boundary of the case when Φ = 30°. As seen, the IL values would be increased in considerable amount if Φ changes to 45°, 60° (or 61°) or 90°.

(d) Receiver at 0.7046m high – from Figure 5.19(d), again the largest IL value obtained is the case of Φ = 60° (or 61°). The next higher IL value is for the case of Φ = 45°, then followed by the case of Φ = 90°. This Receiver is at the shadow boundary of the case when Φ = 90° and is in illuminated zone of case when Φ = 30°. Again, the IL values would be increased in considerable amount if Φ changes to 45° or 60° (or 61°).

(e) Receiver at 0.726m high – from Figure 5.19(e), the largest IL value obtained is the case of Φ = 60° (or 61°). The next higher IL value is for the case of Φ = 45°. This Receiver is at the shadow boundary of the case when Φ = 45° and is in illuminated zone of case when Φ = 30° & 90°. Again, the IL values would be increased in considerable amount if Φ changes to 60° (or 61°).

(f) Receiver at 0.7386m high – from Figure 5.19(f), IL values for the case of Φ = 60° & 61° look very similar. This Receiver is at the shadow boundary of the case when Φ = 60° and is in illuminated zone of case when Φ = 30°, 45° & 90°.

With reference to the above, it is noticed that for receivers deep in the shadow zone, change of Φ (the angle subtended by the cranked plank to horizontal) may not cause significant effect to IL prediction in daily usage. However, for receivers close to shadow boundary, the IL values have been maximized when Φ = 60° (or 61°) at which the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°).

As A-weighted level is more frequently used in our daily application of assessing road traffic noise, the IL in A-weighted level are generated to enable further evaluation. Table 5.2 shows the IL (dB(A)) of Receivers at 0.3m, 0.5615m, 0.6909m, .07046m, 0.726m and 0.7386m high with Φ (the angle subtended by the cranked plank to horizontal) set at 30°, 45°, 60°, 61° and 90°. It is noted that for all receivers, the maximum value of IL (in dB(A)) obtained when Φ is 61° at which the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°).

Following the above discussions, the design of cranked barriers can be optimized when the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°). The optimization provides the largest shadow zone and also maximizes the IL values for receivers close to the shadow boundary of cranked barriers.

5.7 Summary

In this chapter the following works have been done:

1. A Ray model based Keller's geometrical theory of diffraction; solution of Pierce on sound diffraction over corners and wide barriers; and Salomon's method of diffraction coefficient for multi-edge wedges has been developed and validated through experimental and numerical models;
2. Rough estimation of IL values of cranked barriers for receivers based on alternative vertical barriers configuration is appropriate only for receivers at and close to shadow boundary of cranked barriers; and
3. The design of cranked barriers can be optimized when the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°).

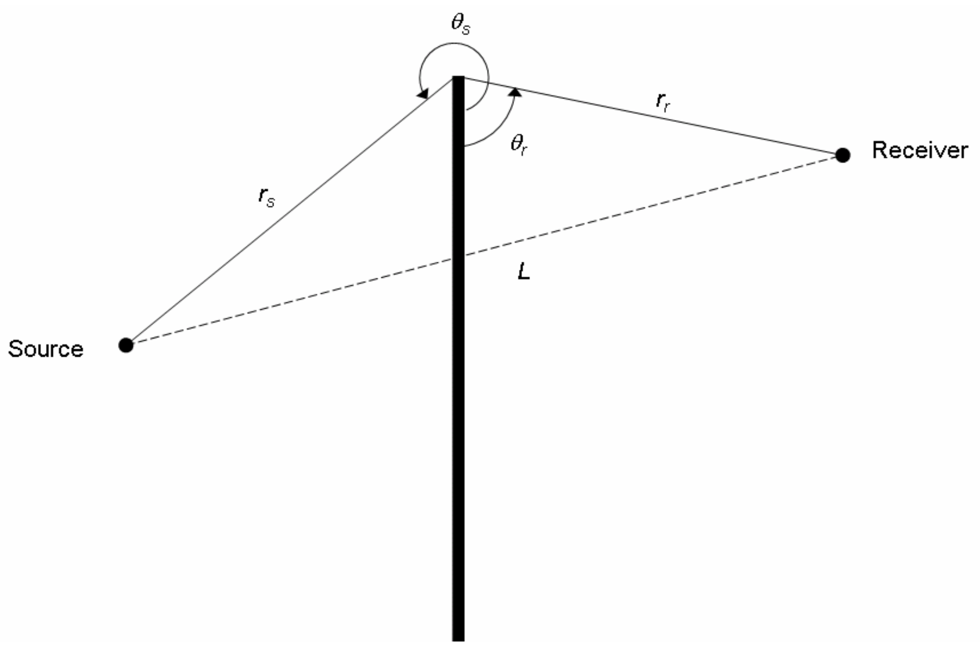


Figure 5.1 – The geometry of source and receiver in the vicinity of thin vertical barrier

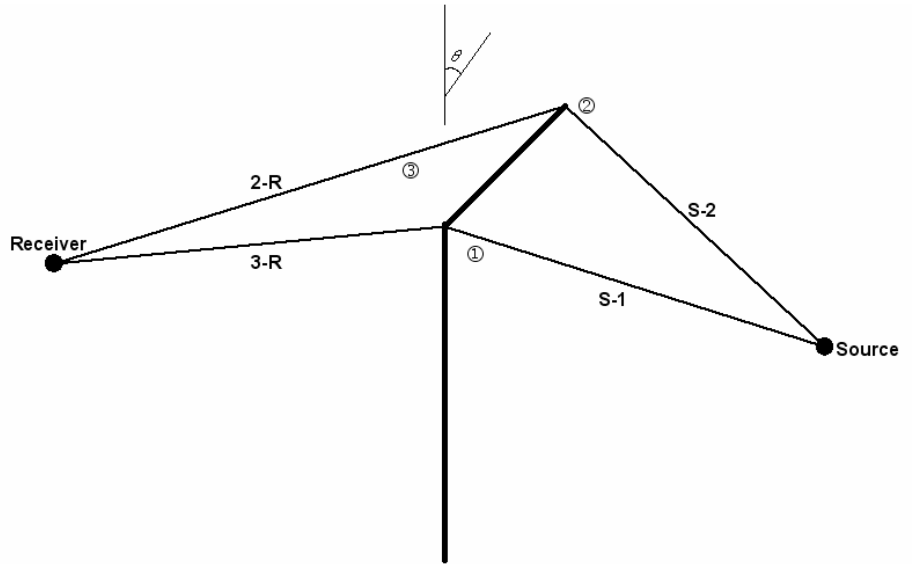


Figure 5.2 – general description of diffracted ray in a cranked barrier

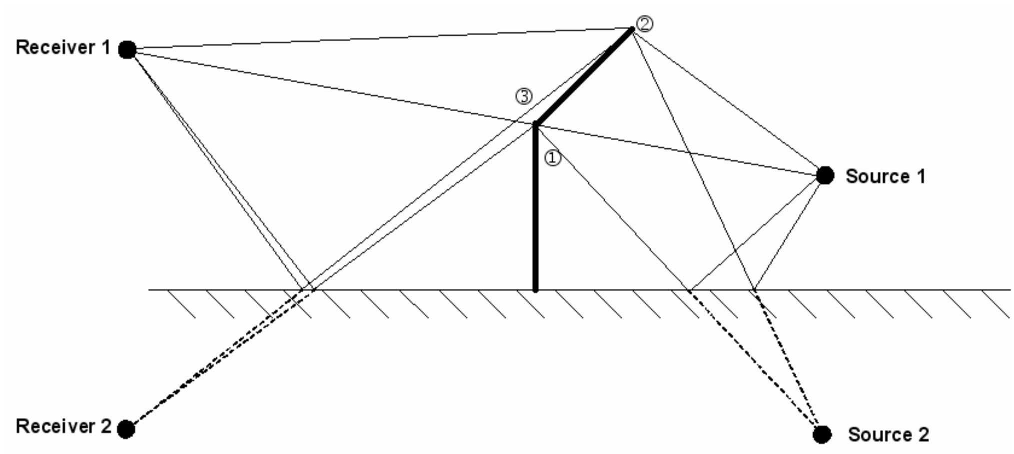


Figure 5.3 – The geometry of source, image source, receiver and image receiver of a cranked barrier with edges ①② &③ locating on an impedance plane

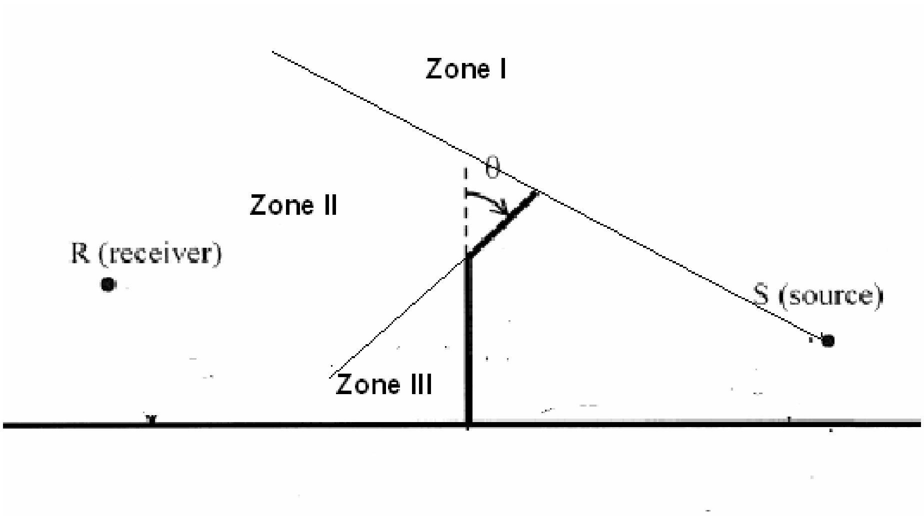
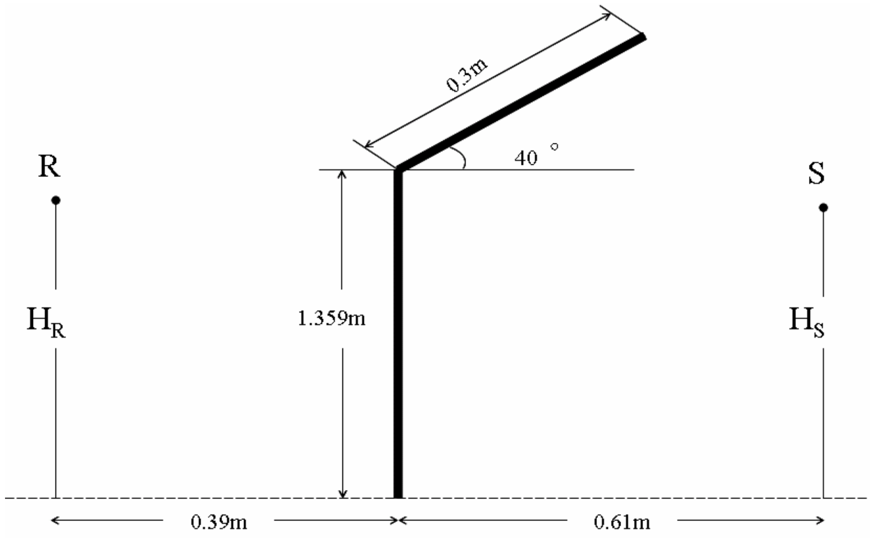


Figure 5.4 – Demarcation of zones for receivers in cranked barrier situation under study

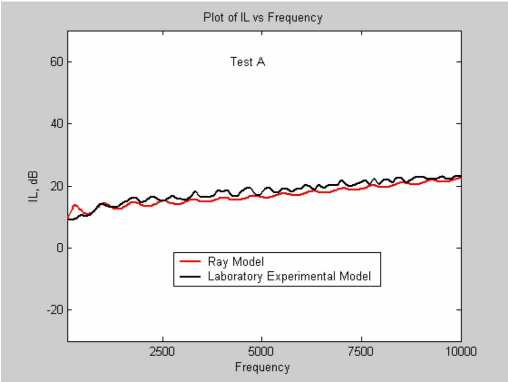
Photo 5.1 – the actual set up of the indoor experiment inside the anechoic chamber

Photo 5.2 – the actual set up of the measuring instrument used for indoor environment inside the anechoic chamber

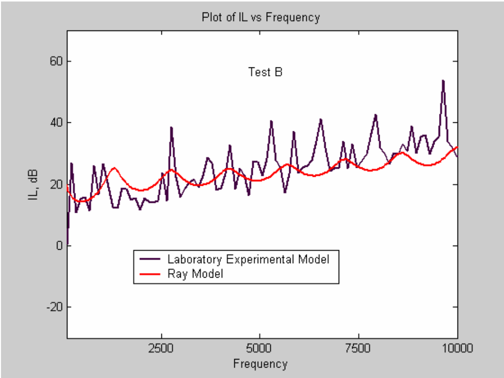


Tests	H_S	H_R	Remarks
A	1.295m	1.308m	Zone II receiver
B	0.523m	1.308m	Zone II receiver
C	0.523m	0.813m	Zone III receiver

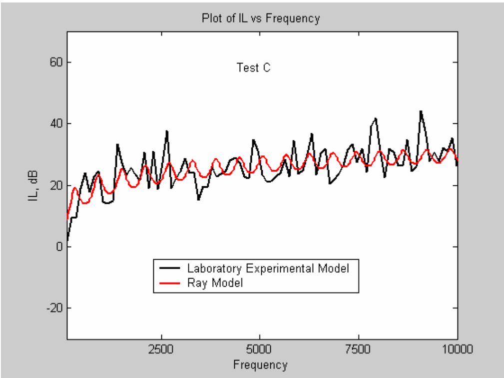
Figure 5.5 – Configuration of laboratory tests conducted for cranked barriers



(a) Test A



(b) Test B



(c) Test C

Figure 5.6 (a) to (c) – comparison of results from indoor experiments with the predictions using the theoretical ray model

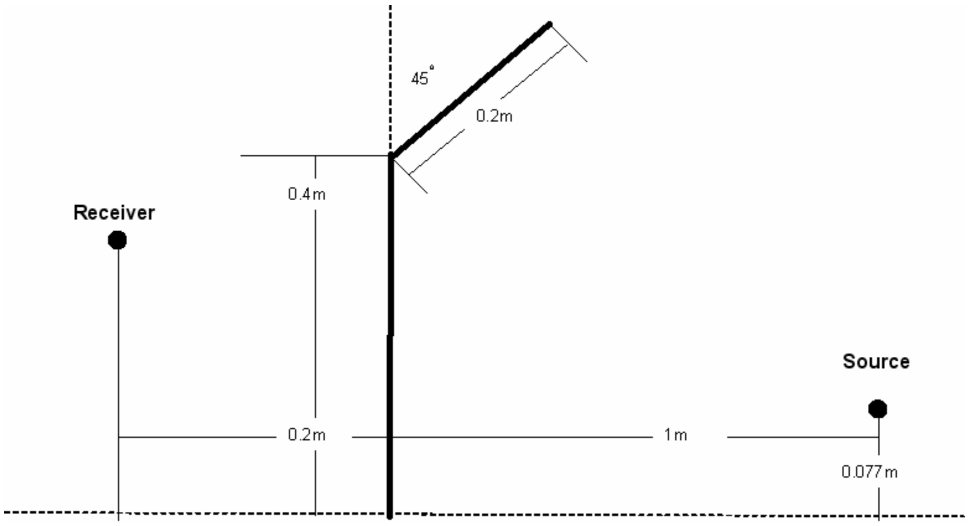


Figure 5.7 – a cranked barrier (0.4m high plus 0.2m long plank extended at 45°) with source at 1.0m away and 0.077 m high and receivers at 0.2m away

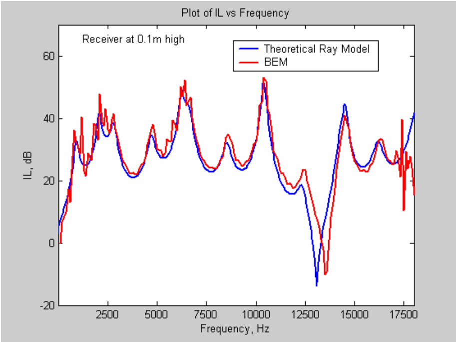


Figure 5.8 (a)

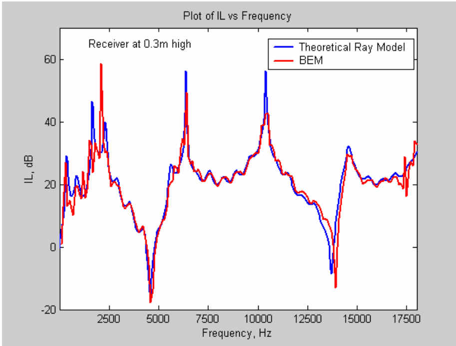


Figure 5.8 (b)

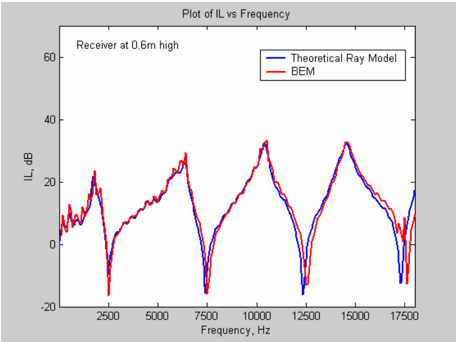


Figure 5.8 (c)

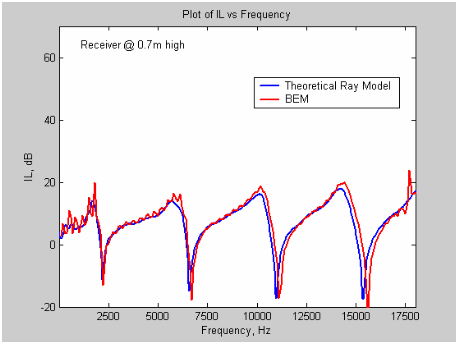


Figure 5.8 (d)

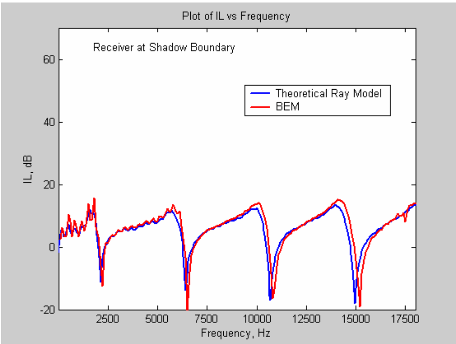


Figure 5.8 (e)

Figure 5.8 (a) to (e) – Comparison of BEM and the ray model of a cranked barrier for receivers at receiver at 0.1m high, 0.3m high, 0.6m high, 0.7m high and at shadow boundary

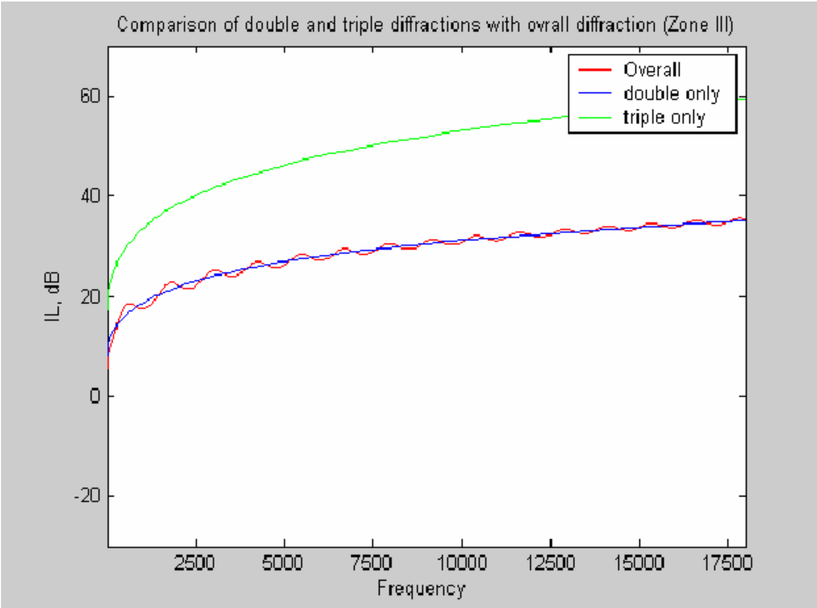


Figure 5.9 - sensitivity test of receivers in zone III following the cranked barrier configuration shown in Figure 5.7.

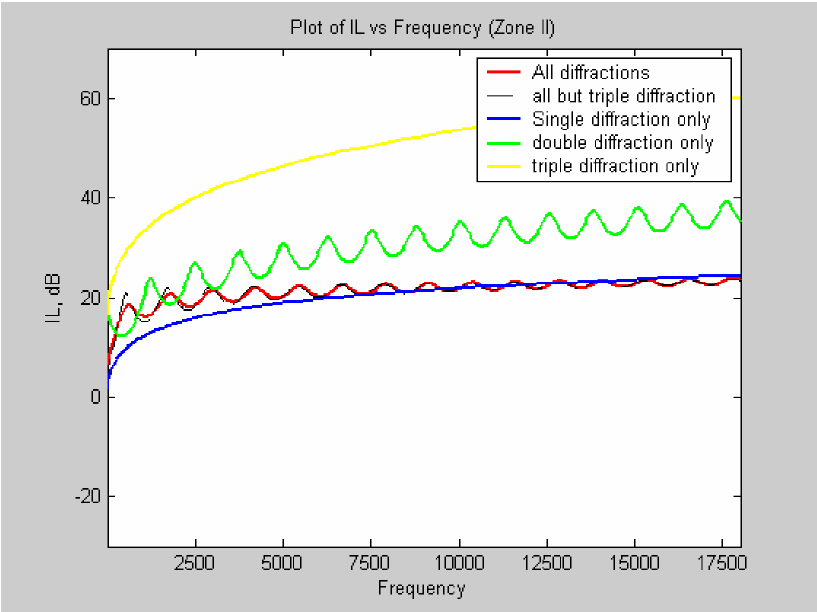


Figure 5.10 – sensitivity test of receivers in zone II following the cranked barrier configuration shown in Figure 5.7.

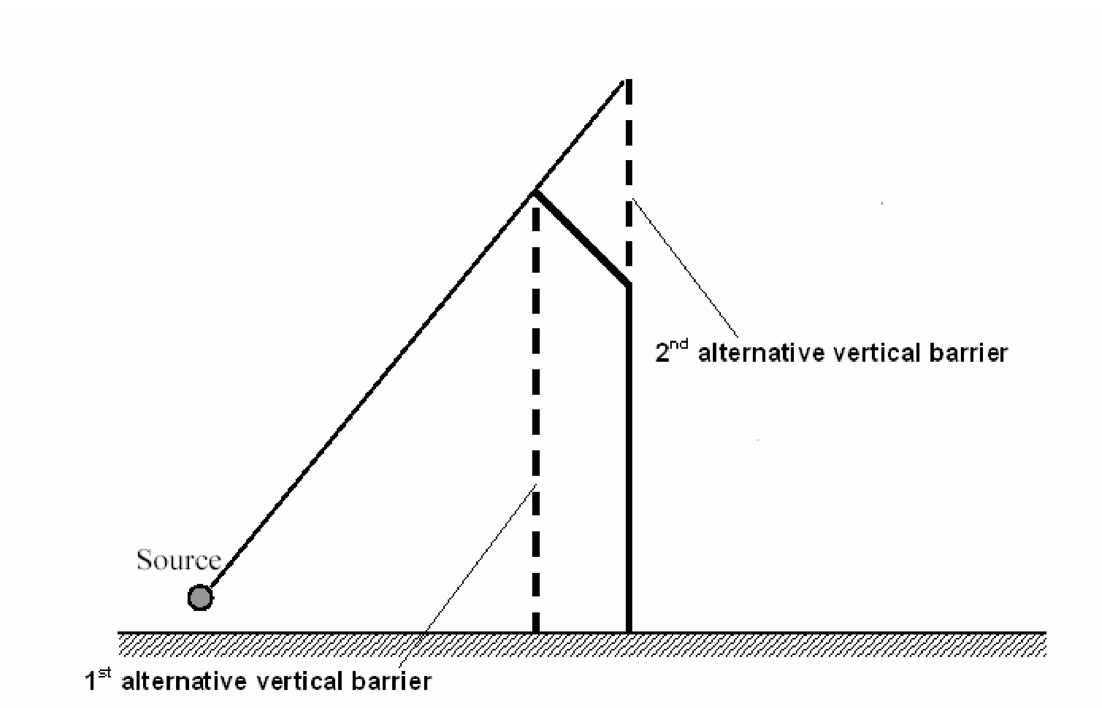


Figure 5.11 – Plan showing 2 possible scenarios of vertical barriers of equivalent heights

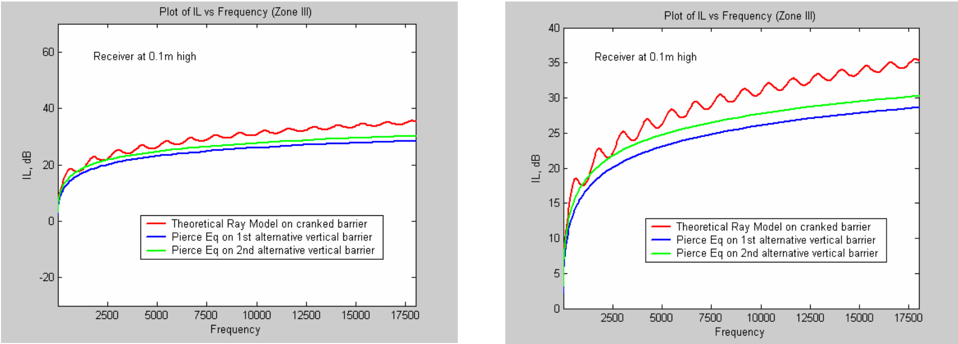


Figure 5.12 – Comparison of IL values for cranked barrier and the alternative vertical barriers with Receiver at 0.1m high

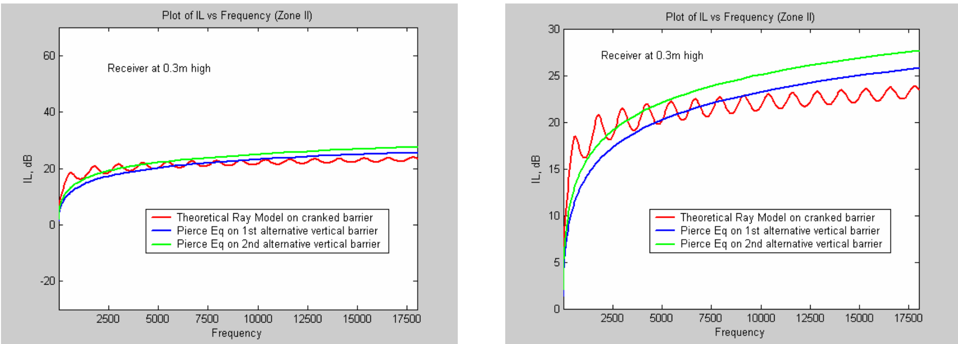


Figure 5.13 – Comparison of IL values for cranked barrier and the alternative vertical barriers with Receiver at 0.3m high

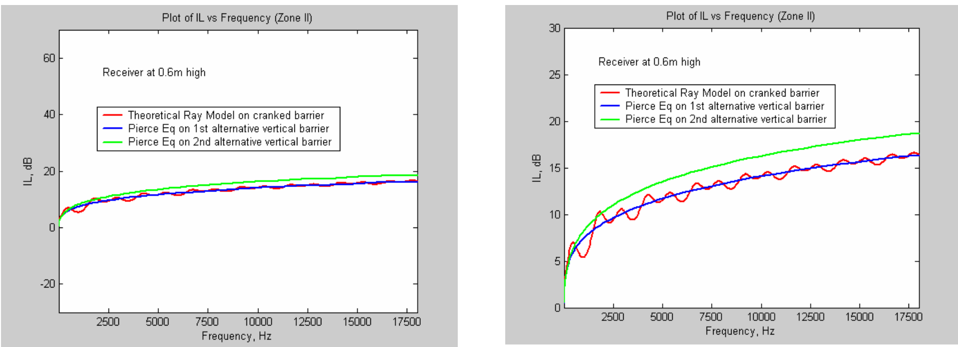


Figure 5.14 – Comparison of IL values for cranked barrier and the alternative vertical barriers with Receiver at 0.6m high

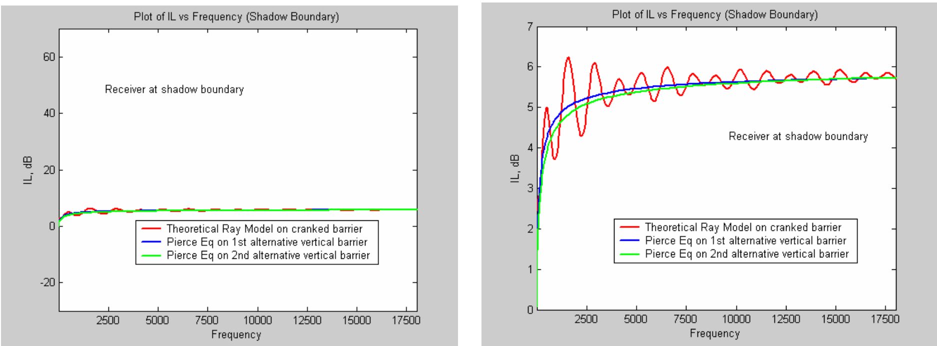


Figure 5.15 – Comparison of IL values for cranked barrier and the alternative vertical barriers with Receiver at shadow boundary

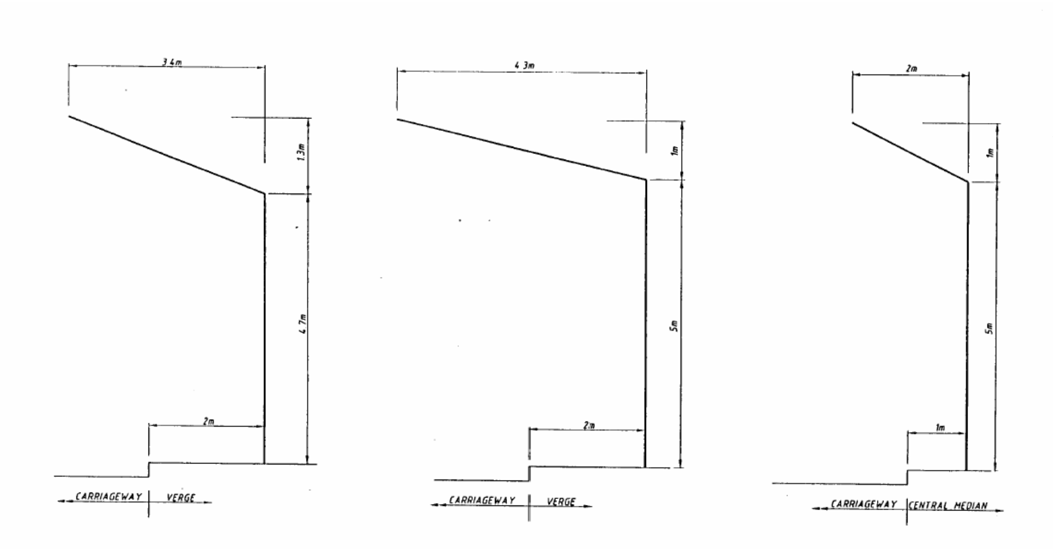


Figure 5.16 – some examples of cranked barrier design in Hong Kong

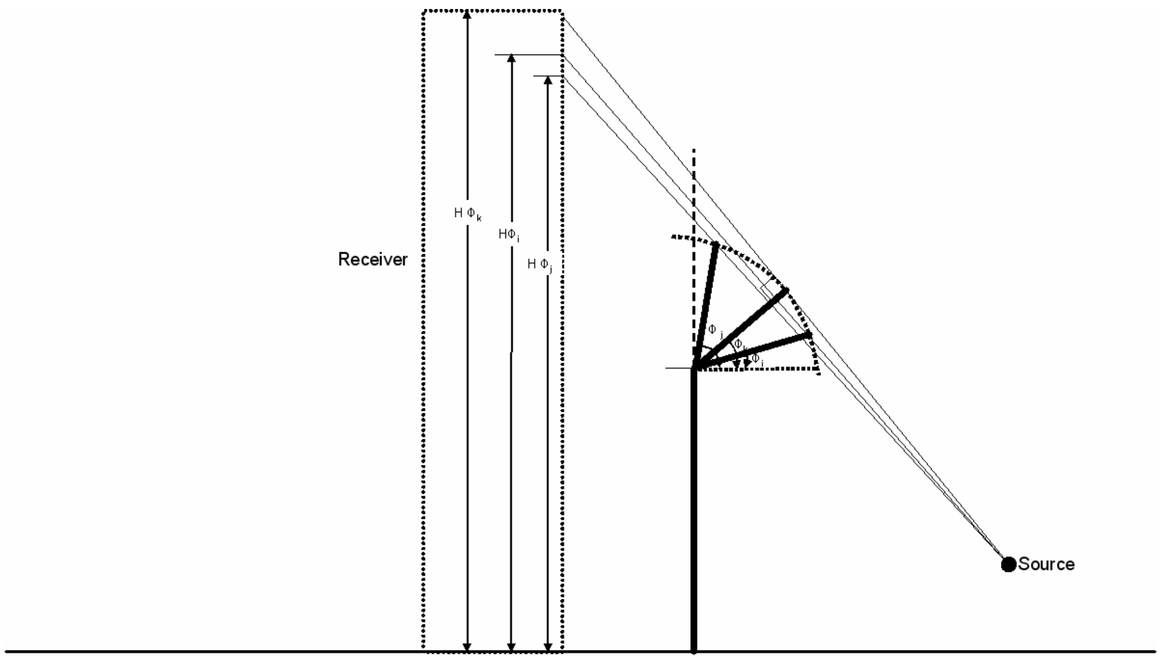


Figure 5.17 – Schematic plan showing comparison of size of shadow zone produced by different angles subtended by the cranked plank to the horizontal

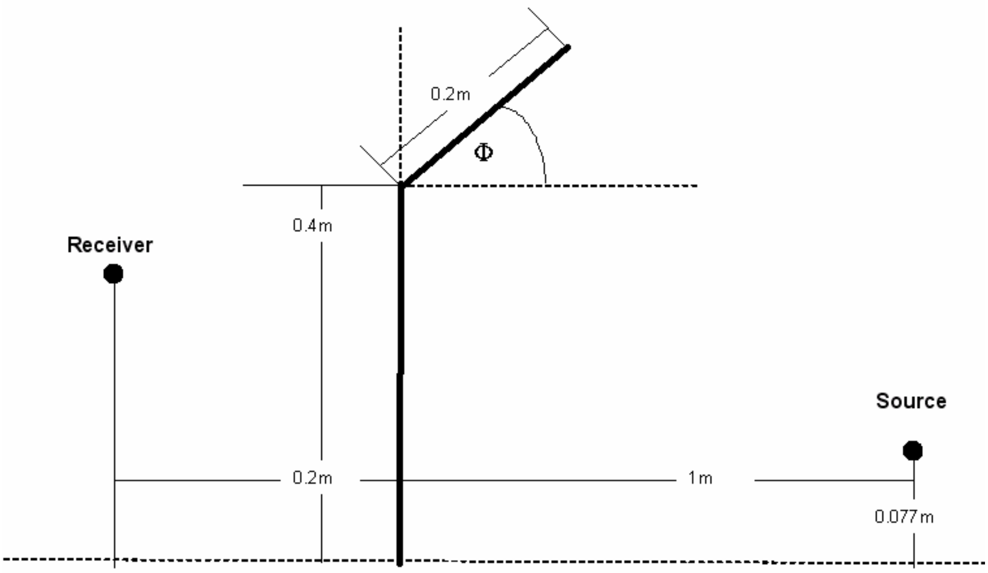


Figure 5.18 – Configuration of cranked barrier under study

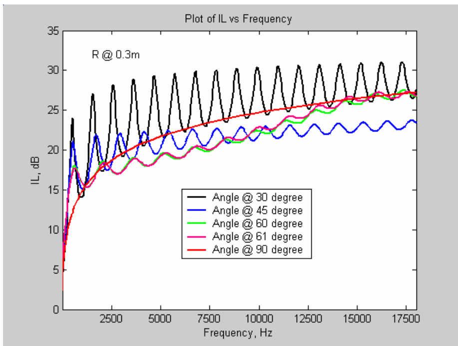


Figure 5.19(a)

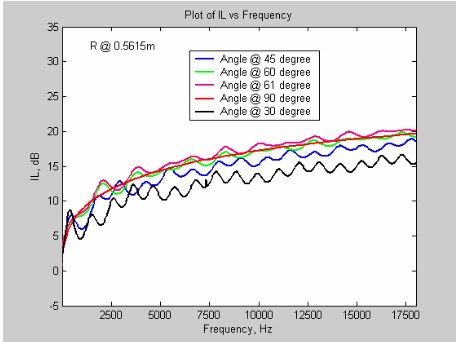


Figure 5.19(b)

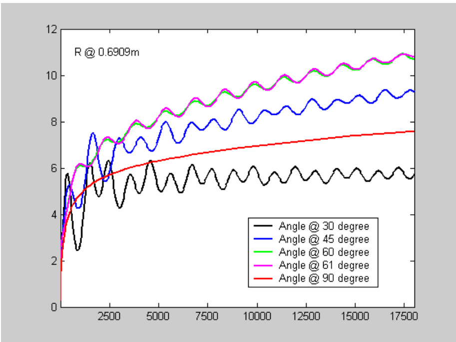


Figure 5.19(c)

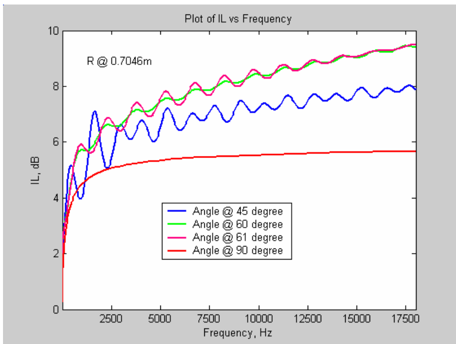


Figure 5.19(d)

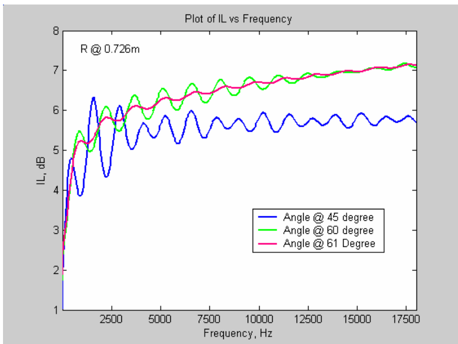


Figure 5.19(e)

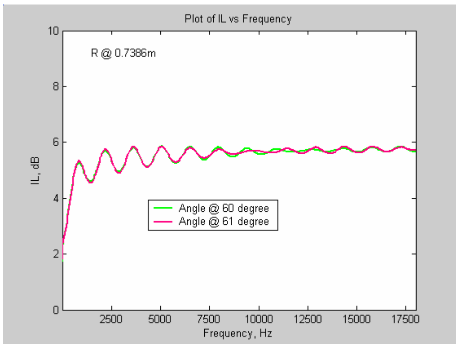


Figure 5.19(f)

Figures 5.19 (a) to (f) – Plots of IL against Frequency of Receivers at 0.3m, 0.5615m, 0.6906m, 0.7046m, 0.726m & 0.7386m high at 0.2m from cranked barrier with source located at 1.0m away on the other side of cranked barrier and at 0.077m high. The angle subtended by the cranked plank to horizontal is set at Φ = 30°, 45°, 60°, 61° & 90°

	IL dB(A)				
Receiver Height	**Φ= 30°**	**Φ = 45°**	**Φ = 60°**	**Φ = 61°**	**Φ = 90°**
0.3m	25.8	25.8	26.3	26.8	24.2
0.5615m	14.2	16.3	18.0	18.7	17.4
0.6909m	10.6	12.2	13.0	13.0	11.4
0.7046m	-	11.8	12.5	12.6	11.0
0.726m	-	11.1	11.8	11.7	-
0.7386m	-	-	11.4	11.4	-

Table 5.2 - IL (dB(A)) of Receivers at 0.3m, 0.5615m, 0.6909m, .07046m, 0.726m and 0.7386m high with Φ (the angle subtended by the cranked plank to horizontal) set at 30°, 45°, 60°, 61° and 90°.

Chapter 6

DISCUSSIONS AND CONCLUSIONS

6.1 Introduction

In dense high-rise cities, road traffic noise is one of the most severe environmental noises affecting the residents. The magnitude of road traffic noise impact amplifies enormously in the past years due to the ever increasing demands of transport need in terms of building more road networks and putting more vehicles in the cities to support the economic growth and social activities. The impact is further intensified when more housing estates and residential buildings are built in cities and buffer separation between trunk roads and residential buildings diminishes sharply. The situations even go worse when extent of hours exposed to road traffic noise goes beyond early morning and late night.

With reference to the literature search conducted in Chapter 1, governments or administrations, either at the federal, regional or municipal levels, are tackling road traffic noise problem through various means and at different fronts. Such efforts are at different hierarchy, levels and stages. For instance, taking early actions at planning stage to avoid putting heavily trafficked roads close to residential estates, statutorily controlling noise emission from individual vehicles, erecting barriers and overlaying low noise road surfacing, restricting unnecessary vehicle movements in residential areas during sensitive hours, providing window insulations to dwellings etc. are different approaches and types of measures taken by governments or administrations. Given the differences in nature, context, effects, costs of the various approaches and measures, it is not appropriate to rank or rate these measures as each of them has their own merits and particular usefulness in tackling road traffic noise. In sum, some measures would, to some extents, compliment other measures. To effectively reduce road traffic noise impact, a package of measures would unavoidably be necessary in some cases. The latest which would likely be the best illustration is the draft "Comprehensive Plan to tackle road traffic noise" (Plan) proposed by the Hong Kong SAR Government in April 2006 to combat road traffic noise [7]. In this Plan, nine enhanced measures, on top of actions which are already in place, are proposed in further tackling road traffic noise. Among the nine proposed enhanced measures, the Plan suggests optimizing the barrier design. This suggestion is in fact in line with the trends and practices in other countries. In Japan, the researchers are looking intensively and closely at different means to improve the efficiency of edge-modifier (i.e. modifier attached to the edge of barriers) and the researchers in the Netherlands are in parallel trying to improve the efficiency of barrier designs by adding special features [91, 92].

Whilst optimizing barrier designs is the right trend, some of the fundamental issues of the road traffic noise assessment or prediction schemes would also warrant to be reviewed so that commensurate packages could be reviewed or included taking into account the latest trend and developments of barrier designs. Against this background, the goals of this study aim at looking into the accuracy of the current assessment and prediction tools in particular in those cases where noise sensitive receivers locate closely at barrier shadow boundary so that measures would not be under-provided in some cases and over-provided in others. To achieve the study goals, the following study objectives are established:

a. Examining and modifying the potential barrier chart adopted by the CRTN;
b. Examining and evaluating the diffraction characteristics of parallel barrier systems; and
c. Examining and evaluating the diffraction characteristics of cranked barriers

To enable achieving fruitful and useful results, it would be appropriate to examine the issues in the context of the legislative requirements, policy and practices in Hong Kong. This is logical as Hong Kong is one of the hyper-dense high-rise cities (6.9 million people living in 1000 sq Km in which about 80% are hilly areas).

6.2 The Legislative Frameworks, Policy and Practices Pertaining to Adopting Noise Barriers to Tackle Road Traffic Noise in Hong Kong

Adopting noise barriers to tackle road traffic noise in Hong Kong started in early 90s. The first roadside noise barrier is about 990m long 1.5 to 4m high vertical transparent panel built on Shing Mun Tunnel Road Approach in Shatin. This was designed in late 80s and completed in 1990. Since then, various forms of barriers including vertical barriers, cranked barriers, semi-enclosures and enclosures were constructed on new and existing roads.

6.2.1 New Roads Projects in Hong Kong

The Environmental Impact Assessment Ordinance (EIAO) that came into force in August 1999 requires that when planning new roads, or projects involving substantial widening of existing roads, the relevant government department or developer must ensure that traffic noise at sensitive receivers will stay within the noise limits (65dB(A)L_{10}(1 hr) for schools and 70 dB(A) L_{10} (1 hr) for residential premises). If through a defined vigorous assessment procedure the predicted traffic noise still exceeds the noise limits, the project proponent must adopt all practicable direct measures including choosing a better alignment, surfacing the road with low noise material and erection of noise barriers or enclosures in practicable manner to reduce the impact on users of noise sensitive buildings in the neighbourhood. In cases where barriers or enclosures alone would not be adequate in mitigating noise impacts, indirect technical remedies in the form of good window insulation and air-conditioner for existing residential flats may be adopted provided that the residual impacts satisfy all three criteria below [39]:

a. the predicted overall noise level from the new road together with other traffic in the vicinity must be above 70 dB(A) L_{10} (1hr));
b. the predicted overall noise level is at least 1.0 dB(A) more than the “prevailing traffic noise level”, i.e. the total traffic noise level existing before the works to construct were commenced; and

c. The contribution to the increase in the predicted overall noise level from the new road must be at least 1.0 dB(A).

6.2.2. Retrofitting Noise Barriers on Existing Roads in Hong Kong

In 2000, the Hong Kong SAR Government established policy under which engineering solutions including noise barriers would be provided on existing roads exhibiting high level of traffic noise (i.e. exceed 70 dB(A)L_{10}(1 hr)) providing that it is engineering feasible for erecting barriers and that funds are available. Engineering feasible basically means that there is adequate space for erecting barriers (adequate strength in case of flyover). Also, barrier erected would neither traffic safety; fire-fighting nor social and business of on-street shops. As at 2007, the Hong Kong SAR Government has programme to retrofit 35 road sections at cost of about HK$3400 Million benefiting 100,000 residents. The policy require that barriers are to be provided in practical manner which means that there is no requirement to bring noise at residential flats down to 70 dB(A)L_{10}(1 hr) [93].

6.2.3 Guiding Principles in Implementing Roadside Noise Barriers in Hong Kong

The Hong Kong SAR Government promulgated in Jan 2003 a set of guiding principles of the provision of noise barriers on roads:

Principle 1: Compliance with existing statutory requirements

Principle 2: Timely implementation of mitigation measures, i.e. noise barriers

Principle 3: Setting priority for existing roads in the retrofit programme according to excessive noise levels

Principle 4: For existing roads, cost effectiveness of noise barriers

Principle 5: Paying due attention to aesthetic design of noise barriers

These 5 principles apply to new road projects as well as projects on retrofitting noise barrier on existing roads [94].

6.2.4 Guidelines on Designing of Noise Barriers

The Environment Protection Department and Highways Department of the Hong Kong SAR Government jointly published “Guidelines on Design of Noise Barriers” in 2001 and its revision in January 2003. The Guidelines provides information relating to the detailed design of roadside noise barriers including vertical and cranked barriers, semi-enclosures and full enclosures. The Guidelines covers various aspects at the detailed design stage including determination of acoustic properties of noise barriers like transmission loss; material selection; and some important tips at design and construction stages. However, the evaluation of barrier effectiveness or insertion loss is not covered as this would have been dealt with during Environmental Impact Assessment or Noise Impact Assessment studies conducted in earlier stages [39].

6.2.5 Traffic Noise Calculation Procedure and Methodology adopted in Hong Kong

The procedures in the " Calculation of Road Traffic Noise" (CRTN) of Department of Transport, United Kingdom is the recognized procedures and methodology used for assessing and predicting road traffic noise in Hong Kong. Section 5 of Annex 10 of the Technical memorandum issued under the EIAO and Section 4 of Chapter 9 of the Hong Kong Planning Standards and Guidelines (HKPSG) indicate that this is only method accepted for the assessment of road traffic noise in Hong Kong [36, 95]. Also, Guidance Notes 12/2005 “Road Traffic Noise Impact Assessment” is in place to provide general reference for practitioners to prepare road traffic noise impact assessment for designated projects under the EIAO [96].

6.3 Discussions

The results of investigations and evaluations carried out in Chapters 3 to 5 would be discussed against the backgrounds of the above legislative frameworks, policy and practices adopted for provision of noise barriers in the following paragraphs. The potential implication, if any, to the practices in assessing road traffic noise and erecting noise barriers as mitigation measures in dense high-rise cities would be explored. The practices in Hong Kong would be used for illustration of such implications.

6.3.1 Examining and Modifying the Potential Barrier

Correction Chart adopted in the CRTN

In the CRTN, a user-friendly attenuation correction chart is adopted for evaluation of barrier attenuation effect or insertion loss (IL) in dB(A) due to presence of barriers or obstruction buildings. Once the geometry relationship between the site, the road and the intervening obstruction are known, then the IL values can be obtained from the chart. As examined in Chapter 3, the attenuation correction chart follows the principle of Maekawa's chart developed some 40 years ago. This potential barrier correction chart was reviewed on the basis of the recent works by Menounou which indicated that a single Fresnel Number (N_1) used in Maekawa's chart may not be adequately capable for estimating attenuation due to thin and long barrier in particular in situation where receivers are close to shadow boundary. With the introduction of second Fresnel Number (N_2) which takes into account the presence of image source, Menounou developed new set of attenuation (or IL) curve for spherical, cylindrical and plane waves for more accurate results of evaluating barrier attenuation effect. This is definitely necessary and significant when public money is spent in providing barriers for noise protection.

Following Menounou's works, the potential barrier correction chart in the CRTN was re-constructed. In addition to the geometry relationship between the site, the road and the intervening obstruction, one would also need to know the geometric relationship between the site, the image of source (i.e. road) and the intervening obstruction. With these two values, one can read from the chart the IL values. Two hypothetical cases were examined and identified that the potential barrier correction chart in the CRTN tends to under-estimate the IL values by as high as 2.3 dB(A) as compared with the new set of curve re-constructed based in Menounou's works. The new set of curve re-constructed based on Menounou's works would have implications on the practice of erecting barriers to mitigate traffic noise in Hong Kong as discussed in the following paragraphs.

6.3.1.1 The Potential Implication to the Practice of Assessing Traffic Noise and Approach in Tackling it in Hong Kong

With reference to the discussion above that when planning and constructing new roads, noise barriers would need to be provided upon identification of noise exceeding the criterion in Technical Memorandum of EIAO and that indirect technical remedies in the form of good window insulation and air-conditioner would further be provided in case barriers and other means like re-aligning of roads etc cannot bring noise to the acceptable level in Technical Memorandum of EIAO. The accuracy of the CRTN in determining the requirement of barriers would become critical.

With reference to the two case studies in Chapter 3, there was a tendency that potential barrier attenuation curve of the CRTN would likely under-estimate Insertion Loss (IL) of barrier by as high as 2.3 dB(A). In other words, for the same configuration of barriers, the noise levels at receivers within shadow zone would experience noise level of at most 2.3 dB(A) lower than the predicted values using potential barrier attenuation curve of the CRTN. At the shadow boundary, the under-estimation was more than 1 dB(A). This would have substantial implication to the practice of erecting barriers for mitigating traffic noise in Hong Kong. Given that the very peculiar Hong Kong situation in which high-rise residential buildings (40 storey or more) are often constructed next to expressway or major highways, cranked barriers, semi-enclosure or even enclosure would be necessary. If the CRTN under-estimates as discussed, some of these substantial structures like cranked barriers may be reduced to vertical barriers or semi-enclosures to cranked barriers. This would not only bring down the overall cost spending on constructing these substantial measures, but it would likely to have savings in the recurrent maintenance cost. Also, landscape architect would welcome this as the aesthetic design for lower and less substantial structure would be relatively easy. The residents living nearby and the drivers that use the expressway would find the less substantial structure less intrusive from aesthetic point of view.

Similar arguments apply in the provision of indirect technical remedies in the form of good window insulation and air-conditioner for existing receivers eligible under new road scheme. It is obvious that the number of dwelling eligible for noise insulation would become less and less.

Oh the other hands, the improved prediction accuracy may imply that less substantial barriers would be sufficient to protect residents in Hong Kong and lesser number of dwellings would be eligible for provision of good window Insulation and air-conditioners. Both implicitly mean lesser public resources and money would be required for noise mitigation works.

6.3.2 Examining and Evaluating the Deterioration of Noise Reduction Effectiveness due to Parallel Barriers in High-rise Cities

It is increasingly common in dense high-rise cities that barriers are constructed on both sides to alleviate road traffic noise on residents living in the high-rise residential estates and Hong Kong is of no exception. There are concerns that multiple reflections due to presence of barriers on the opposite side of roads would cause deterioration of attenuation effect. Although a correction factor has been included in paragraph 36 in the CRTN for this purpose, the deterioration due to parallel barriers have not been looked into systematically. The study is definitely necessary and significant to avoid over-estimation of attenuation in some cases or under-estimation in others.

In Chapter 4, investigation of deterioration of noise reduction effectiveness due to parallel barriers was conducted based on the theoretical ray model adopting the solution for thin barriers by Pierce. Similar approach has been adopted and validated by Li & Kwok [75] in their previous study of parallel barriers. The investigations focus on receivers in two particular Regions, namely Regions A & B where receivers were in shadow region of the real source S_1 (Figure 4.1 referred). Sound rays due to presence of 2 parallel barriers would reach receivers in Region A through diffraction at top of the screening barrier (Barrier A). In the case of receivers in Region B, the sound rays reflected from the reflecting barrier (Barrier B) could reach the receivers directly and through diffraction at top of Barrier A. The investigation identified that the deterioration of attenuation effect was significant if absorption materials are not used. In both cases, the barrier attenuation effect of screening barrier could be degraded substantially. The deterioration decreased when the distant separations of two parallel barriers increased. The decreasing trends can be normalized take into account the distance between receiver and top of screening barrier into the analysis within the parameters adopted in the case studies.

The CRTN discusses the combined screening and reflection effects of parallel barriers of prediction of road traffic noise. A correction factor based on a host of factors including relative height of the barriers and the height of receiver; receiver height; the horizontal distance between receiver and the screening barrier; horizontal distance between two parallel barriers; and the angle of the reflecting barrier for reflections. For comparison purpose, Chapter 4 studied two cases separately using the theoretical ray model developed and the procedures contained in the CRTN.

With reference to two case studies, differences between calculations from the ray model and the CRTN (see Figure 4.17) were noted. The trend of deterioration of noise reduction effectiveness of screening barrier alone identified from theoretical ray model decreased when distant separations between two parallel barriers increased. However, the corrections in the CRTN showed that the deteriorations were relatively constant for two cases (see Table 6.1). For barrier separations less than 30m, calculations from the CRTN in both cases under study showed that deterioration of noise reduction effectiveness of screening barrier alone are constant which were about 1.9 dB(A) and 4.09 dB(A) for receivers in Region A & B respectively. For barrier separation more than 30m, the differences between calculations from the fray model and the CRTN were approximately 1 to 1.5 dB(A) for receivers in both Region A & B.

6.3.2.1 The Potential Implication to the Practice of Assessing Traffic Noise and Approach in Tackling it in Hong Kong

It is useful to note from the CRTN that if all parameters like barrier heights, distance between receiver and source to that of screening barrier remain unchanged, the factor that would affect the IL correction is the horizontal distance between two parallel barriers. Accordingly, this is constant for distance between parallel barriers is less than 30m and hence the calculated IL correction for the combined screening and reflection effects of parallel barriers in receivers in Regions A & B. There is no information in the CRTN indicating why such function is constant for distance between parallel barriers is less than 30m. Taking the situations of Hong Kong as examples, 30m in width would usually be the width of a dual 3-lane road with hard shoulder. Although this is not indicated, it appears that parallel barriers were only assumed for trunk roads or expressway of dual 3-lane. For dense high-rise city like Hong Kong, barriers are commonly found erected at the central median of trunk roads or expressway for noise mitigation which means that the distance between two parallel barriers could be much less than 30m. These may not be the situations considered when the CRTN was developed.

With reference to the discussion above, there is a concern in the efficacy and adequacy of the CRTN in calculating deterioration of noise reduction effectiveness of parallel barrier system. The differences shown in Table 6.1 suggest that the deterioration of noise reduction effectiveness due to existence of parallel barriers would have been under-estimated in many cases and resulted in over-estimation of noise attenuation effect of barriers. Because of these, more substantial and higher barriers would be required in actual case and in other words, some flats may actually not be benefited from erection of barriers if absorptive materials are not added to make the barriers acoustically absorptive. Also, some of the flats could become eligible for provision of noise insulation works for new road projects.

The CRTN would have over-estimated the situation of parallel barriers if absorptive materials are not used. Hence, in some cases, barriers or more substantial barriers would be required to meeting with the legislative requirements in new road projects. Following the same argument, some flats would be eligible for provision good window insulation and air-conditioners.

6.3.3 Examination and Evaluation of Diffraction Characteristics of Cranked Barriers in Dense High-rise Cities

Cranked barriers are commonly used in dense high-rise cities because it can improve the shielding efficiency at a reduced barrier height. However, its diffraction characteristic has not been duly examined and evaluated. Neither is a provision contained in the CRTN nor the current commonly adopted assessment approach has been authentically studied. This study is necessary and significant to achieve accurate estimation for daily application. In Chapter 5, a theoretical ray model has been developed and validated through experimental and numerical models. Based on the theoretical ray model developed, the following two areas have been specifically looked into:

a. the efficacy and adequacy of assessing insertion loss of cranked barriers; and
b. the optimization of cranked barrier design.

The evaluations in Chapter 5 identified that on predicting noise reduction effectiveness or insertion loss of cranked barriers, predicting using the alternative vertical barrier approach for a rough estimation of IL values for receivers at and close to shadow boundary would give reasonable results. However, for receivers in shadow zone and those down deep in shadow zone, the estimation would tend to under-estimated.

On optimizing cranked barrier designs, it is noticed from Chapter 5 that for receivers deep in the shadow zone, change of Φ (the angle subtended by the cranked plank to horizontal) may not cause significant effect to IL prediction in daily usage. However, for receivers close to shadow boundary, the IL values could be maximized by setting Φ at which the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°). Following the above discussions, the design of cranked barriers can be optimized when the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°). The optimization provides the largest shadow zone and also maximizes the IL values for receivers close to the shadow boundary of cranked barriers.

6.3.3.1 The Potential Implication to the Practice of Assessing Road Traffic Noise and Approach in Tackling it in Hong Kong

When analyzing the potential implications of adopting cranked barriers as traffic noise mitigation in Hong Kong with reference to the results found in Chapter 5, attention would surely be paid to the following aspects:

a. The adequacy of the CRTN or the respective guidance notes in assessing noise reduction effectiveness of cranked barriers;
b. The legislative and policy requirements of mitigating traffic noise arising from new road projects; and
c. The improvement to the current practice in designing cranked barrier.

6.3.3.2 Adequacy of the CRTN or the Respective Guidance Note

While there is no provision of assessing noise reduction effectiveness of cranked barriers in the CRTN, the Environmental Protection Department of the Hong Kong SAR Government promulgated in Nov 2005 a Guidance Note GN12 to provide general reference for practitioners to prepare “Road Traffic Noise Impact Assessment” for designated projects under the EIAO [96]. The GN12 suggests to define a virtual vertical barrier at the pseudo-location of a cranked barrier (i.e. the highest edge of the actual barrier) for assessment of cranked barriers. This approach is basically the same as the 1st alternative vertical barriers studied in Chapter 5. With this as background, the findings in Chapter 5 could be applied for evaluation of the situation in Hong Kong.

The discussions in Chapter 5 show that using the approach of virtual vertical barrier for assessing noise reduction effectiveness of cranked barriers would provide good reasonable estimation for receivers at shadow boundary as compared with analysis adopting the theoretical ray model developed.. However, this approach would have under-estimated the noise reduction effectiveness for receivers in shadow zone and those down deep in shadow zone. While receivers in shadow zone and down deep in shadow zone would have large IL values, what causes concerns are those receivers at shadow boundary. Following the recent study of Menounou, a new set of curves is developed in Chapter 3 in which both real and image sources would be taken into account. Investigations and evaluations in Chapter 3 also indicate that the case study results following new set of curves agree largely with that by solution of Pierce. Following this and the discussions above that the CRTN using virtual vertical barrier approach would have an under-estimation of noise reduction effectiveness of cranked barriers at the shadow boundary by about 1 dB(A) .

6.3.3.3 The legislative and Policy Requirements of Mitigating Traffic Noise from New Road Projects

This is critical to the practice of erecting barriers on new road projects in Hong Kong. As discussed above that Hong Kong situation is so peculiar that high-rise residential buildings (40 storey or more) are often constructed next to expressway or major highways and hence cranked barriers would be necessary. If the CRTN under-estimates as discussed, some of these substantial structures like cranked barriers may be reduced to vertical barriers. This would not only bring down the overall cost spending on constructing these substantial measures, but it would likely to have savings in the recurrent maintenance cost. Similar arguments apply in the provision of indirect technical remedies in the form of good window insulation and air-conditioner for existing receivers eligible under new road scheme. It is obvious that the number of dwelling eligible for noise insulation would become less and less.

6.3.3.4 The Current Practice in Designing Cranked Barriers

There is no guidance on how to design cranked barriers in Hong Kong, for instance, how the angle of subtended by the cranked plank to horizontal to achieve better performance. Study in Chapter 5 identifies that the design of cranked barriers can be optimized when the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°). The optimization provides the largest shadow zone and also maximizes the IL values for receivers close to the shadow boundary of cranked barriers.

Against this background, the cranked barrier design in Hong Kong can be improved by following the optimized design identified and further guidance notes would be required to ensure consistency.

As summary, the current practice in Hong Kong in evaluating barrier attenuation effect or insertion loss (IL) of cranked barriers using the virtual vertical barrier would have over-estimated the noise reduction effectiveness of cranked barriers. The improvements discussed above would have implications to the legislative requirements and practice in Hong Kong. In some cases, substantial cranked barriers would not be required to meeting with the legislative requirements in new road projects. Following the same argument, less number of flats would be eligible for provision good window insulation and air-conditioners. Also, maximum insertion loss of cranked barrier could be achieved when the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°).

6.4 Conclusions

Due to host of factors like fast economic growth, limited space for habitable development, concentrated road networks etc., road traffic noise is recognised as one of the most severe environmental noise affecting daily livings in dense high-rise cities. There are different approaches and means to tackle the ever increasing magnitude traffic noise problem in dense high-rise cities, roadside noise barrier is one of the most commonly adopted measures. Because of the high density nature of high-rise cities, substantial roadside barriers like full enclosure, semi-enclosures or very high noise barriers would be needed to provide necessary noise reduction. Many research works have been conducted in past decades in improving the assessment and evaluation of effectiveness; materials; and design of roadside barriers. This study specifically looks into the accuracy of the current assessment and prediction tools like CRTN in particular in those cases where noise sensitive receivers locate close at barrier shadow boundary so that measures would not be under-provided in some cases and over-provided in others. The CRTN has been used for more than 20 years and some of the procedures in assessing barrier attenuation effect would need to be carefully examined in view of the recent findings of various researchers. Such examinations and reviews would help improving the assessment accuracy. Through theoretical and experimental evaluations, this study examined three particular aspects which are significant and have major implications in provision of noise barriers in mitigating road traffic noise impact. These are without precedent.

On the potential barrier attenuation curve in the CRTN, I have successfully improved its accuracy by modifying the curve on the basis of Menounou’s recent works. Test cases conducted shows significant improvements in assessing height of barriers needed and provision of noise insulation to affected dwellings. This could result in decrease in height of barriers to be provided and numbers of dwellings eligible for provision of noise insulation under new road projects in Hong Kong.

On parallel barrier situations which is rather common in Hong

Kong situations given the need to protect residents from road traffic noise, through the theoretical model, I have studied the deterioration of noise attenuation effect due to parallel barriers, I have further identified that the current correction used in the CRTN for parallel barriers is unlikely adequate to cover all situations in Hong Kong.

On cranked barriers, I have developed a theoretical ray model for evaluating its diffraction characteristics. I have further identified that the noise reduction effect of cranked barriers could be could be maximized by setting the cranked plank in such manner at which the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°). I have identified that the current approach of assessing the insertion loss of an alternative vertical barrier would have under-estimated for majority of receivers in shadow zone.

The examinations and evaluations conducted suggest that there are rooms for improvements in the aspects of prediction and designing of roadside barriers. In the case of situations in Hong Kong, the improvements would help refining the provision of barriers; and window insulations and air-conditioners in a more accurate manner. As a result, less substantial barriers would be sufficient to protect residents noise-wise and it is anticipated that lesser number of dwellings would be eligible for provision of "Noise Insulation". Both implicitly means lesser public resources or money would be required for noise mitigation works without compromising the overall protection effects.

6.5 Recommendations for Future Works

The evaluations in Chapters 3 to 5 and discussions in Chapter 6 identify that there are potential improvements in some aspects prediction and designing of roadside noise barriers in dense high-rise cities. The findings are in fact initial results, further evaluations and investigations are recommended for development of fruitful and useful improvements. The ensuing paragraphs enable discussions in these aspects.

6.5.1 Modifying Potential Barrier Attenuation Curve in the CRTN

Following Menounou's works, the potential barrier correction chart in the CRTN is re-constructed. The new set of curves is also user-friendly. In addition to the geometry relationship between the site, the road and the intervening obstruction, one would also need to know the geometric relationship between the site, the image of road (i.e. source) and the intervening obstruction. With these two values, one can read from the chart the IL values. The new set of curve re-constructed based on Menounou's works would have implications on the practice of erecting barriers to mitigate traffic noise in Hong Kong. The improved prediction accuracy may mean that less substantial barriers would be sufficient to protect residents in Hong Kong and it is anticipated that lesser number of dwellings would be eligible for "noise insulation". Both implicitly mean that lesser public resources or money would be required for noise mitigation works without compromising the overall protection effects.

Instead of relying on the new set of curves, polynomial expressions should be developed for incorporation into computational programme for calculating road traffic noise. Also, it should be noted that the study and modification works of Maekawa's chart by Menounou were confined to the shadow zone region and further works should be extended to include any part at the illuminated zone region.

6.5.2 Deterioration of Noise Reduction Effectiveness of Screening Barriers due to Presence of Parallel Barriers

The reflection and diffraction characteristics of parallel barriers with no ground reflection have been investigated using ray model through case studies. For parallel barriers of hard reflective characteristic, deterioration of noise reduction effectiveness of the screening barrier alone due to multiple reflection of screening barrier and reflecting barrier is identified. While 4 hypothetical cases using ray model were examined. Trends of deterioration characteristics of parallel barriers are developed in these cases.

For general purpose, further works based on the results of the 4 hypothetical cases could be carried out to develop new sets of deterioration characteristic curve for parallel barriers. Also, polynomial expressions could be developed for incorporation into computational programme for calculation.

To avoid deterioration of noise reduction effectiveness of screening barrier, consideration should be given to provide insulation at both screening and reflecting barriers. As the deterioration is due to the presence of the ray paths generated from the reflection on both reflecting barrier and screening barrier, insulation should be provided to both barriers. According to reflecting patterns of ray paths, it is not necessary to apply insulation to the entire surface but the middle section of both barriers.

Two hypothetical cases using ray model and the CRTN on deterioration were examined. It was identified that there is a need to review the relevant procedures in the CRTN in particular for distance separation between parallel barriers is less than 30m.

6.5.3 Diffraction Characteristics of Cranked Barriers

The diffraction characteristic of cranked barriers have been investigated through a more systematic and analytical manner. A theoretical ray model has been developed; validated through experimental model and numerical model; and found suitable for daily prediction purpose. Investigations were further conducted to evaluate potential improvement of current applications in the aspects of prediction of sound fields and optimisation of cranked barriers. For the prediction of sound fields, initial findings indicate that the adoption of alternative vertical barrier for predicting the noise reduction effectiveness of cranked barrier may not be appropriate approach. For a rough estimation of IL values for receivers at and close to shadow boundary, predicting using solution by Pierce on 1st alternative vertical barrier could give reasonable results. On optimization, the findings indicate that when the straight shadow boundary line drawn from source to receiver intersecting the tip of cranked plank at perpendicular (i.e. at 90°), the design of cranked barriers provides the largest shadow zone and the maximum better attenuation effect or insertion loss (IL) for receivers close to the shadow boundary of cranked barriers.

In the CRTN, a potential barrier correction as a function of path difference is adopted for calculating barrier attenuation effect. However, the correction was developed on the basis of vertical barrier design. Given the differences in diffraction characteristics of cranked barriers and vertical barriers, it is necessary to develop a separate correction for cranked barriers given that cranked barriers would be widely adopted given its advantages over straight barriers in terms of enhanced noise reduction effectiveness.

Separation between barriers, m	Deterioration of attenuation characteristics IL due to presence of parallel barrier,			
	Receivers in Region A		Receivers in Region B	
	Ray Model	CRTN	Ray Model	CRTN
7 - 56	0.3 - 4.9 dB(A)	1.4 - 1.9 dB(A)	2 - 13.9 dB(A)	3.1 - 4.1 dB(A)

Table 6.1 – Summary of case studies of deterioration of noise reduction effectiveness due to presence of parallel barriers (extracted from Table 4.4)

Appendix

The following is the publication of conference paper produced by the author. They are the output arising from this research study.

1. Maurice KL Yeung and KM Li, “An investigation of diffraction characteristics of a crank barrier in high-rise cities”, Paper for presentation at the 35th International Congress and Exposition on Noise Control Engineering, held in Honolulu, Hawaii, USA on 3-6 December 2006.

2. Maurice KL Yeung and KM Li, “The Modification of Potential Barrier Correction Chart in the ‘Calculation of Road Traffic Noise’”, Paper for presentation at the 37th International Congress and Exposition on Noise Control Engineering, held in Shanghai, PRC on 26 – 29 October 2008.

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