Statistical simulation modelling for stochastically varying acoustical systems and its application to the assessment of impact and amenity, informing improved environmental and land-use planning

Robert John Fitzell

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Sydney School of Architecture, Design and Planning

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Preface

This thesis was written by me and any help that I have had in preparing it, as well as any sources and reference materials that have been used, have been acknowledged in this thesis. This thesis has not already been submitted for any degree and is not being submitted as part of candidature for any other degree.

Signature of Candidate

Author Attribution Statement

The thesis contains material published in the following publications:

1. Fitzell R.J. (2019) “Prediction of Statistical Noise Metrics for Road Traffic”. InterNoise 2019
2. Fitzell R.J. (2019) “Environmental Noise Analyses – A Rethink”. interNoise 2019
3. Fitzell, R.J. (2019) "Expected ambient noise levels in different land-use areas". ACOUSTICS 2019
4. Fitzell R.J. (2019) "Impact and its Magnitude". ACOUSTICS 2019

The thesis content includes the results of analyses carried out, for this thesis, using data extracted from a database containing statistical sound pressure level survey records, designated as the APD database (author professional database). The APD database contains records that have been compiled over a period of more than 35 years. The extracted data involves survey record measurements carried out by the author and by employees of a company owned and managed by the author, using measurement survey procedures designed, approved and supervised by the author.

I designed all studies, extracted and analysed all data and wrote all published papers.

Abstract

The focus of this thesis is land-use planning. The thesis has been written after a career of almost five decades in professional acoustical consultancy practice during which many examples of uncertainty and potential misinformation have been experienced, adversely affecting application of the scientific field of environmental acoustics and, in turn, effective land-use planning. Many aspects discussed in this thesis have parallels in broader fields of environmental management and in land-use planning generally.

The thesis discusses what is meant by the acoustics of an environment, considers its features and the complexities associated with attempts to quantify that environment. Review of current methods of management, using the Australian state of NSW for legislative context, identifies both procedural and communication limitations. It is considered that most of these limitations are common internationally.

Central to the thesis is the assessment of impact and, by inference, amenity. Impact is a loosely applied term used commonly in many fields relating to an environment and of land-use planning, but its potential use as a legislative control is restricted by legal, objective and subjective issues. The implication of good environmental management is an outcome achieving a reasonable magnitude of impact. However, impact is undefined, reasonable is a legally nebulous term while magnitude of acoustical impact cannot be currently determined. This leads to frequently conflicting expectations depending on the viewpoint of the stakeholder. Noise management policy is designed to manage only human annoyance whereas legislation implies that an underlying policy objective is to manage environmental damage in a more holistic sense. Notwithstanding this restricted focus, the methods adopted by current noise management policy provide inadequate guidance on the consideration of impact on amenity.

Current assessment methods for environmental acoustics are unable to consider impact explicitly, nor can they provide a clear foundation improving legislative interpretation. However acoustical impact can be measured explicitly, using methods described in the thesis, with demonstrable benefits.

Early methods of assessment in environmental acoustics used largely manual measurement methods during which operator skill and judgement could reach informed conclusions within a stochastically varying realm. These methods also enabled the identification of aspects now described as the soundscape of an environment and their relevance to a situation, particularly the role of amenity. Although less standardised, these methods were illuminating and technically flexible. Current methods of acoustical impact assessment are not able to allow for the influence of stochastic variance and planning assessment procedures attempt, instead, to reduce evaluation of complex systems to the assessment of a relatively specific, retrospective, metric derived from an equilibrium-state model – a stationary condition that is trusted to be typical for the system operationally.

Almost all environments, and particularly acoustical environments, are stochastically varying systems. The thesis explains how a measure of impact assessment can be achieved for these systems through the analysis of statistical levels – a measurement capability available for some decades but utilised only marginally for legislative, management and predictive applications. Statistical manipulation using reverse transformation sampling is described and its application to quantification of impact is shown.

Among the most significant of many referenced examples of a stochastically varying system is a road transport corridor. The thesis examines road noise prediction in some detail and shows how it can be analysed, including determining a magnitude of impact on nearby land areas using statistically based numerical modelling. The outcomes enable sophisticated prediction of sound level outcomes that discriminate between impact effects in different land-use areas. Many environmentally relevant systems can be similarly examined. Not only can statistically reliable sound immission levels from stochastically varying systems be more robustly predicted than is currently common but the outcomes can be used to evaluate impact more objectively. Outcomes can be predicted that take account of subjective expectations. This has the potential to alleviate many significant communication issues that currently inhibit effective land use planning.

The thesis identifies important areas where current legislation and policy can be improved and presents a logical framework from which to consider their amendment.

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Both men have been leading thinkers in the fields of building and environmental acoustics in Australia and are friends for whom I hold both the greatest of respect and gratitude.

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OUR LANDS

For the great concerts of the Anthropogene
the critics applauded; the audience? Just annoyed!
Forgotten were concerts that might have been.
Twitters and tinkles. Sounds of the void.

The critics heard only the first violin
not the families at work on the theme
who were unnoticed. But the brass played in loud discord!
Did they slumber? Was that part a dream?
The critics followed carefully the rules for review,
no timing askance that they noted.
The rules were not questioned, and
attention was numbed,
The sounds that remained were demoted.

In a great concert of the Anthropogene
are we pleased if we're not highly annoyed?
What of the concert we thought it could be?
Twitters. Tinkles. Sounds of a void.

Do we listen only to the first violin?
What of the families at work on the theme?
Do we not hear the brass play in loud discord?
Do we subsume that part in our dream?
We expect the concert to be carefully rehearsed
so errors askance are avoided.
It is the conductor we question.
Our attention is not numbed.
The sounds and our lands are demoted.

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1 INTRODUCTION

The objective of this thesis is to improve land-use planning by the application of more rigorous assessment of impact on the acoustical environment. Aspects of these concepts may have application to environmental protection more generally. Land-use planning decisions are of very great importance culturally, economically and environmentally. Decisions that fundamentally influence espoused legislative policy at both state and federal government levels are made at a local government level using limited and frequently misunderstood acceptance criteria.

Uncertainties in terminology adversely affects the expectations in land-use planning. This is partly due to the meaning of many terms being assumed and by the diversity of viewpoints of the stakeholders having an interest in land-use planning.

Australian noise control legislation is primarily a response to human annoyance. Annoyance, an anthropogenic reaction, tends to be associated with active impacts – louder noise events frequently of anthropogenic origin within an environmental spectrum in predominantly residential areas. However there is little or no recognition of the role of passive incremental impact, in which progressive erosion of the ambient environment occurs, particularly to pristine and natural environments. Many planning decisions involve issues that affect more than the built-environment in areas where natural contributions to the acoustical environment have already been masked. Criteria based on annoyance alone are insufficient and it is only by recognising and managing both aspects that environmental protection will occur.

A-weighted broadband sound pressure level metrics have widespread and common usage in land-use planning legislation. A-weighted metrics can be technically criticised however, despite criticisms being now extant for some decades, their use has not been supplanted. Sophisticated and narrow-band methods of acoustical evaluation can and do produce a higher correlation with human annoyance. Aspects that can be related to passive impact have been similarly researched, however these methods generally involve procedures that are too complex for use in conceptual land-use planning. It is fundamental to procedures intended for use in land-use planning that they can have relevance to widespread and variable concurrent situations, many of which will not be known in detail.

The influence of differing measurement metrics and assessment criteria, endemic in the procedures used in land-use-planning, is discussed. Many factors have contributed to the evolution of this assessment diversity. Confusion arises from a principle used in environmental noise management where absolute level-based criteria are considered appropriate for one class of noise sources, while relative level criteria are considered appropriate for other classes. Cumulative impact leading to gradual environmental damage is essentially ignored. Multi-factorial aspects commonly apply to a land-use planning decision, leading to a widespread mistrust in the validity of associated planning processes under this framework. Using a mixture of assessment criteria is also counter-productive, eroding communication and leading to misunderstanding, frequently resulting in dissatisfaction with planning outcomes.

Since 1977, the field of soundscapes has been developing with little or no legislative recognition. Soundscape work is subjectively based and has progressed in parallel with the general field of environmental acoustics; however there has been limited interaction between the two epistemologies.

The difference between stationary and non-stationary acoustical systems is discussed, highlighting the prominence of non-stationary systems within the realm of land-use planning and environment generally. Historical development of legislative principles has attempted to quantify complex situations using stationary metrics, requiring that complex systems be envisaged in the form of an equilibrium-state model. This has had negative outcomes. These include a requirement for the diversity of measurement metrics mentioned above, a focus on measures of central tendency that are fundamentally insensitive, so predicted outcomes may appear disproportionately critical under some circumstances but irrelevant in others. It is shown that such metrics are unable to analyse passive impact, and that regulatory decision-making is frequently conducted based on opaque general-case descriptions of development activity. These weaknesses are aggravated by standardised time-of-day procedures that distract focus from identifying periods when maximum impact will occur. Investigations are reported suggesting that a “worst-case” assessment has been examined, without identifying the basis under which the worst-case assessment should be recognised. These unsatisfactory outcomes are the legacy of a limited legislative focus using metrics that are a legacy of somewhat antiquated environmental noise assessment methods.

The work examines impact in a fundamental sense. Impact may be multi-modal and this thesis recognises two fundamental aspects to acoustical impact – one being impact of an active or dominant auditory nature, and the other of a passive and progressively eroding nature. In recognising these opposing concepts the thesis also explains the conflicting requirements of situational extrema involving locations with both higher and lower ambient sound levels.

The role of Emergence, as a definable surrogate for audibility, is discussed. The use of an audibility surrogate is compatible with both soundscape and sound level management principles and is relevant to both active and passive impact circumstances. Audibility is fundamental to the element of acoustics and noise in the consideration of amenity, itself a fundamental consideration in decisions associated with land usage. For a site-specific planning study, elements existing in a locality will influence the relative importance of various land use activity consequences. It is proposed that consideration of soundscapes in identifying elements contributing to an area amenity can enable a source importance function to be included as an effective planning parameter. This has application at a scale of either local or regional studies, will be transparent and better understood by a wide variety of stakeholders. This approach can provide far greater insight to relative contributions to impact on amenity from a development proposal than can be currently achieved using different source-specific compliance criteria.

The need for acoustical land classifications to assist interfacing planning proposals with land in potentially affected areas is discussed. Proposed classifications are used to demonstrate a framework for the land-use impact assessment methods described in the thesis.

The emissions from land uses are stochastically variable due to sources being either physically stationary but stochastically variable, being mobile, or being a combination of both. The simple principle used in numerical simulation is to aggregate statistically justifiable sound emission arrangements, each reflecting a possible instantaneous operating condition, permitting a range of statistically based reliable outcomes to be evaluated over time. As an important underlying principle, time is not incremented in modelling outcome conditions. Instead, the statistical variance of each contributing element is aggregated over an appropriate time period. All elements are considered using discrete source emission and/or location modelling as it is essential to incorporate stochastic variance effects due to both source physical location and of source emission characteristics. The framework required for modelling a range of typical land-use developments examples is discussed. Apart from the acoustical outcomes, other aspects beneficial to land-use planning and management are identified.

The objectives described above are developed through the application of statistically based numerical simulation for stochastic acoustical systems operating within a stochastically varying ambient environment. This technique could be expanded from A-weighted broadband data to use narrow-band input data for specific site studies, however narrow band analysis is unlikely to be useful for land-use planning concept studies. It is shown that a magnitude of change can be determined under both active and passive impact conditions.

As a more detailed study, the thesis investigates the application of a statistical numerical simulation model to a road. A road is chosen as transportation aspects are one of the most complex and technically difficult aspects of many land uses and this example shows the method is capable of the level of flexibility and scaling necessary for such studies. A road, for the purposes of a planning study, could be a freeway, a secondary road, a track, a single vehicle haul road, or a carpark. This level of conceptual flexibility is not facilitated by road noise models in current use. The model is based on commonly available planning input data and its statistical accuracy is reviewed for a range of flow conditions though a field study. The statistical output of the road model is used to predict emergence in the context of a stochastically varying background sound environment to example active and passive impact assessment for different hypothetical adjacent land-use areas.

An over-arching objective in this work is to provide a technical platform bridging the epistemologies of environmental noise and soundscape, enabling the many constructive ideas evolving from soundscapes work to be considered more confidently in legal and regulatory applications, particularly regarding impact on amenity. Recognition of both aspects of acoustic assessment is necessary to enable effective land-use planning. This approach will assist a fit-for-purpose criterion to be applied to an outdoor acoustical environment test in a manner long common to design work for building interior acoustical environments.

A more holistic objective for the work is to enhance the relevance of environmental acoustics in supporting the management of human impact on the biosphere. The term “reasonable” underpins many legislative constructs. However, the focus of environmental legislation has been limited to managing reasonable impacts on human comfort or annoyance alone. It is hypothesised that environmental damage is an outcome of the quantum of land-use activities each considered, individually, to be reasonable. In the same context that more effectively coordinated management criteria will improve understanding of impact, so it is also proposed that improved understanding of impact will assist recognition of the origins of environmental damage. It is a reality that much damage to the biosphere occurs due to human activities. There is no correlation between acoustical energy and the state of the biosphere, however there is a correlation between human activity and acoustical energy occurring within an environment. The metric of environmental noise may be a usefully sensitive precursor to environmental impact triggering the need for more complex biosphere audit techniques such as pre and post specie population counts.

The underlying principle to this thesis is to support predictable outcomes. Substantial science, regulatory and industry effort has been directed to aspects of measurement interpretation. However the condition precedent to good planning is the availability of predictable metrics and predictable outcomes – not just predictably useful analysis but usefully predictable analysis. The thesis presents an objective basis for impact assessment and demonstrates that the input variables are available, by statistically based numerical prediction, for the most complex of environmental acoustical systems.

2 THE ACOUSTICS OF AN ENVIRONMENT, ITS FEATURES, THEIR ASSESSMENT AND THEIR MANAGEMENT

In a legislative context, consideration of the acoustic environment could be considered a mature subject, having been recognised in both technical papers and legislation in the early 1960s and quite widely legislated by the early 1970s. However as this chapter shows, the primary objective of such legislation was, and remains, the control of nuisance and not that of the more holistic objective of environmental protection. There are traceable reasons for this situation, however an adverse outcome is that legislation relating to the acoustic environment is unable to interface constructively with other legislation associated with environmental protection or conservation. The object examined in this thesis is the outdoor, or unenclosed, portion of the environmental acoustics. Policy, in this chapter uses the examples of various policies prescribed under authority of NSW legislature, representing actions or principles adopted with the objective of achieving a range of outcomes concerning environmental noise.

2.1 WHAT IS AN ACOUSTIC ENVIRONMENT?

In the hierarchy of terms referencing environmental sound, the sound refers to audible acoustic energy within the atmosphere, acoustics to the science and technology of sound and its properties, and noise to the subset of environmental sound that is deemed to be unwanted or undesirable [Morfey,2001].

An acoustic environment is a collection of sounds, constantly audible, however the nature and level associated with that audibility is rarely constant even in highly controlled circumstances. Almost all acoustic environments are comprised of numerous contributing sound components, many being unnoticeable due to their familiarity, many being intermittent, but in aggregate amalgamating into the temporal, loudness and prominence characteristics from which the subjective perception of that environment is formed, although it is not clear which of those sounds listeners will actually hear [Botteldooren et al,2011].

An acoustic environment represents a region of the biosphere and is affected by the activities that are encountered within that region. The range encompassed by acoustic environments is a continuum from pristine natural land unaffected by sound of anthropogenic origin to heavily affected land within which sound from a variety of industrial, transportation, residential and agricultural activities occur. An acoustical environment is described almost entirely in subjective terms, many of which do not necessarily correlate with sound pressure levels. An area perceived as quiet and peaceful environment near a running stream may generate higher ambient sound pressure levels than other nearby land areas that are considered less desirable. An environment comprised of sound from naturally occurring sources tends to be considered more desirable than an environment comprised of sound from mechanical sources. An environment in which human activity sounds are audible may be considered more desirable than one in which mechanical sounds alone are heard.

Psychoacoustic response, the relation between the physical world and subjective awareness (Small,1982], explains the way in which acoustic environments are perceived, and is the mechanism due to which annoyance and relative annoyance due to noise is experienced. It is also the mechanism though which passive enjoyment is experienced in a pristine acoustic environment. However research on how people perceive or understand the environment is still in development [Aletta et al,2014]. Consolidation of measurable acoustic parameters that can describe those environments remains inconclusive [Aletta et al,2014],[Kang et al,2015]..

Sound that is considered inappropriate or inconvenient is likely to be classed as noise. The functional or social context of an area generally conveys expectations to an occupant for the acoustical environment in that area. In natural land areas, audible sounds from wildlife are anticipated. If those sounds are masked by other sounds of a different origin – e.g. from road traffic – it may be the absence of natural sounds that is the basis for considering the masking sound to be unwanted, rather than the level itself of that masking sound, which if heard in a different environment may be judged as benign or of indifferent importance.

The definition of noise as unwanted sound is reported to have appeared in the Oxford Dictionary as early as 1225 [Schafer, 1977]. As the classification of noise based on physical attributes developed, being contrasted with music in lectures by Tyndall in the 1870s [Tyndall, 1964] and somewhat similarly compared with tonality by Tyndall's contemporary Helmholtz [Helmholtz, 1877], noise became characterised as sound having no apparent use or musical value. Schafer also noted a modern interpretation of noise being that of "any loud sound" [Schafer,1994]. Both perspectives have complex consequences. The objectives of environmental noise policy, to control outcomes relating to unwanted environmental sound, have a long legislative history. Schafer [Schafer, 1994] records the first example of a noise control by-law being the Senatus Consultum passed in 44BC by Julius Caesar, and referring to the use of wheeled vehicles in Rome at night. The passage of regulations has continued to grow, seemingly exponentially, the majority relating to the control of noise associated with the activities of humans and/or their pets.

Designation of a sound as noise is subjective, established within a frame-of-reference unique to the perceiver and influenced by the interpretation and expectation of that perceiver to any aspect relating to that sound. So far as perceived sound is concerned, an expressed opinion can only be the opinion of the perceiver, and that opinion, ergo, is correct.

Noise defined as unwanted sound in an acoustical environmental (outdoor and indoor) ought to refer to sound that is not part of the natural or intrinsic elements of that environment. Inconsistent terminology has continued to affect community understanding of environmental objectives – ambient noise and background noise both being regular acceptability benchmarks, but both oxymorons as there can be no unwanted aspect. This predominant use of the term "noise" tends to obscure constructive discussion about more fundamental principles, rendering noise as an external object rather than one with which planning and occupants of an environment can engage.

Schafer, a musician, introduced the term soundscape in 1977 [Schafer, 1977] which he saw as being a middle ground between science, society and the arts. In a logical development of the idea of a Soundscape expressed by Schafer, researchers have continued to explore aspects of an acoustical environment that relate to human perception – positive and negative - however this focus on aspects describing the soundscape has not translated to application within regulatory methods of considering an acoustical environment.

There are potential ambiguities in the use of the term environment in acoustical terminology. As a noun, environment generally refers to any defined portion of the biosphere. The adjective – environmental – by general convention identifies the outdoor portions of a subject associated with the biosphere. Environment in an acoustical context has also been used to identify the "habitable" environment and therefore can include both indoor and outdoor areas. The term 'environmental noise' generally identifies the portion of the acoustics of the outdoor environment that is deemed or perceived to be undesirable. Hence there is a need for an environmental classification first, before being able to then identify what constitutes the relevant acoustical environment and, in turn, environmental noise. These distinctions and definitions are currently lacking.

In this thesis, the term pristine acoustical environment is used to identify land within which sound from non-natural sources is essentially absent, or present so minimally as to be considered absent. By definition [US Congress, 1964] wilderness would qualify as a pristine acoustical environment, however a pristine acoustical environment may not be statutory wilderness. The legal definition of wilderness under the US Act is identified as *"an area where the earth and its community of life are untrammeled by man, where man himself is a visitor who does not remain".* However other qualifying parameters were involved – undeveloped Federal land, minimum land area and more – relating to the specific purposes of that Act. Under the NSW Wilderness Act [NSW Govt, 1987] wilderness land is not defined directly on the basis of its acoustical environment, however the definition includes parameters that dominantly affect the acoustical environment and parameters that imply perceived features influenced by the acoustical environment:

(a) the area is, together with its plant and animal communities, in a state that has not been substantially modified by humans and their works or is capable of being restored to such a state,
(b) the area is of a sufficient size to make its maintenance in such a state feasible, and
(c) the area is capable of providing opportunities for solitude and appropriate self-reliant recreation.

There is therefore a fundamental division of the audible environment into sound considered to be innate to an environment, and noise being the portions of the audible environment that obscure mask the otherwise innate elements to the sounds of that environment. This is a useful basis for review of current methods of noise impact assessment and management, all of which were initiated with an objective to manage and abate existing, primarily industrial, noise.

Environmental policy objectives address only the management and mitigation of noise, and primarily in a context of annoyance, quantified by objective metrics. Legal principles are important. To decide what is fair, legal terminology has constructed the hypothetical concept of a reasonable person. A reasonable person is reasonable in the context of whatever case matter is involved, so a universal definition is not able to be stated and each case is decided by a court. This also a subjective basis, albeit as objectively impersonal as is probably possible, but is nonetheless a subjective framework that is the final arbitrator in any dispute or decision. Furthermore, the society that environmental noise legislation aims to protect may have advanced in both experience and priorities and may be able to identify and articulate aspects of that environment that are considered valuable in addition to aspects that are unwanted. Reasonable outcomes and reasonable management of environmental impacts are concepts that are quite consistent with current legal principles.

2.2 THE BACKGROUND TO REGULATED NOISE ASSESSMENT AND MANAGEMENT

The need for action

Impact and the associated fundamental concepts associated with environmental noise assessment was a subject of professional, legislative and academic interest as early as 1934 [Lloyd, 1934]. As a science and engineering discipline, environmental acoustics evolved in the 1960s and 1970s in response to the UK Noise Abatement Act 1960, "An Act to make new provisions in respect of the control of noise and vibration with a view to their abatement" [UK Government, 1960]. The Wilson Report [Wilson, 1963] was probably the first large-scaled investigation into the management of acoustical issues within the environment. Work by Kosten and Van Os [Kosten and Van Os 1962], Kryter [Kryter,1960] and others were published, among which the Kosten and Van Os paper included extensive recognition of subjective aspects associated with environmental noise, many issues of which were later described in a more holistic context by Schafer [Schafer,1969]. In the USA the Environmental Protection Agency was established in 1970 [US EPA, www.epa.gov/history/origins] followed by the U.S. Noise Control Act 1972 and Quiet Communities Act 1978. The Noise Control Act established the Environment Protection Authority in the United States, a division of which was the Office of Noise Abatement and Control (ONAC).

In NSW the Noise Control Act 1975 was gazetted, conferring powers and responsibilities associated with noise and vibration control on the State Pollution Control Commission, a body since re-constituted as the Environment Protection Agency (EPA) under the Protection of the Environment Administration Act 1991.

The need for an assessment basis

A seminal paper of Schultz [Schultz,1978] led to a divide favouring energy-averaged sound pressure level criteria as the basis for the assessment of environmental noise, particularly transport noise. The Schultz paper was widely accepted, somewhat unjustifiably, as a robust basis for the assessment of annoyance across many circumstances. This established a fundamental principle underpinning environmental noise management. It is noteworthy that Schultz himself expressed concern that his findings were incomplete but that they provided a framework foreseen to encourage further research and development. Indeed, the Kosten & Van Os paper proposed criteria pre-dated the technology of integrating measuring instruments but included a presence factor adjustment, referenced below in Table 1, the effect of which was analogous to the energy averaging criteria later outlined by Schultz.

Standardisation and its framework

In Australia, AS1055 was published in 1973 titled "Noise Assessment in Residential Areas" and set out procedures reflected in other international standards of the time [BSI 4142,1968] in which recognition of the different magnitude of noise impact on differing areas of land use was generic to the procedures. While AS1055 was re-titled in the 1989 issue to "Description and Measurement of Environmental Noise", the only content relating to description referred to description of the measurement procedures was by passing mention of "description of the noise being investigated".

Australian, British and International standards at the time proposed that the recurring threshold to ambient sound, subsequently termed the background noise, was equivalent to a statistically determined level exceeded either 90 or 95 percent of the measurement period. Taylor [May,1978] noted international consensus at the time that an "acceptable" level of ambient noise for daytime in general suburban areas, with medium density transportation, was 55dB(A), reflected indirectly in USA guidelines published by the EPA [USA EPA,1974]. The EPA, unlike the Australian, British and ISO approaches in which noise from a proposed or existing potentially offensive noise was compared with an acceptable background noise threshold based on land area usage, took the approach that an acceptable adjusted absolute day/night average noise level could be determined based on annoyance surveys. Important qualifying parameters were included in the early EPA procedures relating to previous community attitude and exposure.

By the time Schafer raised the concept in 1977 of attributes of a soundscape [Schafer,1977], objective measurement principles were well established. May [May,1978] reported that the US EPA levels document was based on analysis of 55 community noise situations, half of which were steady industrial and community noise situations with the remainder being intermittent transportation and industrial situations. He observed that the then generally held noise criterion of Ldn = 55dB(A) corresponded to an estimate of 17% of the population being highly annoyed by the noise, and 1% of the population complaining. At the same time, Schultz published a landmark paper reporting a synthesis of the results of social surveys on annoyance [Schultz,1978] that informed public policy in USA for decades to come.

In early 1981, funding for the US EPA Office of Noise Abatement and Control (ONAC) was rescinded by US Congress [Shapiro,1992], following which, in 1992, a collective of US Federal agencies (FICON) determined that annoyance and the Schultz model would, henceforth, be the agreed basis for policy and legislative planning [Fidell,2003]. However, the relevant Act, the Noise Control Act 1972, was not repealed and the US EPA continues to have a statutory responsibility to implement the Act, lack of funding notwithstanding [Shapiro,1992] [Bronzaft, 2017]. Among other outcomes, Shapiro noted that the retention of the Act meant that State and local governments were unable to adopt noise or labelling emission standards that differed from the EPA standards. This became an obstacle to subsequent development and research into alternative coherent noise impact controls. Noise assessment criteria were clearly based on annoyance with the target beneficiaries of being occupants of dwellings, and in the case of land-use planning policies, residentially zoned or occupied land.

Subjectivity and the concept of intrusive noise

In the 1970s, concurrent with evolving legislation regarding environmental noise, the term 'soundscapes' was introduced by Schafer [Shafer,1977] being the auditory equivalent of visual landscapes and particularly that desirable subjective aspects of an environment were both fundamental and identifiable. Schafer conceived of the acoustical environment differently from the legislators. Legislatively, noise was perceived to be an undesirable component masking the otherwise desirable background sound, however the technical focus of such legislation was on the level of noise due to the offending source and not of the characteristics of the desirable background. The term "signal-to-noise" was already in common use in various branches of evolving audio technology, referring to the ratio of useful signals to non-useful signals. This established, incorrectly, a perspective that prominent signal contributions could be readily quantified and that this feature identified the most important parameter in any measurement context. Subjective factors were already established in legislation conforming with published guiding principles [Kosten & Van Os, 1962]. It is useful to observe, in view of Schafer's criticisms, the contemporary and formal "cautionary comments" included by Schultz in his highly influential paper [Schultz,1978].

The greater complexities of environmental noise management and the relevance of land other than residential land were both recognised [UK House of Commons,1995], while a number of researchers endeavoured to develop and promote a more holistic context for the review and assessment of environmental noise [Casali,1999],[Davies,2001],[Schulte-Fortkamp,2002],[Lercher & Schulte-Fortkamp,2003],[Maurin et al,2003], [Warren et al, 2006],[Brambilla & Maffei, 2006],[DeCoensel & Botteldooren,2006]. The significance of land-owner attitudes to their perceived rights was highlighted [Dunlap,2006], the effect of which has been to constrain legislators in their attempts to control environmental noise at a local government level. Local government is the internationally critical level in relation to land-use planning and approval responsibility. A number of researchers highlighted the relevance and/or implications to noise management of land uses other than simply residential [Taylor et al,2008],[Shepherd et al,2010],[Brown,2010]. The UK Parliament [UK Government,2011] formally recognised these wider perspectives relating to environmental noise, of the indirect implications arising from decisions about land use, and of the benefits to society of land uses transcending those primarily associated with dwellings. In particular, the consequential health and environmental benefits of quiet areas were formally recognised, a banner carried by Schafer since 1969 but, for many years, by too few others.

Notwithstanding the cautionary comments by Schultz mentioned above [Schultz,1978], researchers presenting alternative findings or willing to cast doubt on the adequacy of the long-term energy averaged approach to environmental noise management were sporadic [Namba & Kuwano,1984], [Harder,1996], [Albee,2002], [Lercher & Schulte-Fortkamp,2003], [Fidell,2003], [Samuels & Parnell,2004], [Schomer,2005]. Lockhead [Lockhead,2004] noted that people judge relations, not absolutes, in psychophysical judgement tasks. While the use of long-term energy-averaged metrics remained the primary focus in the field of aircraft noise management, albeit with an increasing call for inclusion of amending parameters seeking to improve the adequacy of the DNL metric, by 2010 an increasing number of workers were recommending more fundamental changes to the basis for the assessment of nuisance from, and control of, road noise [Guarnaccia, 2012], [Stewart et al, 2017], [Hou & Wang, 2017].

In marked contrast to the approach taken to transportation management, the concept of noise intrusion, or emergence, above a background noise threshold has remained entrenched in land-use legislation almost since legislative inception. However, an important legacy of the absolute energy-equivalent criteria approach was that the interaction of transportation decisions on other aspects of land-use planning has been largely ignored, the influence of road traffic noise on the background noise within different land areas is not formally acknowledged, nor has the technical inconsistency between different environmental assessment criteria been adequately addressed. This has continued to erode effective communication between legislators, practitioners and the community.

The importance of being present

Throughout the history of research into regulatory controls on environmental noise, a regularly expressed view was that that the level and/or frequency of occurrence of noise events were fundamentals in the origin of noise annoyance [Schafer, 1969, 1977, 1994], [Powell,1983],[Harder, 1996], [Lercher & Schulte-Fortkamp, 2003], [Gjestland, 2008], [Kacsmarek & Preis, 2010], [Brown, 2014]. These parameters describe sound events and their subjective presence, aspects unrelated to the long-term equivalent energy level of that sound. Amenity, a parameter widely applied to land-use planning decisions, is a complex but immediate outcome of a range of physical components [VGSO,2008]. Energy-averaged conditions alone can rarely serve as a metric able to quantify amenity.

By roughly 2010 a more widespread recognition of fundamental issues affecting the management of environmental noise was apparent, requiring a more sophisticated strategy for both planning and assessment than energy-averaged metrics alone. Retrospective reviewers of social survey data lamented, regularly, the obstacles to policy interpretation of both inconsistently compiled survey data and inconsistent research outcomes. Proposals, primarily addressing aircraft noise, became prominent for the incorporation of a Community Tolerance Level as a DNL amending factor aiming to improve, and thereby preserve, the basis of the Schultz/DNL assessment paradigm [Fidell & Mestre, 2011], [Mestre et al, 2011], [Sizov & Pickard, 2011], [Fiebig & Schomer, 2015], [Taraldsen et al., 2016].

Focus on transportation

Much of the research and development mentioned above relates to noise from transportation infrastructure. A detrimental consequence of the FICON acceptance in 1992 of the energy-averaged sound exposure principle was that research has tended to investigate absolute aggregate levels, to a degree ignoring the aspect of relative levels and, particularly, the ambient environments in which the work was being carried out. The energy-equivalent criteria were thought to explain average community reactions for large areas and planning decisions were made accordingly. This is not unreasonable vis-à-vis the reasonable person, however inconsistencies found in apparent predicted vs actual annoyance remained a problem. Despite contemporaneous cautionary findings [Namba & Kuwano,1980] and the comments of Schultz himself regarding the influence of individual circumstances, research on this aspect was not reported until Lim et al in 2008. One explanation for the variant findings from surveys of community reaction to noise, frequently addressing aircraft noise, may well have been the unaccounted influence on annoyance for individual respondents of their unique circumstances of background noise [Lim et al ,2008].

Understanding quiet areas

The technical complexity associated with the apparently simple notion of a quiet area is clear [Brown, 2011]. What is deemed to be a quiet area is likely to be an area in which unwanted sounds are rarely heard; a quiet area is not necessarily one in which low sound pressure levels are monotonically present. Although, for pristine and wilderness environments, in which either silence or the absence of anthropogenic sound are prominent parameters contributing to the area amenity, any contribution of otherwise absent sound is likely to adversely affect the amenity of that environment.

Auditory preferences

Schafer’s important text [Schafer,1977/1994] formally introduced the term soundscape now commonly referring to the epistemology of auditory aspects of the world and of human interactions with them. This has evolved to an epistemology that considers human perception [Brown, 2011], the concept of which is now sufficiently standardised to warrant formal definition [BS ISO,2014]. This is deemed to be the acoustical environment “as perceived or experienced and/or understood by a person or people, in context”. Additionally, the consideration of appropriateness in soundscape planning and design [Brown, Kang & Gjestland,2011] has also been noted. The considerations of perception, context auditory preferences and appropriateness are important qualifications that have direct implication to issues considered by this thesis.

At the time of Schafer’s publication, legislative efforts to manage environmental acoustics were well established and had evolved through concurrent technological development to measurement-based methodologies. Whereas environmental assessment policies had already made effort to account for subjective audible features – A-weighting measurement technology, subjective weightings for tonality and the like – Schafer introduced the more generic concept of “balance” associated with non-linguistic and non-culturally biased factors. These subjective elements have not, at this time, become incorporated into policy documents, however possible parameters are well summarised by Schafer in a brief table where dominance by the left-term over the right term is perceived to be an undesirable feature leading to what we commonly describe as environmental noise:

Sound/Not-sound
Technological sounds/Human sounds
Artificial sounds/Natural sounds
Continuous sounds/Discrete sounds
Low-frequency sounds/Mid or high-frequency sounds

Schafer's guideline suggested one approach to the incorporation of subjective parameters that might have had application in improved regulation. Researchers and technologists have not yet found a way to associate the insights provided by soundscape analysis with legislative procedures managing environmental noise.

Legislative perspective is a manageable pollutant

The focus of the formative NSW legislation was the management and control of pollution, a continuing context following repeal of the Noise Control Act 1975 by the Protection of the Environment Operations Act 1997 and reflecting the context of the Environmental Planning and Assessment Act 1979 of NSW.

Under the POEO Act, noise is defined to include sound and vibration, while noise pollution is defined to mean offensive noise. "Offensive noise" is defined [POEO Act, Dictionary] as meaning noise:

> *(a) that, by reason of its level, nature, character or quality, or the time at which it is made, or any other circumstances:*
>
> > *(i) is harmful to (or is likely to be harmful to) a person who is outside the premises from which it is emitted, or*
> >
> > *(ii) interferes unreasonably with (or is likely to interfere unreasonably with) the comfort or repose of a person who is outside the premises from which it is emitted, or*
>
> *(b) that is of a level, nature, character or quality prescribed by the regulations or that is made at a time, or in other circumstances, prescribed by the regulations.*

Notwithstanding the uncertainty associated with condition (a) (ii) of the definition of offensive noise above, the underlying legislative principle in NSW is that an acceptable overlay of the existing ambient environment by "environmental noise" can be prescribed. This leads to assessment procedures that aim to measure the amount by which a potentially undesirable noise exceeds, or is allowed exceed, the existing ambient sound. The founding concept of the regulatory procedures used in management of environmental noise is that the object to be protected is the occupants of dwellings, with the nature of undesirable noise sources being characterised as noise from industrial types of activities – activities conceptually associated with a specific site or location.

The underlying principle behind environmental legislation in NSW, but also internationally, is environmental protection is achieved by permitting an acceptable measure of degradation, indeed, licenced by regulation. The principle of environmental conservation can be found in Australian legislation, however only as applied to biodiversity and in legislation at a Federal level [Commonwealth of Australia,1999].

2.3 QUANTIFYING ACOUSTICAL ENVIRONMENTS AND IMPACTS

2.3.1 Technical aspects

Sound manifests as either a steady-state signal – one for which the amplitude and frequency content remains constant with time – or as a sequence of one or more sound events during which either or both frequency and amplitude may vary. Quantifying sound by measurement involves a variety of analytical techniques – narrow band, octave band, broad-band, time-averaged and others. In almost all circumstances, data reduction procedures are necessary to consolidate measurement into a manageable form, and all data reduction is likely to lead to a loss of information of one form or another. To deal with the complexity of circumstances associated with environmental acoustics, a broad-band A-weighted measurement has become the most widely implemented basis for the assessment of environmental levels, though not with universal professional endorsement [Scannell,2003],[McMinn,2013].

Environmental acoustics vary almost constantly due to components originating from either chaotic or stochastic processes occurring within the biosphere. Stochastic, or random, events are events for which observations cannot be predicted with certainty [Mendenhall et al,1981], but for which the behavioural statistics tend to emerge over time, whereas chaotic events are those for which no temporal structure can be identified. A volcano eruption is a chaotic event. Common examples affecting an acoustic environment include weather events, a visit to a locality by a motor-cycle club, anti-social behaviour by road users or operators of music systems, and unsystematic local factors such as a road surface irregularity inconsistently encountered by passing vehicles. In risk management, where the prediction of whether or when a significant chaotic event – e.g. a financial crisis - will occur, Bayesian statistics can be used. For acoustical environments chaotically occurring events can be important, do occur frequently and can be difficult to quantify.

Quantifying the stochastic variance of an acoustical environment involves measurement of the various sound pressure levels over a known period and evaluating the probability density function describing those levels. In acoustical measurement, statistical analysis is an inbuilt function to the measuring instrument.

Most environmental acoustics events refer to sound generated by a system composed of many sources including either, or both, stochastic and operationally independent components. The elements making up the sound generating system can be considered as individual events and aggregated, or the operation of the system in aggregate can be considered as an event. As the number of concurrent and incoherent components in any multiple-source system increases, so the choice of measurement metric becomes less important – in the limit case reaching a steady-state operating system for which all metrics will be equally reliable. These limit conditions, together with individual steady-state sources, represent stationary acoustical emission systems. Such aspects are characteristics of large industrial source systems that were the target of early noise control legislation, and thereby likely influenced early assessment procedures.

2.3.2 Subjective Aspects

Opinion about a sound relates to the audibility of that sound. There are few sounds considered universally to be “acceptable” or “unacceptable”, many internally disparate opinions being the result of linguistic and/or cultural interpretations. Audibility is one of the fundamental senses from which any subjective opinion is formed and is also a uniquely personal capability and perspective. The most robust basis for assessment of the properties of an acoustical environment, including features that may be considered subjective, has been to relate them to objectively observable measurement of sound pressure levels. Audibility is used only indirectly in current policy.

Kosten & van Os [Kosten & van Os,1962], in a fundamental and influential paper, documented a range of criteria directed to the management of community noise expressed in both objective and subjective terms. Some, though not all, of these considerations subsequently found their way into both design standards and associated regulatory documents and, probably, remain relevant today:

> *(i) the characteristics of the noise itself, such as –*
>
> *(a) the overall sound pressure level;*
> *(b) the spectrum, i.e. the way in which the noise is distributed over the entire audible frequency range;*
> *(c) whether or not the noise contains clearly audible pure tones;*
> *(d) whether the noise is presented uninterruptedly, only during the day or also during the night, etc;*
> *(e) whether the noise has an impulsive character, such as that of a drop forge or riveting;*
>
> *(ii) the characteristics of the environment, such as very quiet suburban, suburban, residential suburban, urban near some industry, areas of heavy industry;*
> *(iii) the characteristics of the individual;*
> *(iv) miscellaneous circumstances, such as –*
>
> *(a) whether the noise could have been avoided easily;*
> *(b) whether the noise contains information, e.g. speech and music do, the humming of a ventilator does not;*
> *(c) whether the noise invokes unpleasant associations, e.g. fear of aircraft;*
> *(d) whether the individual is the operator of the noise source or has certain connections with the operator, e.g. the elevator in one’s own flat, an employee of a factory living in close proximity to the factory;*
> *(e) whether the individual has already become accustomed to the noise;*
>
> *(v) the human activity with which the noise interferes, such as sleeping, reading, working, radio or television listening, recreation.*

2.3.3 Objective Measurement Aspects

Quantifying auditory features and their subjective importance is not easy, in part because those features are highly complex and in part because the features are only truly evaluated in real time – quantity of data rapidly accrues to a scale that cannot be readily quantified [Sankupellay et al,2015] . Schafer [Schafer,1994], after noting that "all visual projections of sounds are arbitrary and fictitious", goes on to criticise the disconnect introduced by the methodologies used for objective assessment:

> *Today, many specialists engaged in sonic studies – acousticians, psychologists, audiologists, etc – have no proficiency with sound in any dimension other than visual.*

While that may be a reasonable if somewhat cynical view, Helmholtz, in his seminal text [Helmholtz,1877] acknowledged the reality that objective scientifically based representation of sound is necessary "to render the law of such motions more comprehensible to the eye than is possible by lengthy verbal descriptions". Assessments within an objective framework based in measurement are a pragmatic reality. The use of a broad-band A-weighted measurement unit was standardised in 1944 [Beranek,1960] on the basis that it was considered to measure perceived loudness [McMinn,2013]. Recognising the significance of subjective parameters, Kosten & van Os [Kosten & van Os,1962] proposed objective assessment criteria measured in terms of a Noise Rating Number, to which corrections were added for situations considering impact on, and annoyance of, occupants of residential buildings.

Table 1: Subjective Assessment weightings, after Kosten & van Os 1962

1.	Pure tone easily perceptible	5dB more stringent
2.	Impulsive and/or intermittent	5dB more stringent
3.	Noise only during working hours	5dB more lenient
4.	Noise present 25 % of the time	5dB more lenient
	present 6% of the time	10dB more lenient
	present 1.5% of the time	15dB more lenient
	present 0.5% of the time	20dB more lenient
	present 0.1% of the time	25dB more lenient
	present 0.02% of the time	30dB more lenient
5.	Economic tie	5dB more lenient
6.	Resident in a very quiet suburban area	5dB more stringent
	in a suburban area	No adjustment
	in an urban residential area	5dB more lenient
	in an Urban near some industry	10dB more lenient
	in an area of heavy industry	15dB more lenient

The rationalisation of the early work by Kosten & Van Os using a soft conversion applying the same correction originating from a noise rating, where frequency weightings are level-dependent, to the level-constant A-weighting, in standards and regulations has been the subject of continuing debate and remains much criticised [Schafer,1994], [St Pierre & Maguire,2004], [Benton,2007], [Mestre et al,2011], [McMinn,2013], [Gozalo et al,2015]. Nonetheless, the subjective adjustments of Table 1 that purport to correct for the subjective reaction of occupants of dwellings remain interesting and are traceable through many subsequent National and International codes of practice.

Subjective aspects are recognised as affecting annoyance, primarily if impulsive or tonal features are present, in which circumstance penalty weightings are added to increment the observed equivalent energy level value. These assessment aspects are not contentious, though the basis of their inclusion can appear arbitrary and, in some circumstances, be perceived to have a disproportionate influence on an alleged breach or compliance than has the actual physical measurement. There are exceptions to this general assessment principle, such as those developed by the EPA for use in target shooting ranges, however in large measure the use of the energy equivalent measurement metric, together with a consideration of adjustment weightings, is the basis of the great majority of NSW environmental noise assessments.

The diversity of conditions relevant to an acoustical environment has encouraged a diversity of measurement approaches attempting to quantify that environment. These include the use of measurement time constants (slow, fast, Impulse, peak), broad-band frequency-weighted measurement (A, B, C and D), narrow band measurement using octave, one-third octave and narrower, measurement over agreed or defined time intervals (15 minutes, 1 hour, 24 hours, day-evening-night, sometimes longer) and the use of instrumentation quality grades (type 0, 1 and 2). For temporally varying situations, energy-averaged level measurements have become common, in part, because measurement results across different situations tend to be repeatable. However the energy-averaged measurement may not relate to any observable activity-level or characteristic state of the environment it quantifies.

Statistical sound pressure level metrics define the stochastically variable characteristics of an environment, though require considerably more complicated analytical methods to predict the effect of changes to those elements. Early work was carried out [Eldred,1971] [Shaw,1975] to report land area noise levels on a statistical basis, however analysis of the complexity of level findings almost certainly exceeded readily available computing capacity at the time. Assessment methodologies respond to legislative and standardisation pressures and the widespread use since 1982 of equivalent energy level assessment as the basis for measurement of environmental noise [ISO 1996: Part 1], together with then extant research projects regarding noise annoyance has resulted in assessment procedures and associated research work being dominated by the use of energy equivalent metrics – $L_{Aeq,T}$, L_{dn}, L_{den} etc. Limited research has been carried out into the application of statistically based metrics for noise assessment, though some annoyance assessment work [Lim et al, 2010] has been carried out using equivalent energy metrics examined over very short periods.

Further standardisation of time-of-day aspects have been also standardised to, typically, three daily periods identified as day, evening and night. While this has facilitated a degree of uniformity, these observation periods are not necessarily relevant to the source or issue that may be in consideration, or the periods with which the largest impacts may be associated.

2.3.4 The fundamental concepts underlying regulatory impact assessment

The current assessment and management paradigm applied to environmental acoustics has reached a state where criteria describing an acceptable magnitude of impact is considered, broadly, to be one where regularly occurring noise from a specific land-use activity exceeds the threshold ambient background sound by no more than 5dB(A), and one where the equivalent acoustical energy level over a day period for a transportation source is nominally 55dB(A), both cases being overlaid with differing additional penalty assessment components believed to account for subjective aspects of the particular noise source. Equivalent energy metrics (L_{Aeq}) are broadly considered representative of a regularly occurring but stochastically variable noise source. Various statistically based metrics relevant to specific sources, for example the Traffic Noise Index ($TNI = 4\ (L_{10} – L_{90}) + L_{90} – 30$) [May,1978] have not withstood the test of time.

Fitness-for-purpose in relation to noise interference is considered robustly in the design of internal building environments but is only very loosely applied to outdoor land areas, being inconsistently contemplated as a design consideration for habitable landscape area developments. Fitness-for-purpose can not generally be regulated, however is a logical basis for examining what might be a reasonable outcome.

In relation to transportation noise - roads, railways and aircraft - no formal assessment of impact is undertaken at all, legislative policy instead relying on the action trigger based of the absolute value of a range of energy-averaged metrics above which an annoyance outcome is deemed likely to be unreasonable.

2.4 AUSTRALIAN STANDARD 1055

Australian standards are not regulatory documents however they frequently provide a methodology that is relied upon, or is legally required, by regulatory documents. Many Australian standards have been published concerning acoustics, the majority of which can be traced back to international standards documents and which reflect internationally accepted aims and objectives.

In relation to environmental noise the primary standard is Australian Standard 1055, first published in 1973 and progressively updated / re-issued with the most recent issue being 2018. [Standards Australia,2018]. In its current form, AS1055 is of little use and aggravates obstacles to community understanding. AS1055 has progressively changed to now provide a format and content more appropriately named “Description of Measurement of Environmental Noise” rather than the titles of both past and current versions referencing “Description and Measurement….”.

There are many aspects to the current issue of this standard that are undesirable and inhibit its value as a unifying or guiding document. Excluding the title, description is mentioned in the standard only in the context of reporting a source that is the subject of a measurement survey evaluation. Of approximately 48 pages of content, 21 pages involve technical procedures dominated by definitions of terms with little to no guiding content explaining their purpose or application. Many procedures are, in practice, almost irrelevant. Land category background sound levels included in past issues of the Standard content have been eliminated, removing a useful historical benchmarking role particularly for planning. The applications for which the standard is deemed appropriate are unclear. Much of the content is simply a glossary or dictionary of acoustical terms.

A substantial portion of the standard discusses detailed assessment procedures attempting to provide objective evaluation of impulsiveness and tonality, whereas the relevance of these same objectives might be more effectively achieved by a clearer emphasis in the Standard on description and its purpose.

No other Australian standards provide guidelines for the description of an acoustical environment, although this may be a future outcome of the ISO 12913 series of standards on soundscape [ISO, 2018].

2.5 NSW NOISE REGULATION – CRITICAL REVIEW

Many elements contribute to the scope and intent of policies and procedures used to manage the acoustical environment under NSW legislation. The following review is not intended to paraphrase each element but, instead, to identify aspects of those elements that affect the way in which impact on the acoustical environment and its management may be inhibited.

2.5.1 National Legislation

Common Law – the law of precedent – continues to influence the right of individuals to seek an action arising from nuisance and therefore has relevance, if somewhat limited application.

The Commonwealth legislative powers are defined under the Australian Constitution [Australian Government Parliamentary Education Office, 2012]:

> *The Constitution confers the power to make laws on the Commonwealth Parliament. However, the power of the Commonwealth Parliament to make laws is limited to particular subjects. ……….*
> *…………They include defence; external affairs; interstate and international trade; taxation; foreign, trading and financial corporations; marriage and divorce; immigration; bankruptcy; and interstate industrial conciliation and arbitration.*
>
> *This list of powers given to the Commonwealth Parliament does not expressly refer to a number of important subjects including education, the environment, criminal law, and roads – but this does not mean that those subjects are wholly outside the Parliament's powers. For example, even though the Commonwealth Parliament has no specific power in relation to the environment, it can, under its external affairs power, prohibit the construction of a dam by a State if that is necessary to give effect to an international agreement on the environment. The legislative powers of the Commonwealth Parliament can also be expanded by the Parliaments of the States referring matters to the Commonwealth Parliament under section 51(xxxvii).*

Under the Constitution, Commonwealth legislation takes precedence over State legislation to the extent of any inconsistency. Therefore, in relation to acoustical matters Commonwealth laws regulate the control of noise from defence activities, aircraft noise and health related impacts associated with noise – hearing damage, work health and safety.

Under the Environment Protection and Biodiversity Conservation Act 1999, the Commonwealth has authority over environmental matters deemed to be of national significance. Apart from the extent to which noise from aircraft is an obvious component, environmental acoustics, and of environmental noise management specifically, are controlled within the state and local government legislative domain.

2.5.2 Aircraft Noise Regulation

Aircraft noise in Australia is regulated by the Commonwealth Government, with planning and management of impact being based on a complex energy-average based unit, the ANEF. The principle adopted by aircraft noise management policy in Australia is that the magnitude of annoyance arising from aircraft noise is related to an absolute value of the ANEF, with no reference to the ambient noise conditions that may otherwise apply.

2.5.3 Authorities having responsibilities for noise in NSW

Table 2: Environmental Acoustics Regulatory Authorities

Noise Source	**Framework**	**Appropriate Regulatory Authority**[1]	**Technical Authority**
Aircraft	Air Navigation (Aircraft Noise) Regulation 2018	Australian Government	Commonwealth ADR 83/00
Traffic on Roads	Road transport (vehicle registration) regulation 2007	RMS and Local council	EPA
Individual vehicles	POEO regulations	RMS and EPA, NSW Police	Commonwealth ADR 28/01
Industrial	POEO Act	EPA	EPA
Larger equipment, mowers, chainsaws etc	POEO regulations	EPA	EPA
Construction	POEO Act	Local council and EPA	EPA
Building Services	POEO Act	Local council	EPA
Agriculture	POEO Act	Local council and EPA	EPA
Neighbourhood Noise	POEO regulations	Local council and police	EPA
Maritime Noise	POEO Act	NSW Maritime	EPA
Dogs and Cats	Companion Animals Act	Local council	EPA
Licenced Premises and their patrons	Liquor Act 2007	NSW Office of Liquor, Gaming and Racing	NSW Office of Liquor, Gaming and Racing

Notes:

1. The title Appropriate Regulatory Authority has a formal meaning under part 6 of the POEO Act, however is used in the general sense in this table

2.5.4 NSW Protection of the Environment Administration Act 1991 No 60

This is one of two key legislative instruments under which management of environmental acoustics in NSW is carried out. In addition to constituting the Environment Protection Authority and its administration, the POEA Act identifies the tasks for which the EPA is responsible. In relation to acoustics these include:

> *7 General functions of Authority*
> *(1)…….*
> *(2) The Authority has general responsibility for the following:*
> *(a) ensuring that the best practicable measures are taken for environmental protection in accordance with the environmental protection legislation and other legislation,*
> *(b) – (g) ……*
>
> *9 Powers of Authority relating to environmental quality*
> *(1) The Authority is required to:*
> *(a) develop environmental quality objectives, guidelines and policies to ensure environment protection, and*
> *(b) monitor the state of the environment………………...*

This thesis contemplates the extent to which “best practicable measures” are taken under this legislation and how best to “ensure environmental protection”.

2.5.5 NSW Protection of the Environment Operations Act 1997 No 156

This is the second of two key Acts relating to management of environmental acoustics in NSW. In addition to providing important definitions mentioned above, the objects of the POEO Act that may influence the acoustical environment include:

> *(a) to protect, restore and enhance the quality of the environment …. having regard to the need to maintain ecologically sustainable development,*
> *(b) ………………..,*

> *(c) to ensure that the community has access to relevant and meaningful information about pollution,*
> *(d) to reduce risks to human health and prevent the degradation of the environment by the use of mechanisms that promote the following:*
> *(i) pollution prevention ……….,*
> *(ii) the reduction to harmless levels of the discharge of substances likely to cause harm to the environment,*
> *(iia) the elimination of harmful wastes,*
> *(iii) ….……..,*
> *(iv) the making of progressive environmental improvements………...,*
> *(v) ………...,*
> *(e) ……………..,*
> *(f) ……………...,*
> *(g) ……………...*

Among many responsibilities of the EPA, one is to prepare Protection of the Environment Policies (PEPs) [POEO, Section10]. Under section 10 (b):

> *10 Purpose of PEPs*
> *Protection of the environment policies may be made for the purpose of declaring policies to be observed with respect to protecting the environment in New South Wales and, in particular, for the purpose of:*
> *(a) ……,*
> *(b) managing the cumulative impact on that environment of existing and future human activities.*

An important definition clarifies the meaning of the word “harm” under the POEO Act:

> ***harm** to the environment includes any direct or indirect alteration of the environment that has the effect of degrading the environment and, without limiting the generality of the above, includes any act or omission that results in pollution.*

Under the Act harm, therefore, includes both alteration to the environment and pollution, separably.

And, in relation to waste:

> ***waste** (unless specially defined) includes:*
>
> *(a) any substance (whether solid, liquid or gaseous) that is discharged, emitted or deposited in the environment in such volume, constituency or manner as to cause an alteration in the environment, or*
>
> *(b) …………., or*
>
> *(c) …………., or*
>
> *(d) …………..*
>
> *………………..*

This thesis contemplates the extent to which “cumulative impact” of “existing and future” human activities is considered under this legislation.

2.5.6 NSW Policy and Regulations

2.5.6.1 EPA Policy re Industrial Noise

The EPA published the NSW Industrial Noise Policy in 2000 designed to apply to large and complex industrial sources. The Policy was updated and retitled as the Noise Policy for Industry in 2017. The Policy is sophisticated in so far as it implements dual assessment criteria – one basis being the assessment of an impact from the perspective of noise intrusion, and the second being assessment on the basis of an absolute energy-equivalent level, somewhat resembling the international approach to aircraft noise but refined to take account of the existing ambient conditions and land usage within the relevant area.

Multiple criteria are not an automatic improvement to the integrity of an assessment, as the opportunity for inappropriate criteria to be applied is increased, while the level of understanding by non-technical stakeholders of a reported assessment may well be compromised.

Among many technical controls, procedures are included to determine an assessment benchmark for management of intrusive noise. There is some risk of confusion between two terms, one being the "assessment background level (ABL) and the second the Rating Background Noise Level (RBL) which are derived by the same procedure [EPA,2017,section A1.2]. The RBL has evolved to become the term most commonly used in practice. The RBL is represented by the 10th percentile value of the measured $L_{A90,15\ min}$ noise levels obtained for each of the periods of day, evening and night. This is a robust method of background noise level assessment consistent in principle with the historical procedures noted above.

An important qualification to the EPA procedures referring to the existing ambient conditions and the basis of impact assessment, in the original and updated policy documents but quoted from part B1.3 of the 2017 issue, is:

> *"Where this level is found to be less than 30 dB(A) for the evening and night periods, the rating background noise level is set to 30 dB(A); and where it is found to be less than 35dB(A) for the daytime period, it is set to 35 dB(A)"*

The technical background paper to the Industrial Noise Policy [EPA,2015] seeks to justify (S4.2) the policy of adopting an assumed minimum background noise level but concedes, by cross-reference to ISO1996-1:2003, that this may not be an appropriate strategy for the case of newly exposed sources of noise in quiet rural settings. The assessment procedures adopted by the Noise Policy for Industry are robust in being generally based on noise level assessments derived from 15 minute intervals. However, justification of numerous criteria set out in the Policy is based, instead, on findings reported for studies based on long-term equivalent energy level metrics, absent of consideration of the significance of relativity to background noise.

Both editions of The Policy, and the associated background technical paper, note that the Policy is designed for heavy industry, but comment that it may be useful to inform other regulatory authorities such as local government. No guidance is given to highlight aspects of the Policy that may be quite inappropriate in other circumstances. The Policy sets out robust procedures for environmental noise assessment, however only in areas audibly close to large scale industry.

The recent expansion to the role of the Policy for other development types, some highly unlikely to be surrounded by land uses comparable to those near heavy industry, and the encouragement to other authorities to use the policy as a basis for informed decision making, has introduced significant uncertainty under NSW regulation. The procedures designed for the industrial policy are focussed on land areas adjacent to heavy industry, a fact often not recognised by other regulatory authorities, particularly those working in areas with low background noise.

The Policy documents refer to the influence of meteorological conditions. Despite the prominent note made in the Technical Background Paper [EPA,2015] that "broadly, the INP requires that …meteorological conditions be considered…when present for more than 30 percent of the time", an inflated focus and prominence is given to reporting meteorological conditions by practitioners and by regulatory authorities in an endeavour to ensure technical rigour. Frequently this obfuscates important issues and aggravates already difficult communication with members of the public.

2.5.6.2 EPA Policy re Road Noise

Road traffic noise criteria are documented, by the predecessor of the EPA, in the Road Noise Policy [NSW DECCW, 2011]. These criteria do not relate to industrial or commercial noise management standards, instead being based on absolute assessment metrics based on energy equivalent units. This is consistent with international transport noise management methods. The NSW criteria were initially developed to facilitate road construction whilst acknowledging the reality of noise impact on the surrounding community and the noise design criteria have progressively become more stringent. Associated with these criteria are procedures developed by the then Roads and Traffic Authority, at the time being one of the regulatory authorities. In addition to consideration of road design, the NSW Road Policy used these same criteria to assist local planning authorities to impose controls on new dwellings and other similarly sensitive buildings taking account of the existence of road noise. This ensures that approval of a noise sensitive development would not undermine the adequacy of the road noise planning controls implemented at the time of road construction by the road authority, and thereby limits the risk of an increased future liability for mitigation by that authority.

Current road noise design criteria in NSW are numerically higher, by approximately 5dB(A), than levels recommended in recent planning guidelines issued by the WHO [WHO,2018]. The NSW assessment criteria are determined with reference to the type of road and, except for some building interior activities and recreational areas, make no reference to the type of land use area in which the assessment is to be made.

The stakeholders associated with a road project are all users of the road and, in many cases, include the adversely affected parties. This is an important distinction between applying criteria to the design of a new public road and considering those same criteria relevant to a private development where the beneficiary is a developer with any impact cost being borne by the ambient environment experienced by other stakeholders.

The Road Noise Policy recognises (Part 3.5) that "*Strategic planning policies should address the cumulative impacts of transport and land use development to minimise exposure to unacceptable noise levels*". That is, associated road noise should not, under the road noise policy, be considered separable from the impact of an associated land usage on the surrounding community.

Important comments are made in the policy document (Part 4.3) referring to strategies for traffic-generating developments on existing roads. These include:

> "*Mitigation that is implemented should be applied to the location along the public road from the development to the location where road traffic noise levels from the development are contained within the existing road traffic noise levels*".

A definition of "existing road traffic noise levels" is not provided, however the term could reasonably be considered to identify the level of traffic noise existing on the road in the absence of the development, and:

> "*..it is not appropriate or possible to control vehicle types and movements for residential developments but it may be possible when traffic is being generated from an industrial site.*"

The use of different noise control design criteria for roads from criteria associated with site-based industrial or commercial noise does contribute to community confusion when a development proposal requires an assessment examining site-related activities based on one acceptance criterion, with a second unrelated criterion applied to noise from road using vehicles. It is not uncommon for a primary community concern to be a risk of road traffic noise, with that very aspect appearing to be examined more leniently than other issues about which they are less concerned.

2.5.6.3 Noise Guide for Local Government

The NSW Planning policy [NSW Government, 2006] regime uses a 3-level hierarchy of documents:

1. State environmental planning policies,
   overlaying
2. Local environment plans,
   under which are
3. Associated development control plans.

Under this structure, the control authority flows down from level to level, with the effectiveness of each such document being dependent on the extent to which each layer supports the development of each subordinate layer. A source of planning conflict arises from a standard instrument LEP structure deeming preferred land uses on a land-zoning basis [NSW Government,2006] now effectively consolidated throughout all local environment plans in NSW. These land uses and land zonings do not necessarily correlate with the environmental sensitivity within an area. The Noise Guide for Local Government is issued by the EPA under the authority of the Protection of the Environment Operations Act and is intended to guide Local Government in the implementation of their authority. The Guide consolidates the perspective of noise management in NSW invoked as a retrospective and reactive activity delegated to the lowest level of planning, instead of being part of a proactive and advance planning framework.

The Noise Guide for Local Government is an enlightened document in which considerable emphasis is placed on description of characteristics of noise, of management procedures associated with noise, with a frequent emphasis that the role of measurement may be a supportive rather than a prescriptive element. The Guide does identify aspects, such as audibility, that are not criteria included in other EPA policy documents, but for which local government may not have the technical skills necessary to form independent and reliable judgements. The Guide also notes that there is a distinction between intrusive noise and offensive noise (2.2.1) and that, while cross-referencing the Noise Policy for Industry to define intrusive noise as “5 decibels above the background noise level”, adds comment that exceedance levels larger than 5dB may be acceptable in a range of circumstances. This can have consequences affecting community understanding of what aspect of impact is being evaluated by EPA noise policies.

The original Noise Guide for Local Government (NGLG) introduction advised cross-reference to the Industrial Noise Policy for assessment procedures. This advice has been tempered, however numerous procedures in the current NGLG issue originated in the industrial policy documents. This can be misplaced as local government is unlikely to be dealing with industrial areas and heavy industry in a manner for which the EPA policy documents for Industrial Noise were specifically developed. In particular, the statement in 2.3 of the NGLG that “if the measured background level is less than 30 dB(A), the background noise is usually taken as 30 dB(A)” is problematic, as local government planning decisions frequently involve remote and acoustically isolated areas. The local government user is unlikely to have the level of technical expertise necessary to recognise situations where the use of the Noise Policy for Industry is inappropriate. This error risk is aggravated if a development application for a local project is supported by a professional report on noise that also refers, without an appropriate clarification, to one of the industrial policy documents.

There is a high level of complexity and detail in the information contained in the NGLG, which is axiomatic given the diversity of circumstances likely to occur within the province of local government authority. However, this is likely to tax even the most experienced of council officers. An important limitation is the minimal guidance in the application of the Guide to land-use planning policy, such as a Local Environment Plan or a Development Control Plan. There is no mechanism in this document hierarchy that facilitates environmental or acoustical implications at a planning level. The objectives of the guide are stated, unambiguously in the overview, to be management of local noise problems and in the interpretation of existing policy and legislation.

2.6 ISSUES OBSTRUCTING COMMUNITY UNDERSTANDING

2.6.1 Amenity

Amenity is a complex and frequently misunderstood concept. Yet, in land use planning, protection of present and future amenity is a condition precedent to many approvals.

The term, amenity, identifies “a desirable or useful feature or facility of a building or place”, and in aggregate to “the pleasantness or attractiveness of a place” [Oxford]. The normal legal meaning of amenity in Australia is pleasantness [High Court of Australia,1970]. However pleasantness is a function of numerous elements, or parameters, only one of which is noise. The High Court plainly states that noise is “a relevant consideration”. Others can include character and appearance of buildings, proximity to facilities and infrastructure, absence of noise and offensive odours – essentially the features, benefits and advantages in the environment in question [Victorian Government Solicitor’s Office,2008]. Amenity could therefore be considered to represent an intrinsic value of an environment.

In layman terms, the perceived acoustical pleasantness of an area is mistakenly termed the area amenity. Sound pressure level does not alone constitute a measure of amenity, nor even of acoustical amenity unless quantified appropriately. The considerations of the industrial noise policy and indirectly of the Noise Guide for Local Government are based on a measurement – the L_{Aeq} - that should properly be described as a metric in its application to amenity. The L_{Aeq} unit is not a measure relating to amenity, instead being a retrospective unit that can only review what has passed, not what is present.

NSW legislation could be considered to recognise value in an existing acoustic environment in the Noise Policy for Industry [EPA,2017] by referencing the term amenity. Mestre et al [Mestre,2011] noted the need for improvement in public understanding of predicted impacts, suggesting that “a noise metric expressed in linear units…...might….be more readily grasped by the public”, quoting an example relevant to this work of the number of aircraft flyover sound levels above a given threshold. This approach may partly explain annoyance but does not identify a change to an existing environment. A comparison of ambient energy-equivalent sound levels can disclose differences affecting the amenity for two fundamentally similar auditory environments, however amenity can not be quantified as a sound pressure level in the manner applied by the EPA. Despite the best of probable intent, the inappropriate use of the term amenity in the EPA documents obstructs both community understanding and the development of more effective impact assessment criteria.

2.6.2 The worst-case assessment scenario

In practice, the association between the impact assessment metric and the interpretation of impact by members of the public is opaque. In attempting to imply robustness in assessment procedures, practitioners preparing documents under NSW EPA noise policies frequently utilise the term "worst case" to describe the basis referenced by a reported assessment. While this terminology is not used in the EPA policy documents, reference is made in the Noise Guide for Local Government to a worst-case noise level (Cl 2.3) and to a worst-case scenario being a basis the case of greenfield site planning (Cl 3.1.2).

In fact, NSW noise policy objectives are based on seeking to protect 90 percent of an exposed population from being highly annoyed [EPA,2015]. Source noise levels are reported, by regulation, as an L_{Aeq}, which may be influenced by the highest noise levels associated with a source but is clearly not the worst-case noise level that an affected stakeholder may consider relevant. Table 5 below, as an example, shows the large range of values for the same event that could be presented as "worst-case" even when based on field measurement.

The EPA noise policy approach is to determine or predict levels that describe conditions when the source is considered likely to be loudest, with insufficient regard to what ambient noise conditions might apply at that time. This disconnection is aggravated by the Policy approval of a threshold limit referenced in section 2.5.6.1 above for background noise level, which clearly contradicts the worst-case scenario principle from the perspective of an objector.

An undesirable outcome from implying a worst-case assessment objective is to build an undue emphasis on meteorological aspects in reporting an assessment or a prediction, regardless of how significant the effect of these conditions may be. This information can occasionally be important but is often simply confusing.

Insufficient consideration is given to the magnitudes of stochastic variance of the parameters influencing used in regulatory assessment or prediction. The regulatory assessment premise is to remove unusual or statistically rare circumstances from the assessment and to determine an outcome based on those conditions. Any implication of a worst-case scenario assessment is clearly likely to mislead unless very carefully qualified.

2.6.3 The diversity of assessment criteria

One of the most difficult aspects of noise management confronted by practitioners, legislators and the public is the diversity of noise assessment criteria. These criteria may have derived from more than one reaction factor or consequence – annoyance, health effects, economic considerations, sleep interference, community fear, aesthetics, speech interference – in the context of some of which it is important to note that human reaction to acoustical stimulii is both inconsistent and non-linear.

Some metrics are more convenient to use and are therefore favoured, while others may be more easily understood. However multiple criteria present barrier to communication and can obstruct decision-making. In NSW a helipad is approved under local government authority, is required to conform with EPA guideline criteria while a helicopter is operating but in contact with the ground, but is released from those criteria to be regulated by Commonwealth Law the instant that the vehicle has left the ground. In NSW a commercial development is controlled to criteria issued by the EPA or by local government for activities on a site, including delivery vehicle movement, however effects from that vehicle movement are considered using different criteria when it leaves the site. Developments resulting in a high negative impact on road noise levels may be approved because they are shown to generate a low level of noise impact on an adjacent site. Multiple criteria can result in the risk of impact being misunderstood and, worse, concealed.

Frequently, no whole-of-operation criterion applies to a development against which its' operational approval can be readily measured, at either planning or operational stages.

2.6.4 The Precautionary Principle

The precautionary principle is an important but inconsistently interpreted concept. The Principle is a strategy proposed by UNESCO to cope with scientific uncertainty in Policy and decision-making when there is a plausible indication of possible harm, particularly environmental harm, and that harm is deemed or anticipated to be morally unacceptable [UNESCO Comest,2005]. This has an obvious problem of ambiguity regarding the meaning of risk and of reasonableness when contemplating impact from a land use, under both ethical and legal regimes. The Principle is believed by some to represent a higher-order legal concept that assists in the interpretation of laws and, importantly, requires consideration of not simply a singular act of specific interest, but of all feasible alternatives to that action [Steele,2006]. Under the current acoustical impact assessment paradigm the context of irreversible environmental damage is ignored, while the prospect of gradual erosion of the amenity of an occupied or recreational land area is also partially ignored. Despite these common community concerns, regulatory procedures provide no facility assisting review. The precautionary principle is "built around the idea that the costs of human-made risks should not be externalised, neither to the local environment nor to the environment of other societies or nations" [UNESCO Comest,2005].

2.6.5 The Reasonable Person

The reasonable person is a legal invention used by a court to decide how that reasonable person might have acted in the particular circumstance at question. Whilst being a concept originating in courts of criminal law [Oshinrude,2012] stating that "the reasonable person is a wholly impersonal fiction to which no special characteristic of the accused should be attributed", the concept is more widely applied. In US local noise ordinances law enforcement references the right of "a reasonable person of normal noise sensitivity" [Fahey et al,2016]. The hypothetical reasonable person is unable to be strictly defined as every circumstance is unique and only a court can decide what is represented by the reasonable person relevant to the matter.

Notwithstanding the obvious application of a reasonable person concept in situations relating to annoyance, reasonableness of a proposal is likely to be viewed quite differently if an environmental damage is considered to be a risk risk by a party to a land-use application dispute compared with solely annoyance or personal preference. Where legislative decision making in NSW does reference the reasonable person it is only under the Local Government Act 1919, and then only under readvertising provisions following amendment to an application, that readvertising obligation arises only if, after that consideration, a "reasonably minded potential objector" might be expected to consider the amendment significant [Farrier et al,1999].

Reasonableness is an adjective that is the assumed basis for decision-making but, as discussed below in section 3.1, is not necessarily the basis of land-use planning decision-making.

As far as regulatory procedures are concerned, reasonableness is not mentioned in EPA policy documents other than in the Noise Policy for Industry (glossary, p40) indicating that impact assessment should include consideration of the "reasonably most affected location", and in the consideration of feasible and reasonable impact mitigation treatments.

2.6.6 Feasible and Reasonable mitigation

When mitigation treatment is deemed necessary under legislative regulation, the actual implementation of such treatment is commonly evaluated on a "feasible and reasonable" basis. The parameter used to determine which treatments are reasonable is usually cost, although the instructive intent of, for example, the EPA Noise Policy for Industry is to engage with an affected community when deciding about aesthetic and other impacts of mitigation treatment. Regulators have been progressively expanding the concept of action triggers followed by feasible and reasonable mitigation treatments into various acoustical situations – industrial noise, road noise, construction noise being examples. These principles are not transparent and can be applied disingenuously. In this situation outcomes can be in marked conflict with an important concept underlying the Precautionary Principle – polluter pays [UNESCO Comest, 2005].

2.7 THE CURRENT NOISE IMPACT ASSESSMENT PARADIGM – CRITICAL REVIEW

The current noise impact assessment paradigm is summarised above in 2.3.4. These principles are also in common use internationally.

Important technical limitations affect this generic procedure. Legislative terminology [DECC,2011] [EPA,2017] implies that 'the source' of interest is physically discrete, operationally definable and infers an outcome that will increment an existing ambient environment by some amount. However, the physical relationship between a receiver (observer) and one or more acoustic sources determines whether the sources involved can be examined as an acoustic source, sources-system, or a system of sources. For acoustic environments, evaluation is conducted on the basis that the observer is situated outside the geometric near-field, in what is known as the far-field.

An acoustic system refers to an arrangement of concurrently operating physically discrete sources. Both the source emission levels and the intra-source physical relationships describing a system may be subject to temporal variation.

Acoustic systems may be either stationary in both physical location and discrete-source emission level, stationary in physical location but variable in discrete-source emission level, variable in physical location but stationary in discrete-source emission level, or variable in both physical location and aggregate emission level.

A system that is stationary in both physical location and in discrete-source emission describes what is commonly termed a stationary or a steady-state source. If the discrete source elements are equal the source will generally be described, for the far-field condition, as a physically stationary, steady-state point source, described by an overall sound power emission level.

One commonly encountered sources system - a machine – comprises multiple source elements located in a fixed or stationary physical matrix. For such a source, variation in emission levels of the individual source elements can be quantified, in the geometric far-field, as a physically stationary steady-state source described by an overall sound power emission level with defined directionality components.

For the same machine, if variation in the emission level of any or all sources is present, either or both the overall sound power level and each directional component may be determined and reported as statistically based sound emission levels. This is described as a physically stationary sources-system. If an observer location is affected by more than one sources-system the evaluation can be conducted as an analysis of a system of sources. Where the observer is not able to be in the far-field for the aggregate of all sources and sources systems, the evaluation can only be conducted as an analysis of a system of sources.

Acoustic systems associated with land uses are rarely time invariant and almost inevitably involve one or more sources-systems. When considered in the context of the many observer locations likely to be relevant, evaluation of environmental acoustic systems can only be conducted as an analysis of systems of sources. Many situations involve multiple systems of sources for which, in an attempt at management, differing regulatory compliance criteria are suggested. Development projects commonly involve outcomes amounting to a major change of characteristic surrounding land area usage, and not simply to the impact of a discrete activity on existing occupants within a discrete development area.

Level measurement limitations

The measurement of an equivalent energy level for a steady-state, or stationary, noise event is straightforward and generally repeatable. However, an energy equivalent metric is increasingly insensitive to discrete but significant events as the duration of the sampling period is increased. These aspects are demonstrated using a randomly chosen dataset of property boundary sound pressure levels, measured by the writer in September 2018 over a 6.5 hour period, during which a number of vehicles parked on a site close to the microphone, a trio jazz concert was held inside a building on the site, a number of periods of outdoor socialising occurred adjacent to the building and the attendees then departed. The latter portion of the sample comprises, primarily, ambient sound from unrelated distant sources.

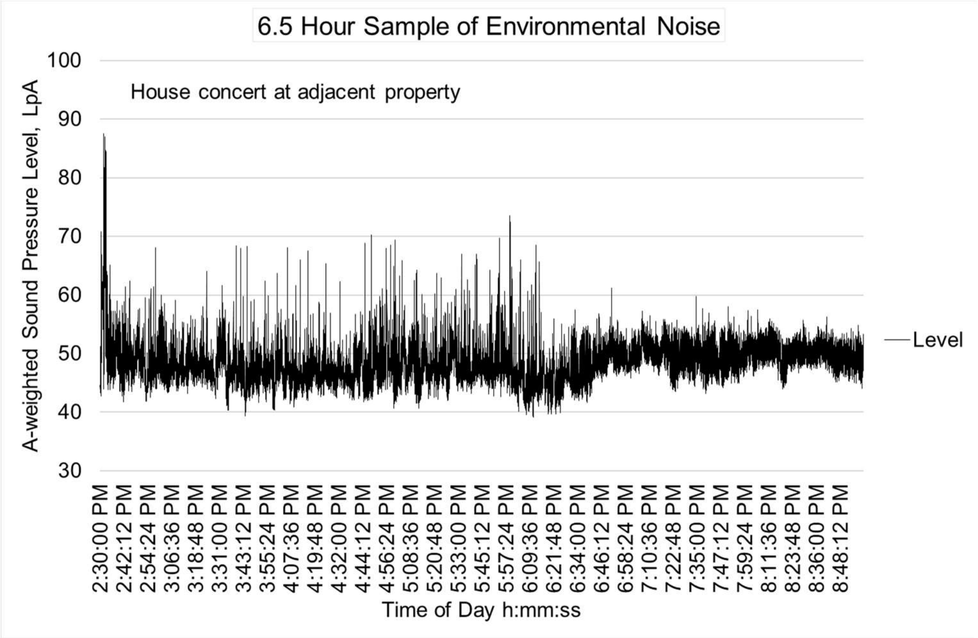


Figure 1: Example Environmental Noise Survey

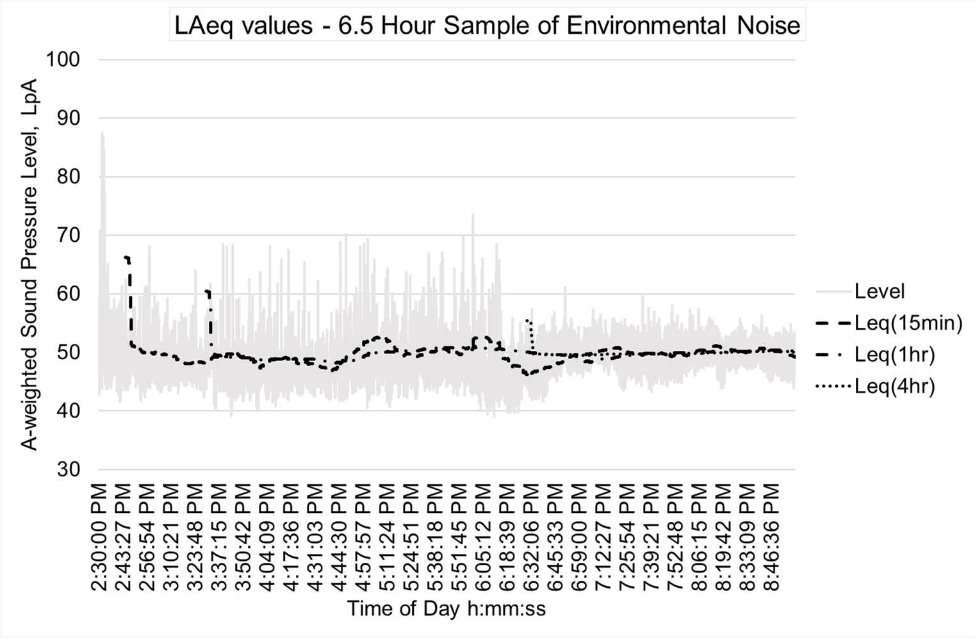


Figure 2: Environmental Noise Survey, L_{Aeq} metrics

To demonstrate issues inherent to the energy equivalent metric L_{Aeq}, used as the regulatory basis for assessment, the data was analysed using rolling sample windows, each commencing 1 second apart. The integrating periods were 15-minute, 1-hour and 4-hour L_{Aeq} metrics, shown in Figure 1 and Figure 2. This is not suggested as an assessment requirement and is used solely to demonstrate features affecting the value of the L_{Aeq}, which are the significance of a chosen assessment period, the potential influence of the arbitrary but instantaneous commencement time, the lack of sensitivity of the energy equivalent metric and the limited value of a reported equivalent energy level in the absence of concurrent knowledge of the level time-series.

All three L_{Aeq} period metrics are strongly influenced by the presence of a short period of relatively loud events (within the first 15 minute period). However, valid L_{Aeq} period level maxima could be reported as 55dB, 60dB or 66dB depending on the choice of the assessment period.

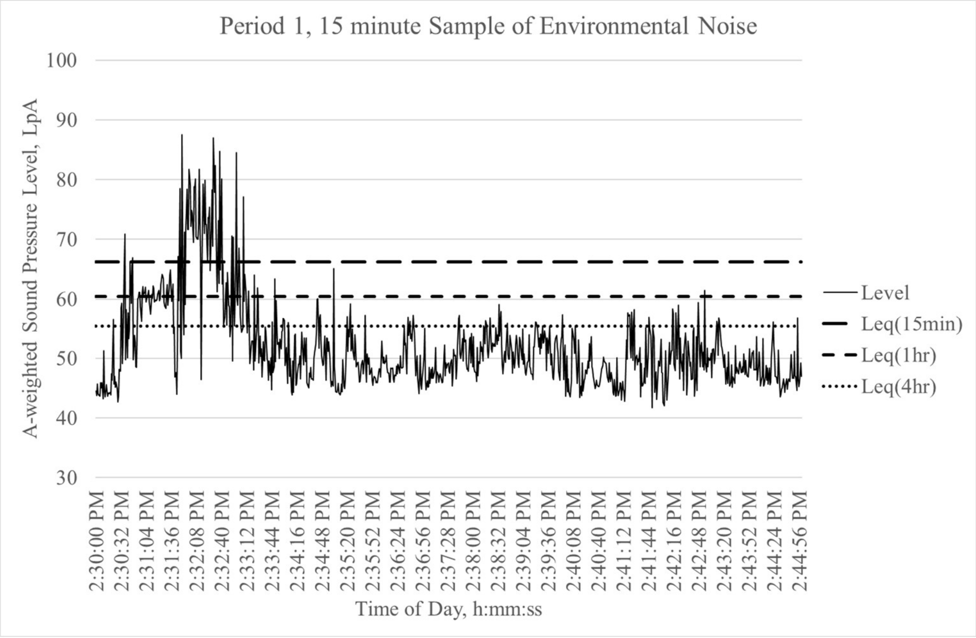


Figure 3: Initial 15-minute survey period sample

If the initial 15-minute period is excluded from the analysis in Figure 1, the presence of substantial and regular level maxima remaining throughout the first 60% of the data, and then absent in the last 40%, is not distinguished by the rolling energy equivalent metrics in Figure *2* other than being briefly relevant for the 15 minute sampling, and for 1-hour and 4-hour data essentially indistinguishable.

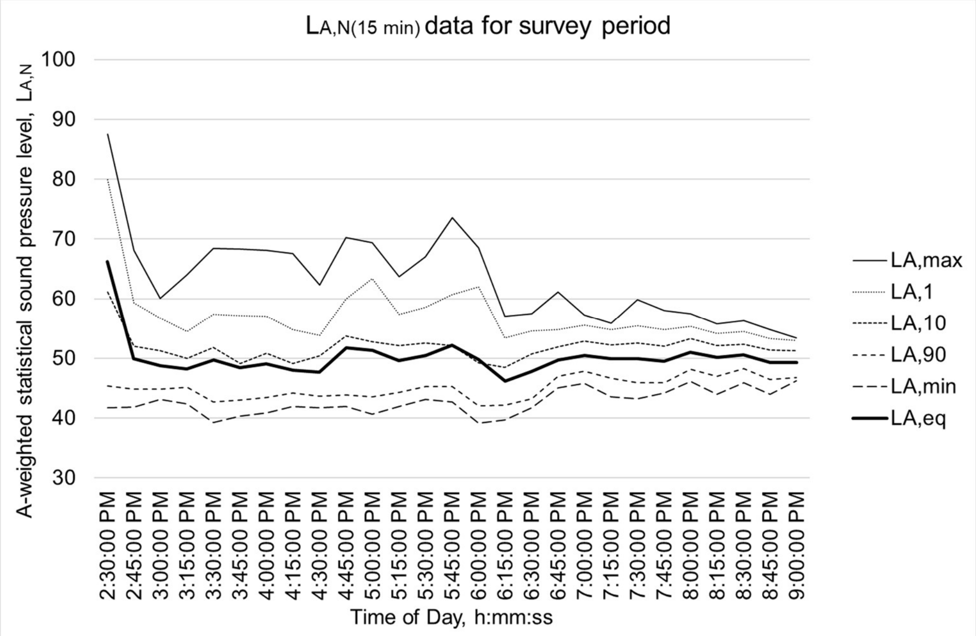


Figure 4: Survey statistical noise levels

Compared with statistical metrics of Figure 4 for the same data, Figure 2 highlights the insensitivity of the L_{Aeq} to the aspects most likely to draw subjective attention, and potential for impact.

Using a similar rolling L_{A90} window for periods 15, 60 and 240 minutes respectively, average L_{A90} metrics are 45.0, 44.6 and 43.9 dB respectively. The lower bound 90% intervals are found to be 42.1, 42.2 and 43.5 dB respectively. The L_{A90} metric can be seen, for this example but from experience generally so, to be considerably less sensitive to the choice of assessment period than is the L_{Aeq}.

Impact Assesssment

A Rating Background Noise Level (RBL) determined from 15-minute statistical data would be reasonably estimated as 43dB(A). The mean L_{Aeq} over the concert period is 51dB, or if the survey had missed the initial sample period a mean value of 50dB. An intrusive noise impact assessment would therefore indicate an exceedance of 7-8dB(A) or if assessed from a full-day perspective, less. Other conclusions could be reached if different L_{Aeq} assessment period intervals had been adopted. If the EPA Noise Policy for Industry were relevant to the site, which it was not, these outcomes would trigger consideration of mitigation, though only marginally so.

Table 3: A Current Noise Impact Assessment Schedule

Parameter	Level, dB(A)
Source L_{Aeq}	50
Rating Background Noise Level (RBL)	43
L_{Aeq} – RBL	7

Comparing Equivalent Energy Levels with Statistical Levels

A steady-state, or stationary, acoustical system is one for which the source emission level and the observer immission level is constant regardless of the observation period. This is not the case with an equivalent energy level. The use of any aggregate noise level statistic alone – L_{Aeq}, L_{A10}, L_{A90}, L_{Amax} etc – assumes that a stochastically varying system can be quantified using techniques that are valid for a stationary system with equally valid conclusions.

Figure 1 and Figure 2 demonstrate the systemic problem affecting an energy-equivalent measurement – the optimum assessment interval can only be determined retrospectively, requiring knowledge of the instantaneous noise level variance. There is no obviously superior metric for this example based on a stationary measurement attempting to characterise the source level. The inter-unit correlation coefficients (n=15,H_0=0.693) set out in Table 4 suggest that an impact assessment based on threshold level changes (e.g. L_{A90} or L_{Amin}) could produce different conclusions, however little difference would be expected if an assessment had been based on other statistical parameters. Excluding the first sample period does not alter this situation significantly, while the coefficients for the subsequent ambient period are markedly different.

Table 4: Correlation Coefficients $L_{A,n}$ vs L_{Aeq}

	$L_{A,max}$	$L_{A,1}$	$L_{A,10}$	$L_{A,50}$	$L_{A,90}$	$L_{A,min}$
Full concert period	0.9	1.0	0.9	0.7	0.4	0.1
Concert period excluding period 1	0.7	0.8	0.8	0.6	0.1	0.1
Ambient period after concert	0.1	0.5	1.0	1.0	1.0	0.9

Figure 1 and Figure 3 both show that a random sequence of sampling observations for a stochastically variable system will not satisfy the conditions defining a stationary system [Morfey, 2001]. A reported measurement is unlikely to reflect any instantaneous observation, nor the impact occurring at that time. Comparable assessment error is likely to apply using any single stationary metric.

Unreliability of the “true” interpretation of the energy equivalent metric value is not unique to the above example. Analysing a dataset from the Bolong Road site survey referenced in Chapter 5.5 of this thesis and comprising approximately 5 days of road traffic noise sampling, produces the results shown below in Table 5. It is mathematically obvious that the L_{Aeq} for stochastically varying noise over progressively longer periods is de-sensitised, as verified in Table 5. All values reported in Table 5 are valid measurement reporting results for the same data derived from energy averaging over different periods, suggesting potentially different impact assessment conclusions. These examples represent increasingly common scenarios in developing areas for which the measurement methods provide little explanation to a regulator, and to a neighbour, about the nature of the probable noise impact.

Table 5: Equivalent energy metrics for 5 days of road noise data, T=15 min, dB

	Day	Night
Overall L_{day}	64.9	
Overall L_{night}		57.2
Highest L_{day} or L_{night}	66.2	57.9
Lowest L_{day} or L_{night}	64.4	55.7
Highest $L_{Aeq15min}$	74.2	66.5
Highest L_{Aeq1hr}	70.4	65.1
Lowest $L_{Aeq15min}$	39.9	26.5
Lowest L_{Aeq1hr}	58	32.2

Important conclusions implied by the above brief review of current impact assessment method are:

1 The L_{Aeq} metric is insensitive to significant level variance in a sample period (*Figure 4*)

2 The L_{Aeq} metric, despite being an averaged unit, may vary significantly depending on the specific sampling period of a level-time variance signal (*Table 5*)

3 The L_{Aeq} metric is no different, statistically, to alternative stationary metrics (*Table 4*)

4 Acoustical impact is currently determined to be the averaged energy exceedance by the pollutant of a stationary benchmark level. This is a stationary value assessment of constant magnitude for the assessment period, in contrast to a dynamic assessment method in which the magnitude by which the pollutant exceeds the ambient environment is constantly varying.

2.8 OBSTACLES TO OBJECTIVE IMPACT ASSESSMENT

Many measurement metrics have been, and continue to be, investigated and have obvious application in research or review of existing situations. Unless the metric can be modelled in advance it is of little value to planning.

Most environmental acoustic situations involve a range in daily sound pressure level of the order of 50dB(A) or more. Many situations involve short duration events, many sources are physically extensive, are comprised of multiple components and are commonly simplified to single stationary elements – for example road traffic considered as a line source. The simple validity test is whether the range of audible conditions encountered in such systems can be accurately expressed by an averaged operating state, which they cannot.

Subjective factors known to influence annoyance, and therefore negative perception, are incorporated by the addition of penalty weightings. Such weightings have been discussed in section 2.3.3 above and, while there have been considerable efforts made to refine the magnitude assigned to such weightings, their application in any particular case can be seen as arbitrary. Importantly, no obvious method has yet evolved that could permit allocation of positive weighting to subjective features considered to be desirable. Important factors influencing perception of acoustic environments have been identified – Saliency and attention-focussing parameters [Botteldooren & De Coensel,2007],[Botteldooren et al,2011],[Kang et al,2016],[Botteldooren et al,2008],[Filipan et al,2008], auditory preferences and auditory dislikes in considerably greater detail than the metric penalty weightings noted above [Axelsson et al,2008],[Marry&Defrance,2013],[Aletta et al,2014] as well as dimensional parameters through which soundscapes might be quantified [Axelsson,2010]. However, no clear method of analysis has yet evolved by which analysis of soundscape data should be analysed [Kang et al.2016].

Soundscape principles have found increasing application in design projects – buildings and outdoor spaces such as parkland – but not, as yet, in legislative land-use planning, including impacts on amenity.

Historically, early environmental acoustic assessment methods were generally restricted to analogue instrument measurement techniques. Beneficially, these techniques did facilitate concurrent subjective review of the sources involved in any given situation as part of the measurement process, permitting judgements about significance, knowledge about the range of instantaneous impact conditions that were observed, together with the ability to identify sometimes very brief duration components within an overall environment. Assigning a relative importance to source components and identifying appropriate assessment intervals is more difficult using post-processed digital measurement techniques. The historical method of assessment based on these measurements identified the average of the level maxima associated with a particular source. This procedure was progressively amended to replace the average-maxima concept with a measurement of the equivalent energy level. Analysis of the relationship between equivalent energy level for a very prominent (dominating) source with its average level maxima, for example the data shown in Figure 1, does suggest that this rationalisation is reasonable. What cannot be emulated, however, is the concurrent subjective filtering of a multiple source system during a measurement to ensure the association of a particular source with the reported measurement level is valid. The manual, analogue, measurement procedure facilitated selective sampling by an observer to obtain valid data within a stochastically varying environment. It is impractical to revert to manual analogue measurement methods as a policy.

Statistical ($L_{N)}$ data can use arithmetic level averaging instead of energy averaging. This enables the statistical interpretation of the likely range of a metric – e.g. the 90th percentile of an L_{A1}, or the upper or lower bound of a 90 percent confidence interval for a chosen metric. The EPA method of assessment for the background noise rating level is a gesture to this approach, but is dataset-specific so is a technique from which the findings cannot be generalised to other locations or other time periods.

A feature that facilitated the adoption of the equivalent-energy metric usage is its relatively simple addition and subtraction whereas calculation using statistical units is difficult.

A fundamental constraint in any procedure using an energy-averaged metric is that the metric is unable to distinguish between one area where a small number of subjectively different sources creates an unstable and constantly varying level and another where a pool of numerous sources produces a stationary system with unchanging level.

Notwithstanding the widespread adoption of equivalent energy metrics, no single metric is adequate to characterise acoustic resources [Lynch et al, 2011].

Mestre et al referring to aircraft noise noted the counter-productive outcomes of acoustical jargon and of arcane measurement metrics in a 2011 report. The report observed that “a family” of A-weighted energy equivalent metrics first fully described by the EPA in 1974 had remained dominant for aircraft regulatory analysis for several decades. The same report observed that the use of these types of metrics demanded “only one appealingly simple assumption – the so called ‘equal energy hypothesis’ – about the origins of annoyance”. The continued usage is one of convenience rather than of predictive robustness. The Mestre report identified perceived major limitations in the use of day-night averaged noise levels in the approach to aircraft noise – being an abstract concept, remote from common experience, unable to be directly experienced, non-intuitive, weak in understanding by the public, bringing a focus to a metric in lieu of descriptive discussion of impacts, inadequately justified, and a statistically poor predictor of high annoyance in communities [Mestre,2011].

The natural outcome of procedures based largely on measurement is that communication between regulators, policy makers and the public - stakeholders in any land use planning proposal - largely involve numerical argument. In contrast, those same stakeholders are likely to use a largely emotional basis in forming their own judgements and opinions, involving more complex risk factors than any stationary numerical assessment metric can quantify.

Brown notes the important concept that a soundscape exists only through human perception and within a context of a particular time, place and activity [Brown, 2011]. This provides a prescriptive foundation for fitness-for-purpose in the design of a specific building or land-use development for a specific user. However, it should be remembered that environmental impact is an outcome that transcends the concept of perception (i.e. human self-interest) and of an effect restricted to perception specific to a particular time, place and activity. Two aspects should be recognised, one being the adverse environmental and community outcomes that have ensued from the application of human self-interest, and a second being the adverse passive impact outcomes that will accrue from sequential impacts, each sufficiently minor to be little noticed but large in eventual aggregate. Human perception is individual and an outcome that is perceived only by those present to be able to perceive does not protect against adverse outcomes affecting both the soundscape and the acoustical environment. This is the corollary to Brown’s observation that “the soundscape of a place may enable certain outcomes/activities without people consciously dissecting why it is that the environment of a place provides so well for that activity”.

2.9 CONCLUSIONS

This chapter has demonstrated that a fundamental question is not asked by current environmental noise impact management methods or their associated assessment procedures – are the predicted outcomes fit for the intended purpose? This omission occurs because the intended purpose of management procedures is fundamentally unclear, lacking identification of subjective aspects relating to annoyance – context and appropriateness - and lacking recognition of value in acoustical environments within which consideration of annoyance may be a distraction from more important considerations. In relation to land-use planning it is also clear that management policies that regulate an approved incursionary level of pollution will inevitably erode existing environments.

NSW environmental noise assessment procedures are consistent with procedures used internationally. These procedures pre-conceive that environmental noise is restricted to relatively loud noise events that undesirably dominate the existing ambient acoustical environment, the result of which is that such procedures are focussed on the abatement of loud noise events.

No current policy considers the existence, the value, or preservation, of acoustically pristine lands. In fact, current NSW policy aggravates this omission by adopting a policy principle that permits a lower threshold limit to be applied when determining an appropriate impact assessment level in such quiet areas. Specifically, NSW policies permitting assessment to be based on an assumed minimum background noise level threshold (30dB(A) at night and 35dB(A) daytime) are unsatisfactory if they are applied in areas other than locations within or adjacent to heavy industry. This strategy must be clearly excluded from any guideline or policy relating to noise impact assessment in any other areas.

The use of an energy-averaged level is widely adopted in NSW environmental policy procedures. There are many aspects leading to uncertainty in the interpretation of an energy-averaged metric particularly when applied to an assessment of environmental noise. This significance is not adequately recognised, nor such measurement adequately cautioned in policy documents.

Magnitude-of-impact is not contemplated by NSW environmental noise management and a levels-based compliance approach only is used. An impact index calculated as the subtraction of an ambient L_{90} from the energy equivalent level of a proposed future imposed source conveys little or no information about the relationship between that imposed noise and the ambient environment it may affect and is an obstacle to community communication. This communication problem is aggravated by the use of different assessment criteria for individual parts of an overall development proposal.

There is insufficient evidence of co-ordination and technical correlation between the range of values deemed, by Policy, to be those appropriate assessment criteria. Rarely are criteria applied to a system in aggregate and there is no objective basis, within those policies, wherein source-specific assessment criteria can be demonstrated to be consistent with criteria applied to other land-use applications.

Procedures that envision a worst-case assessment scenario need the interpretation of that scenario to be carefully defined.

The assessment of acoustical impact on the real or perceived value of an environment is absent in NSW Policy documents because those policies have evolved with a focus on noise annoyance and on the mitigation of existing complaints. Notwithstanding continuing effort to quantify the importance of subjectivity, through the epistemology of soundscape, its application in environmental protection legislature is inhibited by the inability to apply an objective measure to subjective elements. This lack of fundamental progress in environmental management has been obscured by the emphasis in contemporary investigative reporting on sophisticated pictorial presentation of level-based findings, appearing sophisticatedly complex but with little or no designation or description of impact.

Effective impact assessment requires, first, an informative definition for the term impact. This definition is lacking in current legislation.

3 A FRAMEWORK FOR LEGISLATIVE ASSESSMENT OF IMPACT

3.1 PREAMBLE

In 2015 Justice Moore AJ handed down judgement [NSW LEC, 2015] overturning a development consent by Hawkesbury City Council granting approval for temporary use of a structure as a function centre. This judgement raised important considerations concerning “the fundamental nature of the test required” when considering impact. That test was a condition precedent imposed by a Local Environment Plan clause which had been drafted from the NSW Model LEP [NSW Govt, 2006] and is replicated in numerous NSW local government area examples. The clause applies to a development application seeking approval to temporarily carry out an activity that the LEP deems otherwise to be a prohibited land use. The condition precedent to approval is that development consent must not be granted unless the consent authority is satisfied the use will not adversely impact on any adjoining land or the amenity of the neighbourhood.

In precis, professional acoustic reports had been compiled and issued in the context of the assessment criteria promulgated by familiar authorities – EPA and the Department of Liquor and Gaming. Council, in turn, had utilised various of the recommended assessment findings to formulate conditions of consent and had approved the application for temporary use. Justice Moore, however, concluded that the nature of the investigations did not constitute a correct test satisfying the requirements of the LEP sub-clause.

The specific plea upheld by Justice Moore was that the acoustical assessments made in evaluating the adequacy of the development proposal did not address the fundamental test that there be **no** adverse impact (Judgement, cl 69, cl 116, cl 125, cl 126) and had, instead, concluded that the predicted impact would be considered “acceptable”. In examining this plea, Justice Moore determined that technical standards derived from those applied by an external regulator – OLGR in that case – envisage “*merely an acceptable impact rather than absence of impact*” (Judgement, cl 119). In a corroborating qualification (Judgement, cl 97, cl 102) Justice Moore noted that “*mitigation measures*” proposed for management of acoustic impact do not constitute elimination. These judgement findings identify clear obligations to parties involved in this type of proposal.

The specific requirement for approval under the LEP examined by Justice Moore was that the proposed activity “not adversely impact on adjoining land” or “adversely impact on the amenity of an area”. There is, however, a broader question raised by Justice Moore’s ruling – how does environmental noise assessment quantify the magnitude of any impact, what quantifies an impact that can be deemed satisfactory, and what does a requirement for no impact imply? Current environmental noise management legislation provides no foundation to contemplate the magnitude of an impact.

The definitions of terms relating to environmental impact are complex and difficult because those definitions require context. The dictionary definition of impact - a marked effect or influence – is strictly an inference, having meaning only in the context of an action and an outcome. Impact is due to one or more causal factors but is an impact on something.

Land use planning involves making decisions based on information that, it is assumed, addresses the objectives and policy imbued in any related legislation. Efficient, and certainly legislative, decision making involves consideration of whether a predicted outcome from an action will be either true, or not true. This is a more fundamental test than many appreciate:

> It is true that this outcome will occur?
>
> OR
>
> It is not true that this outcome will occur?

The logical decision being made is whether an outcome will, or will not, be an outcome that has been described, but not necessarily a decision on what else might occur. If the applicant excludes, or is unaware of, impact-related aspects of the proposal the regulatory test does not automatically investigate that, being based usually on whatever regulatory criteria have been cited. In contrast, emotional decision making is frequently framed [Cheng, 2019] as a test of opposites envisaging that the decision-maker should consider the probability that a different outcome may occur. This ambiguity in the basis of expected decision-making can be aggravated when assessment is based on averaged-state metrics, as that averaged state may be insensitive to, or even remove from consideration, the condition that may be the origin of the emotional concern – for example, loud noise events. An averaged state may be perceived by an objector to be an opportunistic generalisation potentially protected by aspects of legislative decision making that contemplate reactions based on the “reasonably minded potential objector" [Farrier et al,1999] without any parallel reference to a reasonably minded applicant. This affects how a community will interpret the meaning of impact assessment and in their expectations of a planning review process.

There are important differences between these two aspects to decision making, without important foundation for which unsatisfying outcomes are highly likely. Cheng notes

> *"We can try to use logic to construct arguments about the real world, but no matter how unambiguously we build the argument, if we start with concepts that are ambiguous, there will be ambiguity in the result."*

Three elements require definition in order to facilitate reliable decision-making:

1. What defines the impact,
2. what is the nature and scope of the proposed activity (and its associated consequences), and
3. what impact is reasonable in the context of the particular situation.

Outcomes considered to be no impact are entirely different if one assessment contemplates levels of annoyance, while another contemplates the preservation of a valued environmental aspect.

3.2 ASSOCIATING CHANGE WITH IMPACT

3.2.1 Identifying and Defining Impact

A broader focus to environmental acoustic management recognising acoustical environments as potential assets [Brown, 2011] is one of many objectives suggested by soundscape practitioners. This would automatically broaden the context for the consideration of impact, though only if the protection of those aspects is required legislatively. In NSW an approach recognising value in environmental quality would be consistent with the POEO Act in both the definition of offensive noise and of the objective of Part 10(b) of the Act referenced in section 2.5.5 above. However, under the current limited definitions of the POEO Act the process of land-use decision-making is unable to invoke a value judgement of "what is here to be protected?" when the procedural legislative test is limited to "pollution is allowed but will the level of pollution comply with a deemed-acceptable limit?"

The principle approving a measure of pollution without a more robust focus on longer term cumulative effects, as well as sometimes widespread effects, is seriously flawed. Schultz noted that most instances of deteriorating environmental conditions are a consequence, not with ill-intent, of lifestyles of humans and that conservation can only be achieved by behavioural change [Schultz,2011]. This observation recognises that environmental deterioration is entropic, associated with numerous sequential changes each of minor magnitude. Improved environmental impact management policy must evolve from the insight that the magnitude of environmental change arises from a sequence of individually incidental events unlikely to be recognised by policies that contemplate only large magnitude events.

Minor changes may in aggregate be far more significant than the discrete larger scale individual-event-based changes contemplated by many legislative policies, because there is frequently no convenient means to measure the effects of minor changes. Cumulative impact effects has been a matter of substantial concern in environment and land-use planning, internationally, [Runge,1998] and is recognised in NSW case law [Gloucester Resources Limited v Minister for Planning,2019],[Friends of Tumblebee Incorporated v ATB Morton Pty Limited,2016]. The significance of broad-scale diffuse impacts, particularly those associated with infrastructure, is also recognised [Tulloch et al,2019] and the International Finance Corporation has, indeed, published a handbook addressing the subject [IFC,2013].

The term "impact" is undefined in NSW legislation, in NSW case law and, apparently, in international law. Whereas "acceptable" impact may be case dependent in the same manner as is the reasonable person, this does not appear to preclude the definition of a type of impact that is perceived to be the focus or objective in a statute. The Oxford definition [Oxford, 2019] of impact refers to "a marked effect or influence", and in the context of the environment the term impact management generally refers to management of a negative effect. The Federal Parliament adopted [Commonwealth of Australia,1995] a more holistic and fundamental working definition [Hede,1993] being:

> *The environmental impact of an action is the difference between the state or condition of the environment which occurs as a result of that action being taken or withheld, and the state or condition which would otherwise occur.*

This is a clear and objective description of impact and can be applied to any interpretation of the environment – the biosphere, a preferential environment occupied by humans, or a situation relating to societal health. This definition supports informed communication between developers, regulatory authorities and potentially affected stakeholders for land-usage impact assessment by providing a context for obvious questions:

1. Where is the impact borne?
2. What are the anticipated changes that may generate an impact?
3. Are the predicted impacts positive, negative or both?
4. Who incurs a negative impact?
5. What magnitude of impact is foreseen?
6. Is that magnitude reasonable?
7. How can that impact be described to non-technical stakeholders?

Acoustical impact occurs because a new sound replaces, partially or wholly, audible sound that was previously present. This principle is no different from environmental bio-diversity impact where an impacting organism may wholly or partially replace an existing organism or may indirectly cause part or entire demise of the existing organism. In either case, the impact is measured by the magnitude of change to the existing condition at the impact location.

3.2.2 Describing Cause, Change and Impact

With few exceptions, sound generated by land use activities varies almost constantly and is comprised of many sources, each of which may also vary constantly. A description of a proposed activity has therefore to include each of the potentially significant conditions that should be expected. The factors that describe impact are:

1. The ambient condition
2. The activities that generate sound and their magnitude
3. The difference between the future condition and the current ambient condition.

One could add a fourth factor, being the extent to which this impact should be recognised as one of a number of anticipated cumulative impacts.

The reader will recognise that these factors are similar to the current assessment paradigm, so the pre-requisite to improving assessment of impact is to consider what conditions are compared and what aspect of difference is examined. The concept of relating impact to the energetic masking of the ambient condition by an imposed sound is not new – a relative audibility concept. In fact this emulates fundamental concepts described in 2.3.4 above in common use since the inception of noise control legislation. Subsequent and more recent research, concerned with loud noise events such as vehicle pass-by, has compared simulated event level waveforms and how they rise above steady ambient sound [Brown & Tomerini,2011],[DeCoensel et al, 2012],[Iannone et al,2013],[De Coensel et al,2016], however these techniques are unable to examine the probability that an event will exceed stochastically variable ambient sound. The author proposes the use of Emergence [Fitzell,2019].

Emergence refers to the condition when sound generated by a source rises above that of all other concurrent sources. Emergence is an instantaneous quantity – auditory emergence occurs now.

The Emergence of sound from a specific source is described mathematically by Equation E1.

$$Emergence = Lsource - \sum(Li) \qquad \textbf{E1}$$

$$\begin{aligned}&where\\&Lsource > \sum(Li)\,, and\\&\sum(Li)\ is\ the\ instantaneous\ energetic\ sum\ of\ all\ concurrent\ sources\ other\\&\quad than\ the\ source\ of\ interest\end{aligned}$$

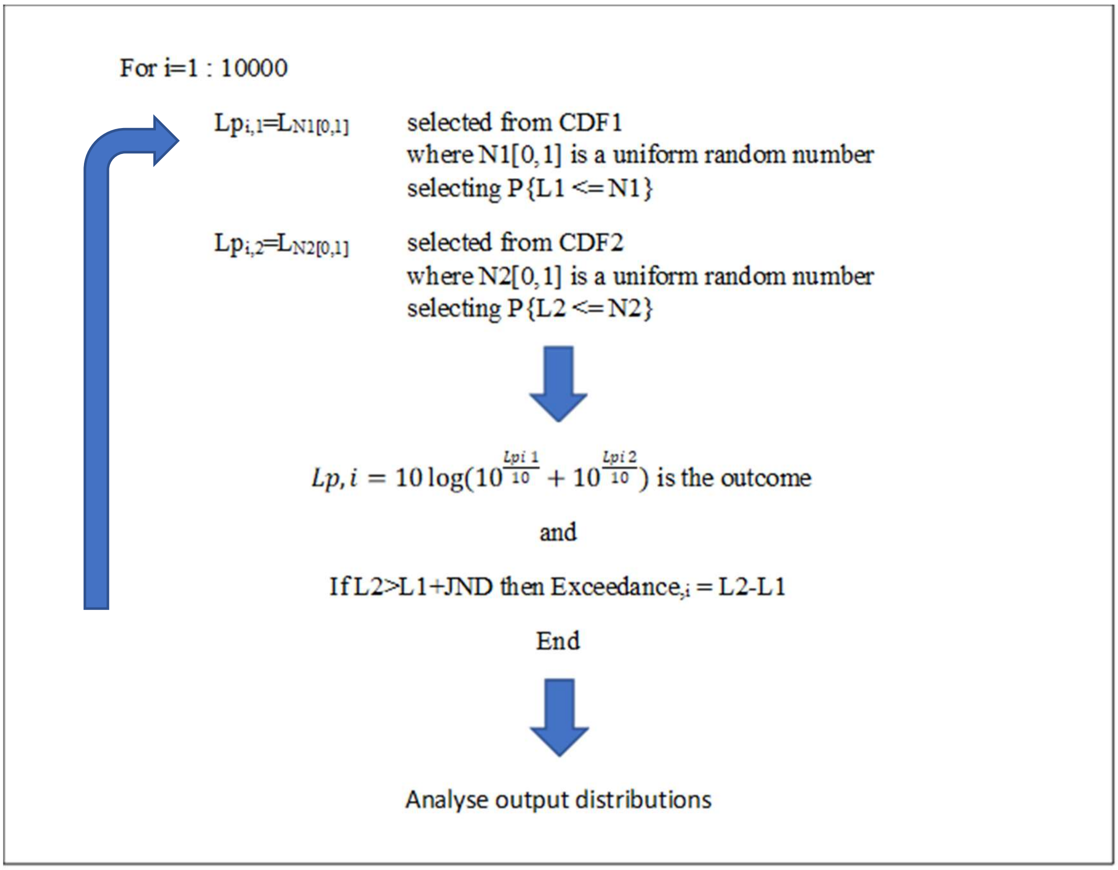
To measure Emergence directly requires an audibility-guided sampling system, the simplest example of which is a manual (and probably analogue) survey system. Emergence is an instantaneous quantity which, when examined over a time period, will aggregate to a range of values. To predict Emergence requires a method of modelling that enables the assessment of the stochastic probability of level occurrence at any instant of time for both the proposed land use activity and the ambient condition. Emergence is a dual parameter function, defining both magnitude and probability of occurrence. Mathematically, the probability (P) of occurrence of Emergence at each incurred level is described by Equation E2.

$$P(Emergence) = P\big(Lsource - \sum(Li\,)\big) > 0. \qquad \textbf{E2}$$

Equation E2 precludes the use of any stationary or equilibrium model. It also precludes the use of modelling based on averaged or equilibrium energy activities. This requires a statistically based sound level emission model based on a more carefully compiled activity model for the proposed aggregate land use than is currently in common use.

The interaction between two incoherent or independent noise systems can be statistically modelled using iterative inverse transformation sampling. The repetitive application of the algorithm of Figure 5 permits calculation of the probability that sound from the new source will be lower, or higher, than the ambient sound environment, as well as the distribution levels representing the existing and new sound combined. Inverse transformation sampling involves the conceptually simple process of randomly sampling concurrent instantaneous levels representing each condition of interest and computing the instantaneous aggregate outcome for each sample [Fitzell,1991]. Through iterative summation, the statistics of the outcome aggregate level – L_{A1}, L_{A10} etc – can be determined, as well as the statistics of the differences between L1 and L2 at any instant of time.

By extension, sampling of N-number of sources as well as the concurrent ambient sound pressure levels can determine the Emergence of each of the N sources in any combination of interest. Where a subjective feature of a source is considered to affect its audibility, the Emergence for that source can include specific weighting factor added to the contributory sound levels generated by that source. The ability to apply selective subjective weightings to individual or discrete source components is, alone, a major impact discrimination outcome.



```
For i=1 : 10000
    $Lp_{i,1}=L_{N1[0,1]}$    selected from CDF1
                              where N1[0,1] is a uniform random number
                              selecting P{L1 <=N1}
    $Lp_{i,2}=L_{N2[0,1]}$    selected from CDF2
                              where N2[0,1] is a uniform random number
                              selecting P{L2 <=N2}
    $Lp,i = 10\log(10^{\frac{Lpi\ 1}{10}} + 10^{\frac{Lpi\ 2}{10}})$ is the outcome
    and
    If L2>L1+JND then $Exceedance_{,i}$ = L2-L1
End
Analyse output distributions
```

Figure 5: Inverse Transformation Sampling Algorithm

3.2.2.1 Emergence – outcomes that describe impact

To describe outcomes using the algorithm of Figure 5, changes to statistical levels in examples based on a relatively quiet ambient area are considered below, examining the introduction of three differing new sources. The three new "sources" are a steady state source such as an air-conditioner, generating a sound pressure level 5dB(A) higher than the ambient L_{A90}, the second a new freeway generating a sound level of 55 dB L_{Aeq}, and a third hypothetical new source, varying stochastically in much the same manner as the ambient sound but generating an L_{Aeq} level 5dB(A) higher than the ambient L_{A90}. That is, two are consistent with the 5dB limit exceedance principle and one conforms with a common road design level target.

Table 6: Input data, statistical levels at recipient, dB

	L_{Amax}	L_{A1}	L_{A10}	L_{A50}	L_{A90}	L_{Amin}	L_{Aeq}
Ambient Sound Pressure Level, dB	67.3	57.6	49.4	43.3	40.0	37.3	47.7
A: Steady state source L_{A90} + 5dB	45.0	45.0	45.0	45.0	45.0	45.0	45.0
B: Freeway traffic at L_{Aeq} = 55dB	70.0	62.5	58.6	53.1	48.2	41.1	55.0
C: Stochastically varying source L_{eq}=L_{A90}+5dB	64.6	54.9	46.7	40.6	37.3	34.6	45.0

Table 7: Outcome statistical levels, ambient plus each source operating individually, dB

	L_{Amax}	L_{A1}	L_{A10}	L_{A50}	L_{A90}	L_{Amin}	L_{Aeq}
Steady State Source L_{Aeq} = L_{A90}+5dB	67.3	58.1	50.7	47.2	46.2	45.7	49.6
Freeway traffic 55dB L_{Aeq}	69.4	63.8	58.9	53.7	49.7	42.0	55.7
Stochastically varying source L_{Aeq}=L_{A90}+5dB	67.6	60.1	51.5	45.8	43.4	39.2	49.6

One immediate observation comparing Table 7 with Table 6 is that the relationship between the values of the input source statistics and most outcome statistics is not trivial.

Emergence can be calculated for each of the three conditions with results in Figure 6.

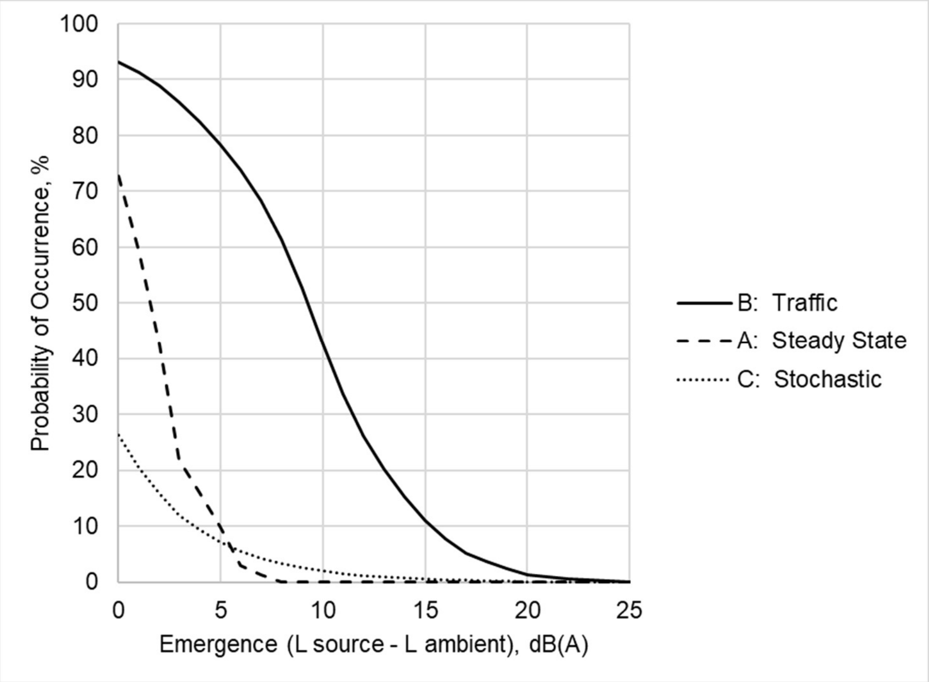


Figure 6: Emergence for each Table 6 input source considered individually

Comparing that Emergence with conventional metrics summarised in Table 8 below shows importantly different conclusions. The influence of sound from road traffic evident by Emergence is large, dominating the existing ambient sound levels more than 90 percent of the time. For the other two imposed source conditions, despite the intrusion (L_{Aeq}-L_{A90}) being "satisfactory" at 5dB, sound from the introduction of the steady-state source is emergent for more than 70 percent of the time. The stochastically varying source, at the same equivalent energy level is emergent only a little more than 20 percent of the time. Conventional impact assessment of Table 8 below would, however, consider two of the sources to be equivalent, and very substantially less than the third. The outcomes shown in Figure 6 are not identifiable from any obvious association of the input level statistics.

Table 8: Conventional impact assessment metric

	L_{Aeq}-L_{A90}
Steady state source L_{A90} + 5dB	5 dB
Freeway traffic at L_{Aeq} 55dB	15 dB
Stochastically varying source L_{Aeq}=L_{A90}+5dB	5 dB

3.2.2.2 Probability of Being Audible

The ability to consider potential audibility of a source within an acoustical environment is one of the most powerful outcomes of the assessment of Emergence. Audibility is a complex issue affected by many parameters, however sound at an A-weighted level higher than that of the concurrent ambient sound is more likely to be audible than a sound with an A-weighted level at or below the ambient sound. Emergence provides important information about potential audibility. DeCoensel and others have discussed auditory attention using a similar concept, expanded to consider both level and informational masking by examination of narrow band exceedance [DeCoensel et al,2010]. This approach has obvious application to design in specific case studies, and has long been common in building design, but is too complex for the variety of situations and prevalence of unknown factors affecting impact assessment to be used widely in land-use planning.

Audibility does not necessarily translate to being noticeable. Botteldooren et al have modelled the role of attention as a factor influencing annoyance, in a paper discussing exceedance derived using both loudness and A-weighted metrics [Botteldooren et al,2008]. In proposing an attention model the paper proposes two opposing mechanisms, one being a bottom-up attention mechanism triggered by an emergent signal (signal-to-noise, saliency) and the other being a top-down mechanism relating to personal sensitivity, emotional state, task involvement and the like. This approach offers a framework describing artefacts of psychoacoustic reactions and their role in subjectivity. However, any evolving application as a rating system is likely to commence with raw data expressed as Emergence, and such application will relate to annoyance rather than environmental change.

3.2.2.3 Relative Source Emergence

A development project frequently involves multiple operating sources - for example the source statistics set out in Table 6 including the ambient sound could represent technical data applying to a development land use proposal. In this case an analysis would examine Emergence based on the running threshold due to the aggregate of sound from all other components, including the ambient. This can provide a surrogate indicator of the relative audibility of each of the source components and permits conclusions such as those summarised in Table 9.

Table 9: Emergence of each source with all sources operating concurrently

Component	Aggregate Emergence
Existing ambient	3 percent
Steady state source $L_{A,90}$ + 5dB	0 percent
Freeway traffic at $L_{A,eq}$ 55dB	82 percent
Match ambient variance but $L_{A,eq}=L_{A,90}+5$dB	2 percent

This ability to identify the relative Emergence of source components is not possible using existing impact assessment methods. The sound level contributions set out in Table 6 and Table 9 would be an unusual case regarding traffic noise, however the findings highlight the problem of concealment using different assessment criteria if a development contains complex source systems. Transportation noise not only may dominate noise from concurrent site-based activity for locations in close proximity to a site, impact effects may be quite widely distributed and remote from the site. If the example is contemplated differently, with sound from the on-road transport component excluded and assessment restricted to site-based activities alone, a not uncommon approach, markedly different outcomes summarised in Table 10 would be concluded. The most striking observation is that the steady-state source suggested by Table 9 to make no contribution to overall impact is, instead, the most important source component suggested by Table 10. This example casts considerable doubt on the impact assessment principles based on discrete source-specific assessment criteria.

Table 10: Emergence for concurrent site-based sources without traffic

Component	Aggregate Emergence
Existing ambient	18 percent
Steady state source $L_{A,90}$ + 5dB	36 percent
Match ambient variance but $L_{A,eq}=L_{A,90}+5$dB	8 percent

3.2.3 Impact Assessment Foundations

An outline of current methods of impact assessment was summarised in 2.3.4 above. Quantifying impact differs from simply recognising the existence of impact and Justice Moore's ruling clearly identifies the need to both identify and consider the magnitude of an impact.

Acoustic impact, particularly in quieter areas, is complex. Impact is commonly perceived to be negative, but can also be positive. Current methods of assessment contemplate only how much higher the sound pressure level from a planned activity will be compared to the background level and describe this, frequently, as intrusion. However this does not recognise how stochastically varying sound pressure levels from a source will rise above the stochastically varying ambient sound pressure levels, which also includes loud levels. The term Emergence describes impact both objectively and subjectively more effectively than the current common descriptor of intrusion. Intrusion implies only interference and from louder events - "The call of a lyrebird emerged" conveys a different aspect than "the call of a lyrebird intruded". Emergence, and therefore impact, may occur passively. Consider the conditions where "in the quietest passages of the recital, the sound (noise) of air conditioning emerged", or "as a flock of birds drifted away, the sound of the freeway emerged". The negative aspect of the sound is its undesirability in the context and in neither of the above examples does the impacting sound rise above the benchmark termed the background level. Inappropriateness is a clear descriptor of an undesirable impact as is intrusion, but is difficult to quantify. Emergence of a sound is a useful impact descriptor.

Many outcomes may affect the environmental impact from one of two concurrent conditions (ambient A and imposed B). These include:

- What is the probability that the level of B will exceed that of A at any time?
- What are the magnitudes of that exceedance?
- What will be the stochastic characteristics of the future (impacted) ambient levels (A+B)?
- All of the above, but for condition A, plus numerous $B_1 \ldots B_N$ anticipated future sound sources.
- Is impact affected by the appropriateness of the source in the context?

The likelihood of experiencing inconsistency in the current impact assessment method identified as a measure of a stationary metric exceedance of the stationary background sound level is easily recognised by the 90 percent probability that ambient sound pressure levels will themselves be higher than that same background sound level. In order to understand impact it is necessary to understand level relationships between the auditory components at any instant in time.

3.3 THE MAGNITUDE OF AN ACOUSTICAL IMPACT

The magnitude of an acoustic impact relates to the magnitude of change caused to an ambient acoustical environment. This impact could be represented by an entirely new source, an increased prominence of loud events from an existing source, or an increased probability that an existing source masks other existing and preferred sources. The limitations to current methods of assessment are most evident when considering moving and stochastically varying noise systems, where the nature of changes are too complex for methods of measurement and assessment to resolve. Similar limitations occur, though originating in a different fundamental weakness, with impact from development types that are a change to land usage and therefore likely to introduce a change to the nature of the audible acoustical environment. Emergence is a surrogate for audibility. Assessment methods based on Emergence therefore have intrinsic relevance to issues for which annoyance is relevant as well as issues where protection of existing assets is relevant. Emergence, and therefore impact, is a complex parameter unable to be quantified using stationary sound level metrics.

3.3.1 Active and Passive Impact

It is through identification of aspects distinguishing active and passive impact that a legislative connection between environmental sound and soundscape can be contemplated. The two types of impact arise from different manifestations – active impact involving interference, intrusion and attention focussing and being an impact type mostly related to annoyance, and impact identified by concealment and masking of properties that may be the attributes or simply the features of a surrounding ambient environment. Active and passive impacts distinguish between situations involving audible components that are appropriate to an environment type and those where those components can be considered inappropriate. These principles are summarised below by example, in Table 11.

In planning applications, the role of appropriateness may require a hypothetical ambient sound environment to be envisaged. For example, active impact assessment for a planning proposal in or near a land-use area that is intended for change, such as a proposed housing estate in a rural area, will require impact assessment using a hypothetical ambient sound environment. The assessment based on passive impact for a similar changing land-use area may also require assessment using a theoretical ambient sound environment, however such substitution in place of the existing ambient sound environment should be more formally justified.

Table 11: Active and Passive Impact

Situation	Example / description	Active Impact	Passive Impact
A new source considered to be appropriate in the context of existing or intended surrounding land-uses	A proposed shopping centre in an existing or proposed urban setting.	X	
A new (additional) sound source in an environment characterised by comparable existing audible content	Both subdued and loud, event based, sources	X	
A new source in an environment with no existing comparable or compatible audible content	Subdued sound level or Loud sound level, event based		X
Any source considered to be inappropriate in the context of existing or intended surrounding land uses	A major transport development within an existing or planned housing estate		X
Associated terminology:		Interference Intrusion Distraction Conspicuous	Masking Context-altering Distracting Subliminal

Passive Impact: sound from a new source that permeates, like floodwater, inundating an existing ambient environment, concealing the lower ranging sounds first. Passive impacts tend to evolve and accumulate over time.

Active Impact: sound from a source similar to others in an existing ambient environment, overlaying and increasing the ambient sound to a louder, but otherwise similar, environment. Allowance for a Just Noticeable Difference (JND) threshold within the Soundscape is appropriatee. Active impact effects can manifest rapidly.

The attention model factors mentioned above in 3.2.2.2 largely relate to active impact in both bottom-up and top-down mechanisms. This helps clarify that active impact effects relate largely to perception and annoyance outcomes, while passive impact effects relate largely to fundamental change.

An alternative expression for ‘Active Impact’ could the term ‘Auditory Impact’, however for this thesis Active Impact is preferred being less likely to result in confusion or misinterpretation as an outcome that is measurable by other perception parameters.

3.3.2 Subjective Considerations

Environmental noise impact assessment involves almost exclusively measurement-based procedures. In fact, some assessments could be conducted with no noise measurement at all, instead identifying the causal risks of impact and how they can be managed. For example, If a proposed activity will attract 30 motor vehicle movements to a site, can 30 compensating motor vehicle movements be removed from access routes by management? This type of approach is rarely employed,but is both straightforward and unambiguous.

People react to sound quickly and may remember the effects and impacts for a long time. Determining an optimal assessment period relating to human reaction to environmental sound is therefore impractical, or likely to be so variable as to be meaningless. For critical listening, interference from background sound is reported to commence from as low as 7dB below the signal of interest [Chappel et al, 2016], however it is generally accepted, and indeed research into hearing aids has concluded, that a change of 3dB is a threshold above which reliable auditory outcomes can be expected [McShefferty et al, 2015]. In recognising that active impact is a measure relating to probability of annoyance, or to change in an already anthropogenically dominated environment, analysis of active impact should include allowance for a just noticeable difference (JND) threshold of at least 3dB.

It could be argued that the threshold of interference to an existing ambient sound commences as much as 7-10dB below the ambient levels, however considerable research would be required before changing to either JND assessment threshold – zero dB for passive impact and 3dB for active impact. An outcome of further policy research may be that JND could be a defined variable where that JND is source-specific and represents a desirable environmental acoustical feature – for example those envisaged by Schafer [Schafer,1994].

The magnitude of passive impact will always be higher than the active, or intrusive, impact. This aggravates the deficiency in NSW environmental acoustic policies that consider only annoyance. The choice of which type of impact is a priority will depend on which aspect of change to the ambient environment is dominant.

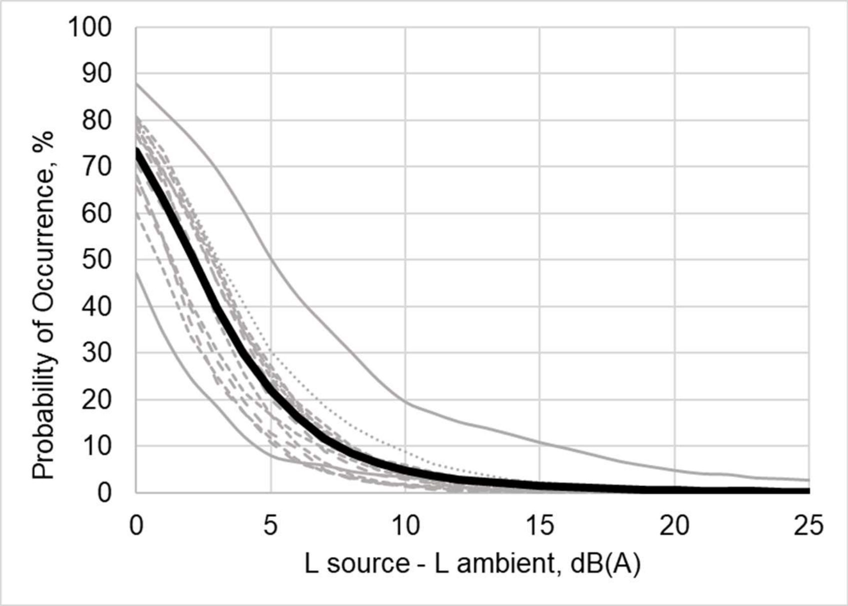


Figure 7: House Concert Emergence for each 15-minute period

The House Concert example described in section 2.7 above suggested a noise impact assessment using current methods as summarised in Table 8. By comparison an assessment of Emergence for the same data is summarised below in Figure 7 showing the emergence for the array of 15 minute survey periods plus the mean concert emergence in bold, and again in Figure 8 for the average Emergence condition.

Figure 8 shows that the event generated an average level of active impact of 40%, determined by shifting the curve by the value of JND (3dB) to the left. Passive impact however exceeded 70 percent. To a layman this means that for 40 percent of the time the concert activities might have been audible and apparent, but had the observer's focus and interest related to aspects of the existing environment, for 73 percent of the time that existing ambient environment was actually concealed. Figure 8 also shows that, on average, noise from the concert was more than 5dB(A) higher than the ambient for only 20 percent of the time but did exceed the ambient noise by up to 25dB(A) very briefly.

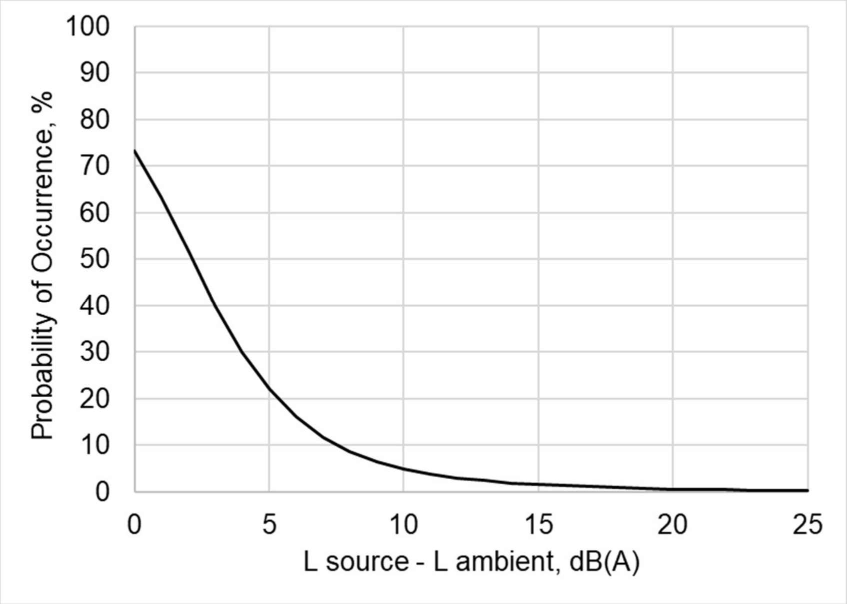


Figure 8: Average House Concert Emergence

The scope of these types of findings compared with current and conventional impact assessment can be understood by the table of impact measures summarised in Table 12, comparing findings summarised previously in Figure 6 with the active and passive impacts obtained from the Emergence method. For that example, the impact of road traffic is large, dominating the existing ambient noise environment for 93 percent of the time. Active impact, the closest parallel to current conventional impact assessment is shown to be 22 percent for the case of a steady-state source – for example heavy industry – but for a stochastically varying source at the same equivalent energy level only 12 percent. The disparity in magnitude of passive impact is more significant, with a steady-state noise dominating the ambient for over 70 percent of the time and approaching the magnitude of impact imposed by traffic. Table 12 demonstrates the inability of the conventional impact assessment method to distinguish between two quite differing sources.

Table 12: Comparison Impact Assessment, Table 8 vs Figure 6

	Conventional L_{Aeq}-L_{A90}	Passive Impact	Active Impact
Steady state source $L_{A,90}$ + 5dB	5 dB	72%	22%
Freeway traffic at $L_{A,eq}$ 55dB	15 dB	93%	86%
Match ambient variance but $L_{A,eq}$=$L_{A,90}$+5dB	5 dB	26%	12%

3.3.3 Subjective weightings

In considering subjective weightings – tonality, impulsiveness etc – the addition of this type of weighting to an overall source L_{Aeq} level is unlikely to reflect the subjective elements of a multiple-source sound system, leading to either over-statement of the weighting or to the weighting being ignored when it should apply. Emergence defines the probability that the sound pressure levels from a source or system will be higher than the ambient sound levels. If subjective penalty weightings are applied to relevant and specific source components, the importance of that source may be clarified based on its' Emergence, potentially with and without a subjectivity weighting.

For clarity, subjective weightings have not been applied in any of the examples discussed in this thesis. However it is acknowledged that some form of weighting, both positive and negative, is a likely requirement for active impact assessment, though unlikely to apply to passive impact assessment.

One example describing a possible research direction to identify appropriate and inappropriate elements within an occupied environment – residential, commercial, town centre, recreational, etc – is work reported by Marry & Defrance [Marry & Defrance,2013]. This involved analysis of in-depth interview records relating to sound perception of occupants within three public squares, producing results that are anecdotally similar to widespread professional experience of community noise attitudes and which may present a pathway to establishing positive as well as negative penalty weightings.

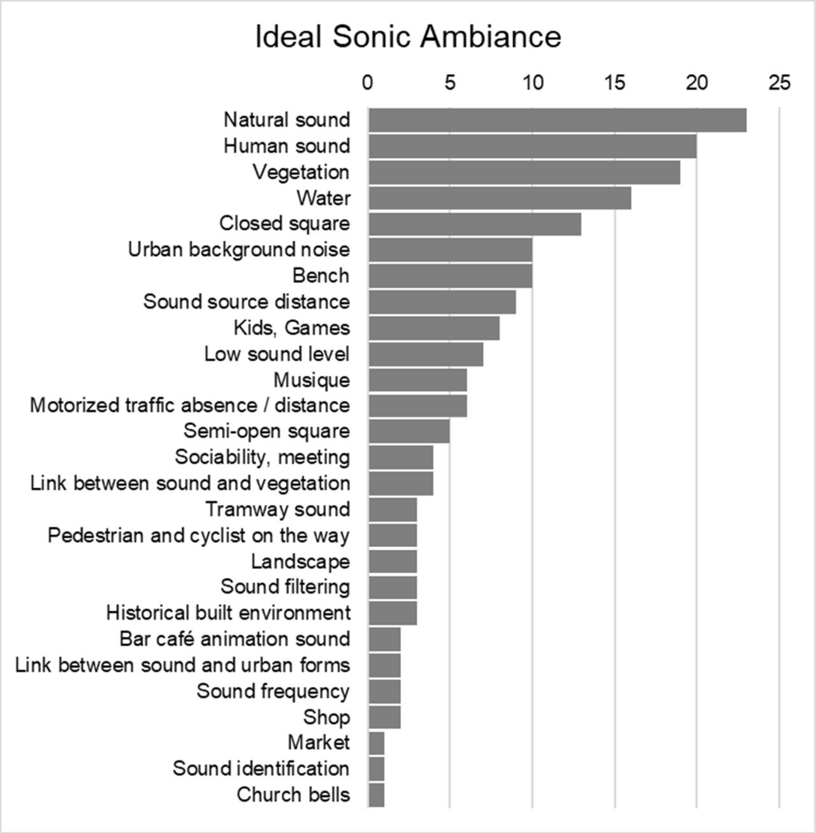


Figure 9: Positive auditory elements for public squares (after Marry & Defrance)

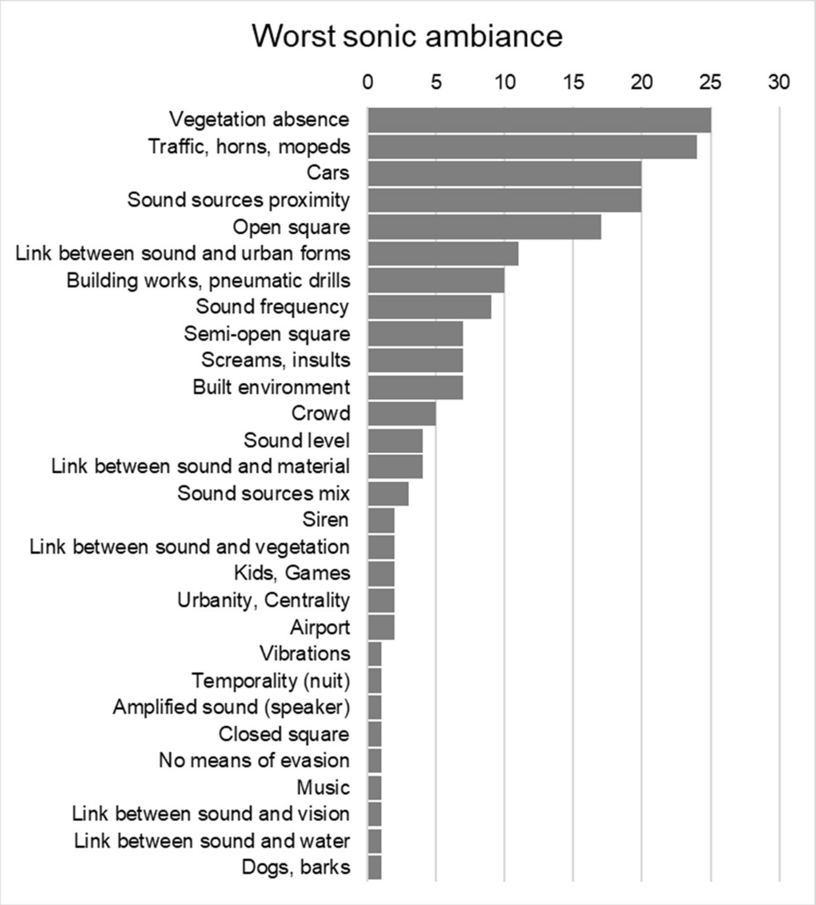


Figure 10: Negative auditory elements for public squares (after Marry & Defrance)

3.4 A REASONABLE MAGNITUDE OF IMPACT

The terms “acceptable” and “reasonable” are widely used in assessment outcome conclusions considering environmental sound, often without sufficient qualification. It was noted above in section 2.1 that the interpretation of these subjective terms is, finally, the province of a court. However, to facilitate planning decisions guiding assessment criteria are required. In the context of planning legislation, a reasonable magnitude of impact would be a level that results in no significant adverse effect on the amenity of an area [NSW Government,2006].

3.4.1 Historical indicators

Current, or conventional, assessment methodology uses the metric included in the Table 12 example. This methodology originated in work cited earlier by Kosten [Kosten & Van Os,1962], is traceable through standards such as AS1055 and contemporary international publications, and remains current in regulatory procedures such as those of the NSW EPA [NSW EPA,2017]. Early versions of these standards included guidance on the anticipated community response to an environmental noise impact, based on the initial version of this same metric [ISO1996,1971] [May,1978]. This guidance, information such as Table 13, was discontinued in later issues of these standards, however reflected a widespread contemporary opinion from which evolved the now familiar acceptance criterion limiting the conventional assessment metric of source L_{Aeq} minus ambient L_{A90}, to not more than 5dB.

Table 13: Community Response Estimated by ISO/R1996:1971

Amount by which the corrected intruding sound level exceeds the corrected criterion, dB(A)	Estimated community response	
	Category	Description
0	None	No observed reaction
5	Little	Sporadic complaints
10	Medium	Widespread complaints
15	Strong	Threats of community action
20	very strong	Vigorous community action

All of these procedures can only relate to an assessment of active impact. The implication from the historical outcomes is that a “reasonable” magnitude of active impact can be measured by the measurement of Emergence and using which an Emergence value of 5dB(A) can be considered to measure a marginal magnitude of impact. Table 12, in turn, suggests that an Emergence-based impact of between 10 and 20 percent could be considered to be an impact magnitude that is “reasonable”.

Passive impact has not been historically recognised. Considering ambient sound pressure levels that correspond to a change to a perceived land type is one way to provide a concept of an acceptable magnitude of impact for situations where passive impact is relevant. Land begins as one land type and is changed progressively to a different land type, usually by a sequence of individually “acceptable” changes, or impacts – the entropy of environmental acoustics. All land commenced as wilderness or acoustically pristine uncontaminated land and progressively evolved to the land types now commonly accepted, at least as far as land occupied by humans is concerned. Comparing typical ambient sound levels associated with different land use areas therefore identifies the overall magnitude of passive impact equating to a change in resultant land classification - the characteristics of the original land are sufficiently masked that the land is now perceived to be fundamentally different.

Table 14: Average daytime statistical sound levels for different land use areas, dB

	L_{Amax}	L_{A1}	L_{A10}	L_{A50}	L_{A90}	L_{Amin}	L_{Aeq}
Acoustically Pristine Land	60	49	40	32	26	23	39
Rural	66	56	48	43	39	36	47
Quiet Suburban	69	61	54	47	44	42	51
Suburban	74	66	61	56	53	50	58
CBD	82	74	69	65	61	58	66

Table 14 summarises average daytime statistical sound pressure levels for different land areas determined from the survey levels database described later in 4.2.2 below. The average aggregate passively impacting sound pressure levels (Table 15) sufficient to change each land type to different land having ambient statistical sound pressure levels at the next higher category, has been calculated using iterative inverse transformation sample modelling. By then examining the sampled emergence for each component of the remnant ambient sound, and of the impacting sound, enables the magnitudes of passive impact associated with each land transformation to be estimated. Table 16 suggests that a passive impact of approximately 90% sufficiently changes land that it should be classified differently.

Table 15: Average impacting sound immission levels associated with land uses, dB

	L_{Amax}	L_{A1}	L_{A10}	L_{A50}	L_{A90}	L_{Amin}	L_{Aeq}
Rural activity impact	66	54	47	42	38	36	46
Quiet Suburban activity impact	66	60	52	45	41	40	49
Suburban activity impact	77	68	61	55	50	48	59
CBD activity impact	80	72	67	63	60	58	65

Table 16: Aggregate passive impact required to change land use area type

Land change	Passive Impact
Acoustically Pristine to Rural Land	93%
Rural land to quiet suburban	70%
Quiet Suburban to suburban	90%
Suburban to CBD	91%

Because this method of impact assessment involves a linear scale, it is also possible to calculate the acceptable magnitude for each of a number of iterative "acceptable" changes so as to represent a consistent and reasonable planning policy. This approach would explain a long-term planning policy outcome and would allow for a sequence of impacts from more than one stage of development. The aggregate magnitude of impact from a sequence of impacting changes can be calculated using equation E3.

$$x = (1 - i)^n \qquad \textbf{E3}$$

$\quad where$

$x \text{ is the residual portion of the ambient environment}$

$i \text{ is the passive impact imposed at each stage}$

$\quad and$

$n \text{ is the number of sequential stages}$

Equation E3, which is represented graphically in Figure 11, describes the relationship between the number of permissible developments after which the aggregate result of which will be an impact of 90 percent on the original land – the land will be by then fundamentally changed to a higher classification. Figure 11 links the limit to permissible impact per stage to the number of development stages allowed for in the policy. That is, Figure 11 shows that a policy implemented to allow for a sequence of, say, 10 development changes to be made, can permit each change to generate an impact measured at 20 percent. However, where a larger multiple stage development is foreseen, with 40 expected additional developments, the permissible impact limit for each stage can be no more than 5 percent.

In addition to providing a structure for outcome-oriented planning controls, the identification of a magnitude of impact has other potential benefits. For example, where a large development is proposed and will result in a nett change to fundamental land type, costs such as infrastructure or environmental compromise necessary to support that changed land use can be properly identified as an outcome imposed by that development proposal alone. If a number of impacting development change stages are adopted as a planning policy, the incremental imposition to future infrastructure expansion costs can be estimated and, if appropriate, amortized accordingly.

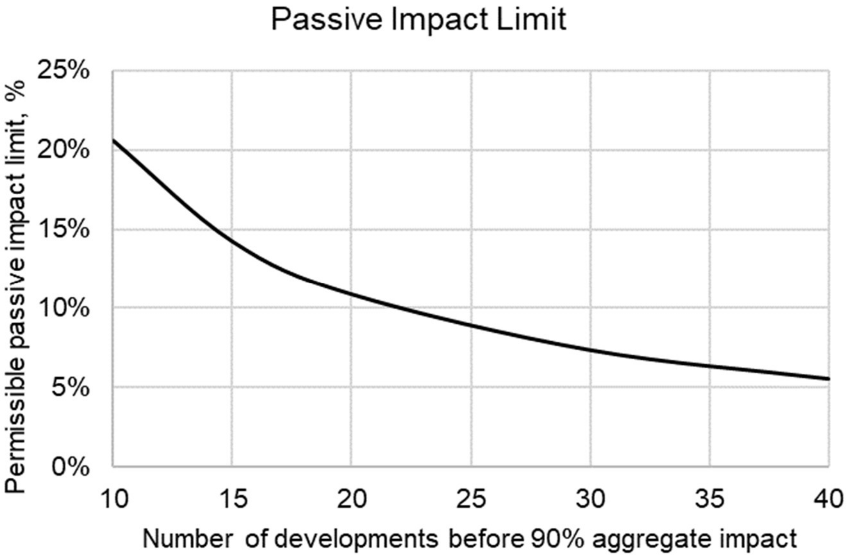


Figure 11: Permissible passive impact limit vs number of approved planning changes

The primary outcome benefiting planning decisions using these techniques is the current interpretation that an approved planning change has been deemed to be "acceptable" is replaced with an interpretation that the change has been deemed to be "reasonable".

Where no impact is a requirement, such as the introductory case to this chapter, the required limit to passive impact is, unambiguously, zero percent.

3.4.2 Context for Current WHO Traffic Noise Guidelines

Road traffic noise impact is the subject of regular community debate, particularly as new roads and associated development extend into less urbanised areas. Noise from vehicle activity associated with a development proposal is frequently considered to be acceptable on the basis that the predicted levels comply with road noise criteria, where in fact the example of Table 12 shows the magnitude of impact from traffic for that example could be overwhelming. The current state-of-the-art in relation to acceptable road traffic impact control guidelines are imbued in WHO guidelines [WHO,2018]. One set of plausible statistical parameters that would satisfy WHO guidelines are summarised in Table 17. These parameters are based on results from historical road traffic level surveys.

Table 17: Example average statistical traffic noise complying with WHO Guidelines, dB

Description	L_{Amax}	L_{A1}	L_{A10}	L_{A50}	L_{A90}	L_{Amin}	L_{Aeq}
WHO Day Traffic Guideline	65.7	58.9	53.7	49.3	44.8	39.6	51.1
WHO Night Traffic Guideline	59.4	53.5	47.9	41.2	35.8	31.8	45.0

By comparing the impacting traffic noise levels summarised in Table 17 with the average land use area ambient statistical noise levels given in Table 14, the potential magnitude-of-impact resulting from WHO compliant road traffic noise can be described for each different land area type. It is worth noting that the impacts evaluated below refer to average ambient noise conditions and therefore under-estimate the impact on approximately fifty percent of each area classification.

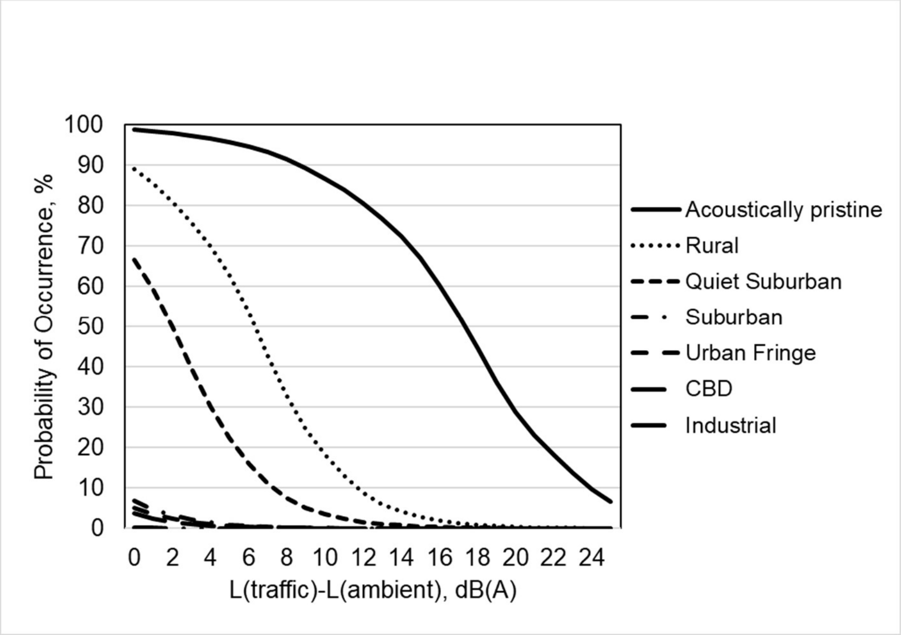


Figure 12: Emergence, WHO Daytime road traffic guidelines

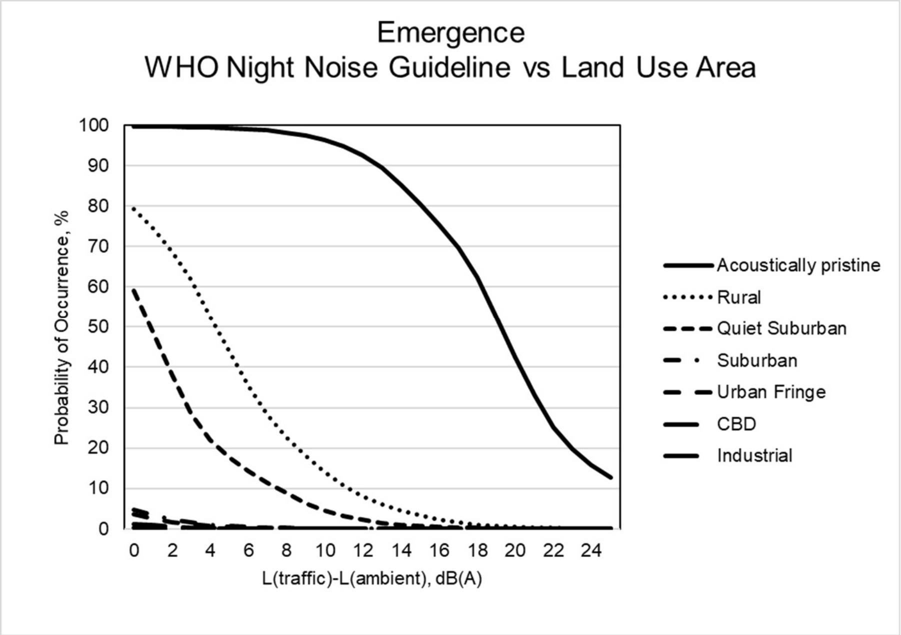


Figure 13: Emergence, WHO Night road traffic noise guidelines

Table 18: Magnitude of impact from WHO compliant road noise vs land areas

Impact Type	Acoustically Pristine	Rural	Quiet Suburban	Suburban	Urban Fringe	CBD
Daytime Passive	99%	89%	66%	7%	5%	0%
Daytime Active	97%	76%	40%	2%	2%	0%
Night Passive	100%	79%	59%	5%	4%	0%
Night Active	100%	62%	29%	2%	1%	0%

The road noise emergence described in Figure 12 and Figure 13 produce the impacts summarised in Table 18, showing that WHO guidelines should provide very good conditions for suburban, commercial areas and for portions of quieter suburban areas where traffic may already be a feature, with louder noise events only rarely more than 10dB above the ambient noise. Impacts remain very high for acoustically pristine areas and rural areas, and for quiet suburban areas isolated from main road corridors. These outcomes suggest that policy based on implementation of the WHO noise level criteria alone will not preserve quiet areas. Historically, attempts to quantify the impacts from traffic have involved stationary measures of emergence – L_{Aeq}-L_{A90}, L_{A1}-L_{Aeq}, L_{A1}-L_{A90} and the L_{A10}-L_{A90} used briefly some decades ago in calculating a Traffic Noise Index [May,1978]. Few of these have proven effective though, in part, this may be a natural consequence of inability to predict level statistics for traffic. In NSW, project road design criteria have included wake-up management design targets as discrete as the $L_{AF1,1\ minute}$ despite none of these metrics being reliably predictable by any means other than from survey measurement for a, hopefully, similar system. This assessment criterion, $L_{AF1,1\ minute}$, conveys an intent of diligence but is largely an irrelevant complication given an anecdotal response only within most assessment projects and unlikely to be functionally different from the L_{Amax}.

An area for further research to supplement these Emergence-based impact assessments, possibly identifying an appropriate vehicle or traffic noise subjectivity weighting, is through saliency and associated attention focussing assessment [Botteldooren et al,2008] examining the correlation of attention focussing with statistical metrics such as the Traffic Noise Index.

3.4.3 Relationships to Existing Metrics

Outcomes from the examples described above, including both day and night conditions, have been analysed using inverse transformation modelling to determine the magnitudes of active and passive impact in each case, and compared with common statistical measurement metrics under current assessment paradigms. This provides a useful review of the magnitude of impact might be expected for analysis based on current and, superficially, more convenient indices. These findings are set out below in figures 12 to 15.

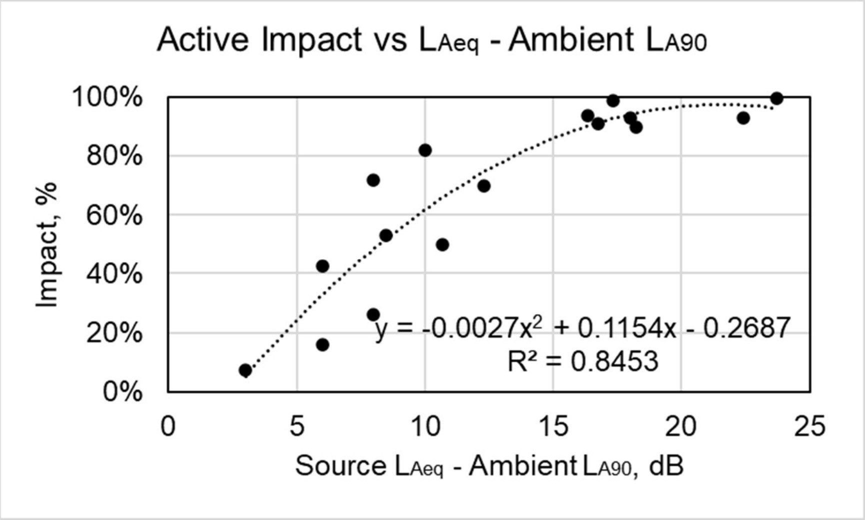


Figure 14: Magnitude of Active Impact compared with current assessment metrics

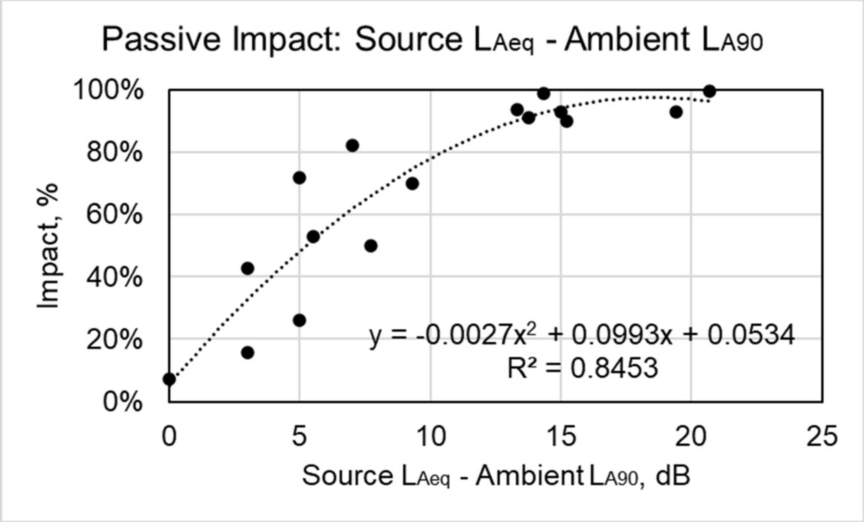


Figure 15: Magnitude of Passive Impact compared with current assessment metrics

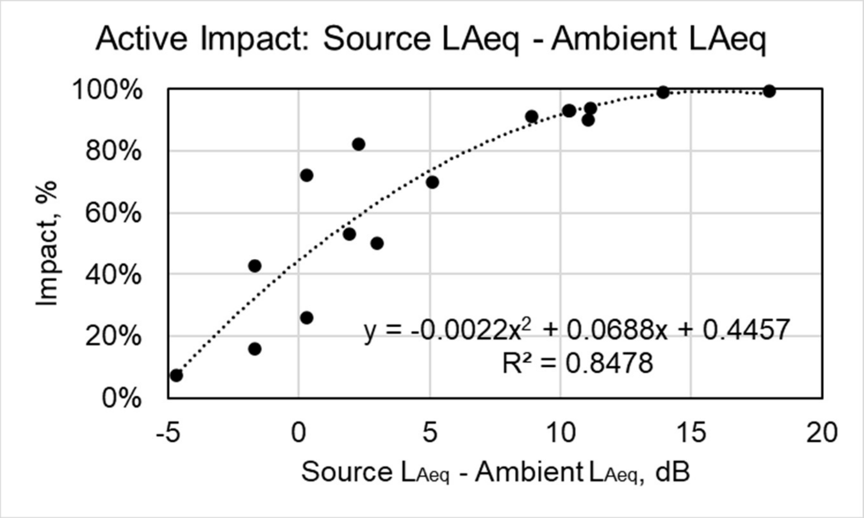


Figure 16: Magnitude of Active Impact compared with current L_{Aeq} metrics

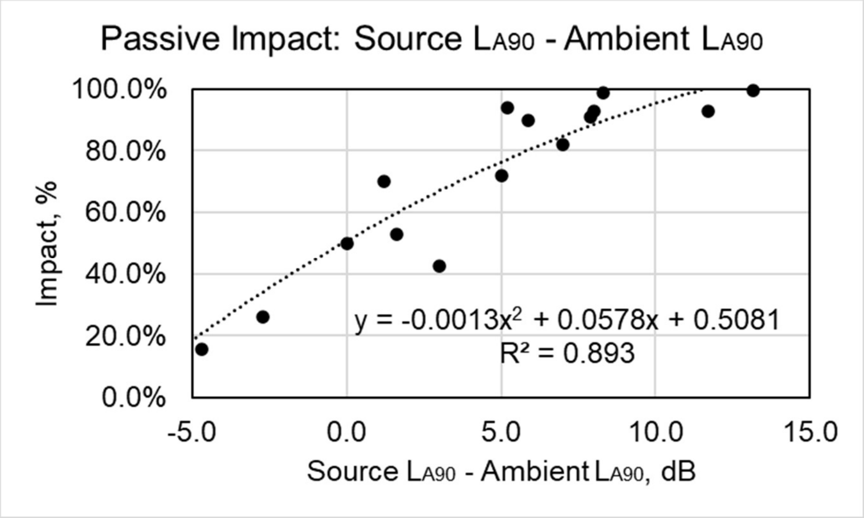


Figure 17: Magnitude of Passive Impact compared with current L_{A90} metrics

The above charts do not obviate the need for dynamic impact assessment for site specific work, as they are derived from the specific examples above rather than a population study. However they can provide useful early stage design parameters, particularly at a development concept design stage. It is interesting that the trend lines suggest changes to L_{A90} are a marginally better predictor for magnitude-of-impact than the current index of L_{Aeq} – L_{A90}. This is an important finding, as it strengthens a hypothesis that a focus on intrusion in noise assessment procedures has resulted in oversight of more significant overall contributions to adverse passive impact.

It is also significant that a reasonable level of impact requires the statistical parameters associated with an introduced source to be below those same parameters for the existing ambient sound.

3.5 CONCLUSIONS

A method quantifying both active and passive impact levels has been described. This method has many benefits. Apart from utilising the full sound pressure level measurement description of an environment, a critical planning benefit is that assessment is based on clear functional descriptions of the source system representing a development proposal. This enables the inclusion of appropriately targeted subjective penalty weightings for only those elements to which they should reasonably be applied and offers the prospect of positive attribute weightings if such weightings can be developed.

One pre-requisite to a robust impact assessment is a rigorous examination of the ambient environment. This should examine existing conditions for both subjective content and sound pressure levels as both are relevant to the assessment of active and passive impacts. For conceptual planning situations it may be necessary to base impact assessment planning on a conceptual ambient sound environment. Some methods of considering how to do this are included in the next chapter.

Impact must be recognised as the change that will occur in the impacted entity and not simply envisaged as a prescribed permissible level of incursion.

Impact on an acoustic environment must be considered from different perspectives depending on whether the impacting auditory events represent features already present in the impacted area, or they are new features. An environmental noise impact assessment must identify acoustical attributes of potentially affected lands to be able to express the risks to that land in the context of the operating features of a development proposal.

The risk of erosion to attributes of an area of impacted land can be quantified by the probability at any instant that sound from the development proposal will be higher than the ambient sound in that area of land.

Passive impact assessment formally recognises value in the existing environment, the criteria for the management of which is not derived from human annoyance.

Where a development introduces a new emergent sound, inappropriate to the area, the control of passive impact may be the appropriate criterion. Where that emergent sound can be characterised as similar to prominent features of the existing ambient environment, the control of active impact is likely to be the appropriate criterion.

Passive impact is a parameter unrecognised by current methods of noise impact assessment, despite generating more demanding management requirement than active impact and being more critical to increasing areas of lands affected by expanding development.

Equivalent energy metrics are shown to be insensitive to important stochastic details of the sample period for which the metric applies. Equivalent energy metrics are shown to be incapable of measuring passive impact.

Annoyance criteria rarely have relevance in the assessment of impact on acoustically pristine land.

Significant limitations arise in the use of equivalent energy metrics where non-stationary acoustical systems are involved. Equivalent-energy metric assessment can conclude that an impacting source will be louder than the existing ambient sound and, therefore, potentially identifiable, however these assessments are unable to discriminate between markedly different environmental circumstances. This can erode the adequacy of otherwise well-intended planning.

The impact outcomes based on Emergence can be compared on a linear scale and so are more likely to be understood by a wide range of development stakeholders. In doing so, the methods and provide a basis for transparent long-term policy decisions. Limiting impact assessment criteria can be summarised as Table 19.

Table 19: Limit magnitude of impact criteria

Characteristics compared with ambient noise	Impact Criterion	Acceptable Magnitude of impact
New characteristics involved	Passive	20% (or Figure 11)
Similar to, or already existing, in the environment	Active	20 %

When considering the application of Table 19 it is important to note that the magnitude of active impact is always less than that of passive impact, due to the presence of a just-noticeable-difference threshold. A common issue in land-use applications is the basis by which an assessment of development applications to carry out what is otherwise a prohibited land use under the current zoning for that land under a small number of case-specific clauses of the NSW Model LEP, discussed earlier in 2.5.6.3 and in 3.1. A condition precedent to such approval may be either demonstration of no consequential impact, for which an acceptable magnitude of impact is zero percent, or demonstration of a reasonable consequential impact, which should logically be evaluated using only passive impact criteria. This is because the test ought to automatically imply, being an otherwise prohibited activity, that new characteristics will arise consequential to the proposed the land use.

4 MODELLING PRINCIPLES FOR STOCHASTIC ACOUSTICAL SYSTEMS

4.1 PREAMBLE

An important purpose in carrying out analysis of surveyed data is to infer useful future outcomes. Chapter 3 negatively criticises the use of stationary measurement metrics, but notes that statistical metrics are, themselves, stationary metrics representing one specific parameter of a dataset. Both measurement analysis and predictive modelling require a more sophisticated analytical structure than is currently utilised. This chapter examines the sometimes conflicting factors associated with the task of quantifying stochastic acoustical systems. The objectives in land-use planning involve long term outcomes. Input variables need to be established with similarly long-term perspectives. Whilst active impacts may manifest rapidly and in a short-term context, the range of stochastic variance in ambient conditions require that ambient conditions for an impact review be quite carefully researched.

The choice of a suitable survey duration, particularly when evaluating ambient conditions, is not trivial. Significant features affecting an environment include annual trends in both weather and vegetation, seasonal effects, circadian features, working week and week-end aspects. A survey of ambient sound pressure levels over a week is nothing more than that – a week of data from which appropriate benchmarks for impact assessment must be derived.

There will always be exceptional conditions falling outside the findings from even the most rigorous of surveying.

There are two basic stochastically variable systems associated with land-use planning situations – the ambient acoustical environment and the, usually, stochastically variable acoustic emission from the land-use activities. Impact assessment requires that both systems be modelled. This chapter discusses the technical and analytical issues associated with deriving appropriate statistical levels that adequately describe the stochastic variation of both ambient sound level conditions and those likely to arise from proposed land uses.

4.2 THE FOUNDATION FOR IMPACT ASSESSMENT – AMBIENT CONDITIONS

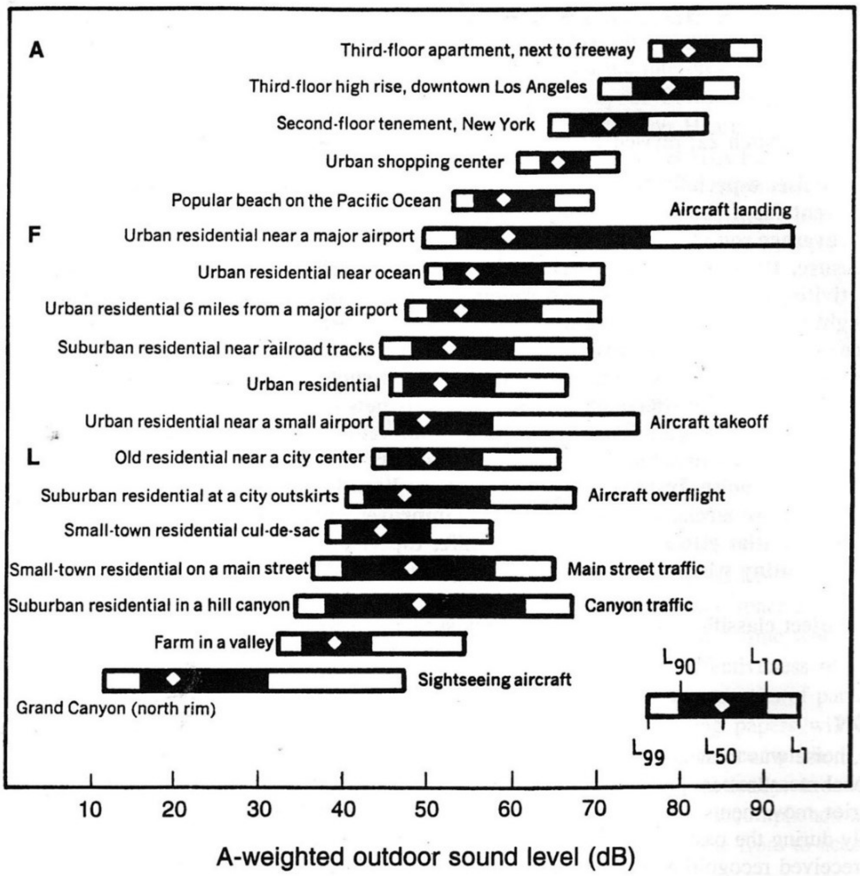


Figure 18: A-weighted ambient sound levels, after Eldred (1971)

Important early work was reported by Eldred [Eldred,1971], referenced above in Figure 18. This showed the extreme range of ambient sound level conditions and the range in magnitude of probable Emergence that could be experienced from a new activity affecting different types of area. Little publication of further work has followed these early findings, probably affected by curtailment of the role of the US EPA in relation to noise.

For a concept land-use planning study, the application area may be undecided, or may be represented by a range of potential areas, for which an estimate of ambient sound conditions may be necessary. Until the 2018 issue, Australian Standard 1055 provided tabled values under the general heading of "Estimated average background A-weighted sound pressure levels for different areas containing residences". These tables have been substantially reiterated in NSW EPA planning policy documents but provide only background levels represented as an estimated L_{A90}, being silent regarding the range of ambient sound pressure levels and level statistics.

Where practical, ambient conditions should always be measured directly, ideally validated by subsequent benchmarking of those measurements against independent reference conditions.

4.2.1 Land Classifications

It is an overlaying complication that many aspects of land-use planning could be considered arbitrary. Planning decisions involve, a priori, regulated classifications applied to different parcels of land. These classifications serve purposes that devolve from numerous and differing legislative policy objectives. Development criteria can change significantly at any time due to a zoning change, and land in one region may be regulated quite differently from seemingly similar land in another region. Acoustical land classifications are not regulated although they can be loosely correlated with land-use classifications. Acoustical classifications were included in AS1055 until being recently discontinued, however weaknesses in the bases of those classifications limited their practical value. These historical classifications can be cross-referenced to still-current environmental noise planning documents issued by the NSW EPA. In the same manner as zoned land classifications are used, an acoustical land classification is a necessary pre-requisite to considering potential environmental impact at a planning level.

This thesis proposes the adoption of Land Sound categories (LSC), to be used as a basis for benchmarking ambient acoustical conditions, as summarised in Table 20. These categories reflect, though are not identical to, those used previously in AS1055, including a further category for acoustically pristine land.

Table 20: Land Area Environmental Sound Categories

Land Use Area Sound Category (LSC)	Description
0	Acoustically Pristine Land (see 2.1 for discussion)
1	Rural Land
2	Quiet Residential Land
3	Suburban Residential Land
4	Urban Residential Land
5	Central Business Districts
6	Industrial Land Uses

These categories are given planning context by Table 21. Neither the Australian Standards nor NSW policy documents contemplate the preservation of acoustically pristine land, nor the preservation of very quiet land. Recently published WHO guidelines [WHO,2018] has recommended the preservation of quiet areas as a guiding principle for noise policy. It is important to note that the WHO has issued guideline noise levels only for areas relating to human health and, by implication, for residential land areas only.

The respective descriptions given in columns 3 and 4 of Table 21 are referenced in AS1055:1997 and in columns 5 and 6 from Table 2.3 of the EPA Noise Policy for Industry [EPA,2017]. The EPA land classifications coordinate with those cited in Standard Instrument – Principal Local Environmental Plan, New South Wales Government, version 15 August 2014. While there is overlap across columns 3 to 6, reasonably good correlation shows the general intent of both documents.

Table 21: Land Sound Area Categories (LSC) and land usage

LSC[1]	Land Type[2]	AS1055[3]	AS1055 Description[3]	ÈPA NPI classification[4]	EPA NPI Description[4]
0	Acoustically pristine	N/A		N/A	
1	Rural	R1	Negligible transportation	RU1-primary production	Dominated by natural sounds; little or no road traffic, sparse settlement
				RU2-rural landscape	
				RU4-primary production small lots	
				R5-large lot residential	
				E4-environmental living	
2	Suburban	R2	Low density transportation	RU5-village	Local traffic, intermittent flows, evening noise levels defined by natural environment and human activity
				RU6-transition	
				R2-low density residential	
3		R3	Medium density transportation, some commerce or industry	R3-medium density residential	
				E2-environmental conservation	
				E3-environmental management	
	Urban			R1-general residential	Aggregate sound of many unidentifiable, mostly traffic and/or industrial related sound sources
4		R4	Dense transportation, some commerce or industry	R4-high density residential	
				B1-shop top housing	
				B2-local centre	
				B4-mixed use	
5		R5	Very dense transportation, in commercial districts or bordering industrial areas		
6	Industrial	R6	Extremely dense transportation, within predominantly industrial areas		

NOTES:

1. LSC identifies the Land Sound Category based on the Land Area Uses identified in column 2 (see Table 20)
2. Land area uses in column 2 are common usage titles for the land classifications used in NSW and EPA land regulations.
3. Categories listed in column 3 and descriptions in column 4 refer to the Noise area categories described in recently superseded issues of AS 1055.
4. The EPA planning classifications and descriptions summarised in columns 5 and 6 are those cited in Standard Instrument – Principal Local Environmental Plan, New South Wales Government, version 15 August 2014, referencing the Noise Policy for Industry.

4.2.2 Reliable Ambient Sound Levels

Sound levels are influenced by meteorological conditions. Of these conditions, wind and precipitation have the most significant effects, due to differing influences. Wind generates turbulence around a measuring microphone that is indistinguishable to the microphone diaphragm and so generates what is commonly termed microphone noise. Wind also generates sound within surrounding vegetation and influences the propagation of sound from a source, differing markedly when upwind or downwind of the source. Rain generates impact sound at or near a microphone and may quite substantially influence sound generated by some sources – e.g. tyres on a pavement. Notwithstanding these effects, they are almost constantly present in any outdoor environment and in some instances statistically cancel one another – louder source propagation conditions compensated by louder ambient conditions.

The consequence of considering background noise almost solely in the context of the L_{A90}, particularly in a historical framework of acoustical measurement being represented by a single, carefully controlled, observation, has led to an excessive focus on meteorological influences. This concern has been noted previously in section 2.5.6 but is important to reiterate. Removing intermittent and temporally discrete periods from a large dataset can be undesirable, particularly for a survey of ambient conditions, as the very procedure of surveying and processing statistical records will control for such effects if appropriate allowances are made in data processing for sample variance. Taken to its logical conclusion, elimination of situations where wind effects are common could potentially prohibit valid impact assessments in areas near the coast, and in locations affected by routinely occurring temporal conditions such as the western Sydney basin drainage flow.

Providing the number of surveyed measurement sample periods is sufficient to be statistically reliable (typically 30 relevant samples or more) and that no more than roughly ten percent of those samples are suspected to include affects from high wind and/or rain, ambient statistical levels should be reliable without filtered removal of periods potentially affected by weather. In a similar manner, long-term measurement level stability, particularly with respect to temperature, of a measuring system is more relevant in obtaining reliable statistical levels than is the absolute measurement accuracy for a single measurement.

The underlying principle required for valid benchmark assessment is to ensure surveying is conducted over sufficient and appropriate measurement periods.

In the circumstances where direct measurement of ambient conditions is not possible a prediction method for likely ambient conditions is needed. Ambient level prediction is not the focus of this thesis and could justify a separate research project, however a framework enabling estimation of more than simply the background sound levels suggested by superseded Australian Standards, or current guidelines of the NSW EPA, is investigated below. This review, based on historical survey records of ambient noise levels, provides guidance on data processing methods relevant to both site-specific measurement survey data and regional comparative record data. Either can provide reliable ambient survey benchmarks necessary for impact assessment.

4.2.2.1 Author Project Dataset

A database of ambient sound levels is maintained by the author containing records from professional acoustic consultancy practice. This dataset will be referred to hereafter as the Author Project Dataset (APD). The APD records consist of individual data files containing ambient sound levels recorded at site locations primarily in the eastern areas of NSW and southern Queensland, obtained during a period from 1990 to 2017. Each survey file represents ambient sound pressure level data from a single outdoor location over various but extended periods, processed by the survey instrumentation into statistical sound pressure level records for sequential periods, the great majority of which were for periods of 15 minutes. The APD dataset represents a quantity of randomly compiled surveys of the stochastically varying ambient sound levels in a number of locations, the only variable being the land classification. The sampling process is random as is the content and the statistics of the aggregate of conditions represented by each land classification has relevance.

Data files represented by the APD dataset consist of professionally conducted survey records of ambient sound pressure levels, for which data the following criteria were satisfied:

1. The date, location and instrumentation used for the survey is known.
2. The data represents ambient sound pressure level data, recorded for the purpose of benchmarking for a potential land development project and was not associated with a problem or complaint investigation.
3. The AS1055 land area usage classification (LSC) according to Table *21*, relevant to the time of survey, was able to be determined.

4. The origin of the data is professional records. Further data mining from the larger professional record could have produced a larger project dataset, however would have further biased the dataset content to data relevant to categories 2 to 5.
5. The data was professionally validated at the time of survey, including the suitability of the measuring instrument noise floor.

Table 22: Author Project Dataset

Land Sound Category (LSC)	N, sites	n, samples
0	1	439
1	8	2911
2	13	29619
3	10	12033
4	22	20570
5	26	17902

The APD survey data consists entirely of A-weighted sound pressure level statistical data obtained with instruments set on fast response. Each datafile contains comma separated variable data in the format of Table 23.

Table 23: Author Project Dataset record format

<table>
<tr><td colspan="11">File Header Data:
AS1055 land category, expanded to include LSC zero.
Number of record periods in file
Traceable Record of Data Origin
Year of survey
Location and Description of measurement site
Statistical Sample period in minutes.</td></tr>
<tr><td>Date</td><td>Period Start Time</td><td>Lmax</td><td>L1</td><td>L5</td><td>L10</td><td>L50</td><td>L90</td><td>L95</td><td>Lmin</td><td>Leq</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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</table>

Weather condition records are not part of the data record. Data files were excluded where associated professional review records identified the occurrence of weather events that were considered sufficient to have distorted the data. The data files represent raw survey data. A small number of the older file records required data-conditioning to delete an invalid period record generated during automatic instrument restart events. All raw survey data files were manually edited to remove partial period data at the commencement and at the end of the overall survey period.

Survey Instrumentation comprised of one of four classes of instrument:

Rion NA28 type 1 sound level meter
Acoustic Research Laboratories EL015 type 2 sound level logger
Acoustic Research Laboratories EL215 type 2 sound level logger
Acoustic Research Laboratories type 1 sound level logger
Acoustic Research Labs Ngara type 1 sound level logger

1. Data referred to $L_{A,fast}$ sound pressure level records, generally determined over intervals of 15 minutes however a number of 5 minute duration samples were included in LSC 2 areas.
2. Data comprised continuous sample periods over 24 hour periods, post-processed to separate data into time of day periods of day (07:00-18:00), evening (18:00-22:00) and night (22:00-07:00).
3. Data for land category area number 6 was excluded from the analysis as intrusive noise is not generally a consideration of noise management policies for these areas.
4. Where data was missing – affecting L05 and L95 data only for a portion of the dataset – a linear interpolation between adjacent statistical values was applied.

4.2.2.2 APD Data Analysis

The APD data is used here, sorted according to land category to examine statistical parameters on a per-category basis, disclosing intra-category parameters. This conflates overall level variance effects with inter-site effects. Within a land category, variation in overall data records is the aggregate of intra-site variance – time of day effects, effects local to the survey site, etc – and the inter-site differences distinguishing one site from another and resulting from more widespread influences. While site specific predictions would be of interest where the objective is to avoid the need for site ambient survey measurement, there is no interest here in such a proposal. The objective in the research is to assist planning by considering how impact may present differently as a result of different ambient sound levels that can be anticipated within areas of land that are identified on a land classification basis. The validity of these findings is obviously dependent on the validity of the original site classification allocated to each survey location.

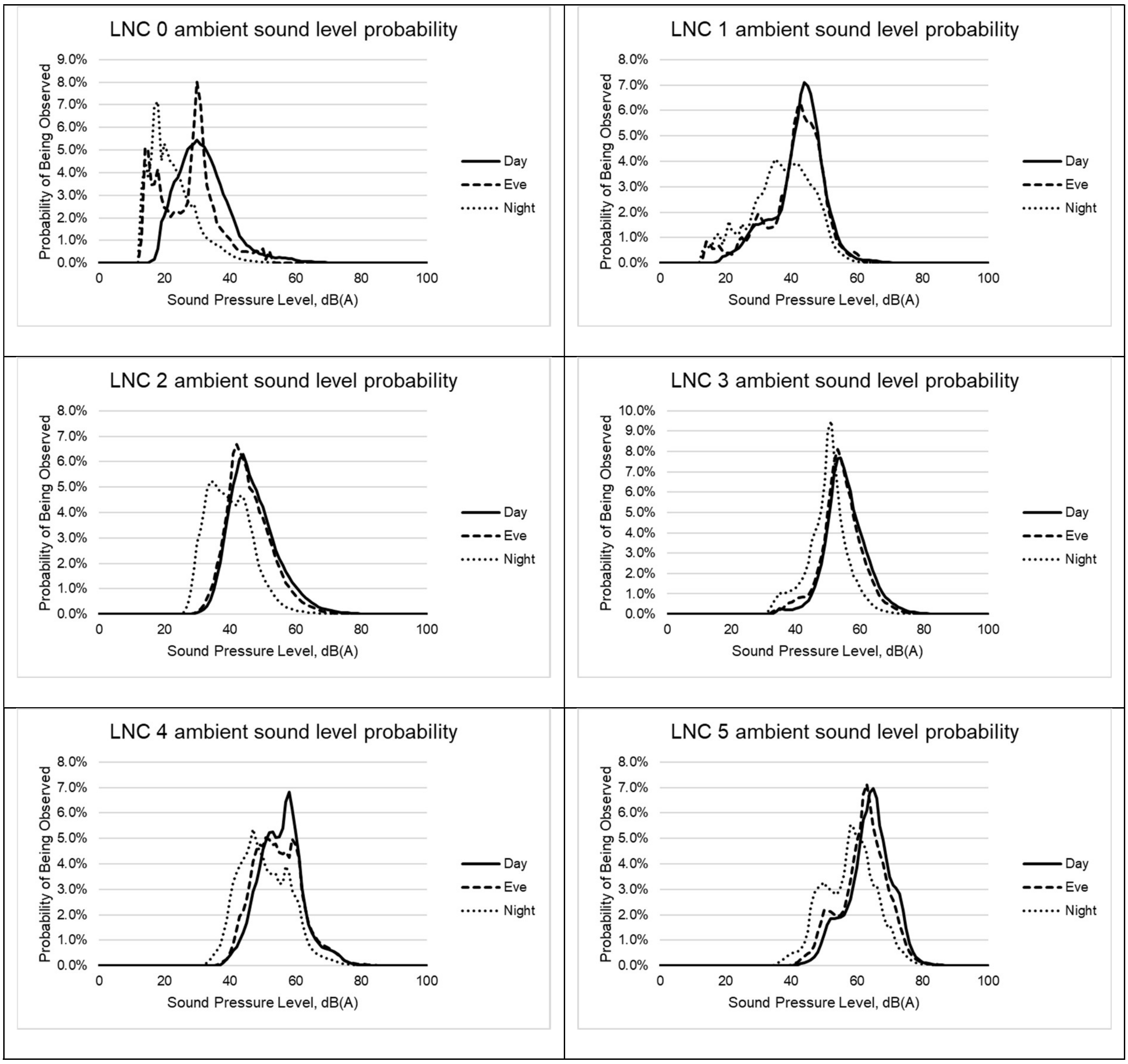


Figure 19: Land Sound Category probability density functions for APD data

In order to analyse the APD data, reconstructed bin counts were compiled to a bin resolution of 0.1dB from the aggregate record APD set. For each period sample, step-averaged bin counts were distributed between the known aggregate count values able to be determined from the value of each L_{AN} statistic, recreating a population of instantaneous sound pressure levels representing each sub-population described by the land type and time of day. Each sample generates a sequences of stepped bin populations able to be then aggregated into overall bin-counts representing the dataset population. The resultant sound level distributions are presented in Figure 19, the purpose of which is to demonstrate the subjective insight, based on solely measured ambient sound pressure levels when associated field inspection, that can be obtained from appropriate sound level probability density functions when compared with the more common cumulative distributions of Figure 20 and, worse, that of simply an L_{A90} or L_{Aeq}.

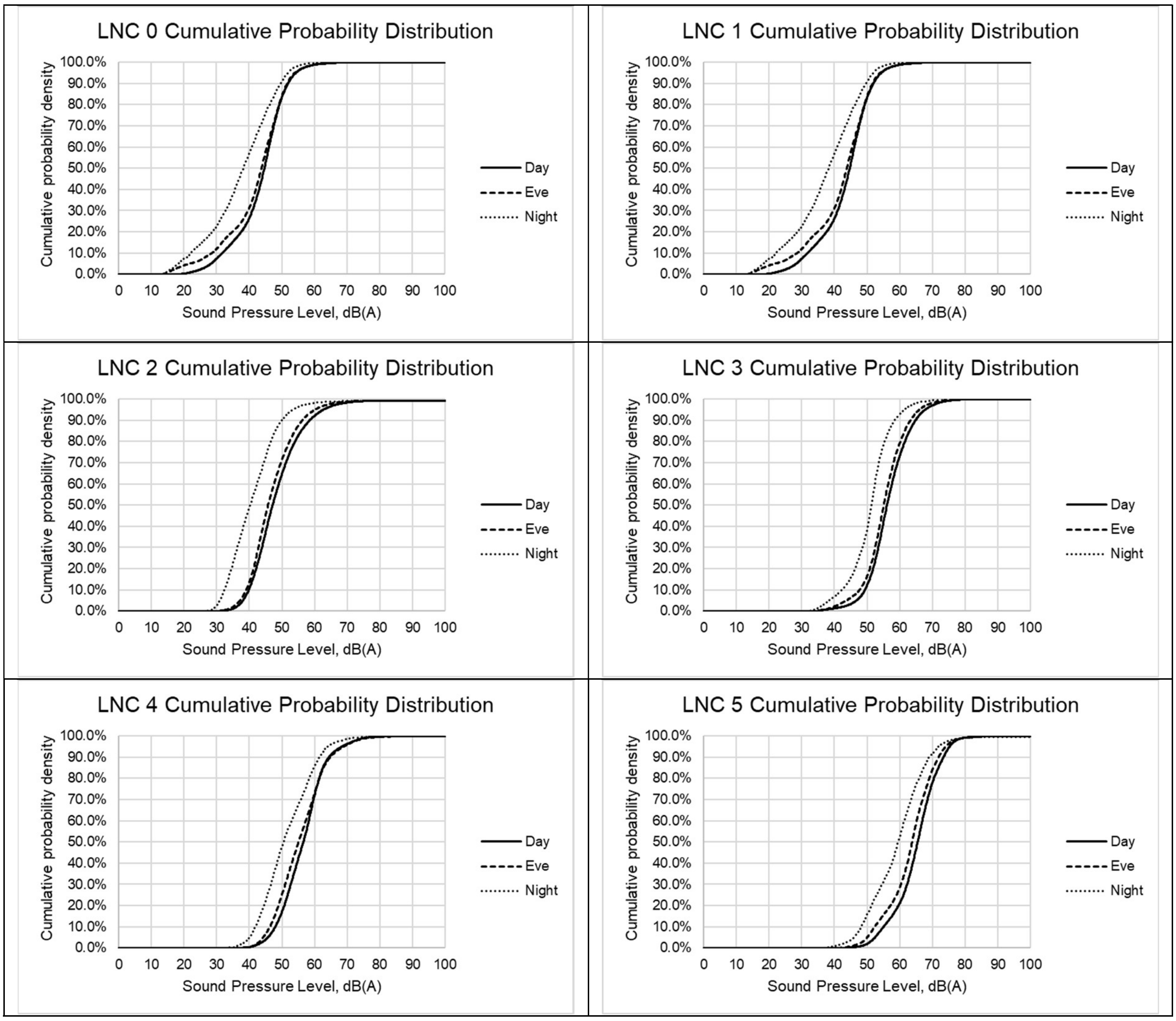


Figure 20: Land Sound Category cumulative distribution functions for APD data

More traditionally, the APD data was also analysed to determine mean and standard deviations of the sample period values for each statistical sound pressure levels for each Land Sound category population.

Table 24: APD mean sample level statistics, $L_{AN,TOD}$, vs LSC, dB

LSC	TOD	L_{Amax}	L_{A1}	L_{A5}	L_{A10}	L_{A50}	L_{A90}	L_{A95}	L_{Amin}	L_{Aeq}
R0	Day	60.5	48.8	44.2	40.2	31.8	26.6	24.9	23.1	38.8
	Eve	49.3	38.9	35.7	33.1	27.1	24.3	22.3	20.4	31.0
	Night	44.9	32.1	28.7	26.1	21.8	19.6	18.6	17.5	25.3
R1	Day	66.2	55.8	50.5	48.0	42.7	39.5	37.8	36.3	46.7
	Eve	58.5	51.2	47.8	46.1	41.6	38.4	36.4	34.8	44.0
	Night	55.4	47.5	43.8	41.9	36.8	33.2	31.7	30.5	39.8
R2	Day	69.0	61.4	56.4	53.7	46.9	43.7	42.2	41.9	50.9
	Eve	64.1	58.2	54.0	51.4	45.5	43.1	42.0	41.6	49.0
	Night	54.3	48.7	45.3	43.7	40.1	38.3	37.4	36.9	41.7
R3	Day	77.2	69.1	64.4	62.2	55.9	51.7	49.8	48.5	59.6
	Eve	75.7	67.3	62.6	60.5	54.4	50.8	49.3	48.2	58.0
	Night	69.5	61.6	56.8	54.7	50.0	47.8	46.6	45.6	52.9
R4	Day	73.8	65.6	62.1	60.5	56.1	53.0	51.3	50.1	58.2
	Eve	72.5	64.8	61.2	59.6	55.2	52.1	50.5	49.3	57.4
	Night	67.7	60.5	56.6	55.0	50.9	48.4	47.1	46.0	53.1
R5	Day	81.8	73.9	70.2	68.7	64.8	61.3	59.4	58.0	66.4
	Eve	79.6	72.0	68.4	66.9	62.9	59.6	57.7	56.4	64.7
	Night	76.3	69.1	65.3	63.5	58.3	55.0	53.5	52.5	61.1

Table 25: APD sample standard deviations vs LSC and TOD, dB

LSC	TOD	L_{Amax}	L_{A1}	L_{A5}	L_{A10}	L_{A50}	L_{A90}	L_{A95}	L_{Amin}	L_{Aeq}
R0	Day	7.9	7.1	6.4	6.6	5.8	4.6	4.1	3.9	6.5
	Eve	7.3	8.4	8.8	8.6	8.5	7.8	6.7	5.6	8.2
	Night	11.1	10.4	9.4	8.0	5.6	4.3	3.5	2.8	8.2
R1	Day	7.4	6.1	5.4	5.9	7.0	7.4	7.4	7.5	5.9
	Eve	8.4	8.3	8.3	8.6	9.1	8.8	8.5	8.4	8.3
	Night	10.4	10.7	10.1	10.1	9.4	8.7	8.3	8.0	9.6
R2	Day	8.4	7.8	7.3	6.8	5.8	5.1	4.8	5.1	7.1
	Eve	10.5	9.1	7.8	6.8	5.2	4.8	4.7	4.7	6.9
	Night	11.3	9.4	7.9	7.2	6.0	5.8	5.7	5.6	7.4
R3	Day	7.1	5.8	5.4	5.3	4.6	4.2	4.2	4.2	5.0
	Eve	7.5	6.1	5.8	5.7	4.9	4.5	4.4	4.4	5.3
	Night	9.1	7.0	6.5	6.2	5.4	5.2	5.1	5.1	6.1
R4	Day	7.1	6.1	6.0	6.0	6.0	5.7	5.5	5.5	5.7
	Eve	8.5	7.5	7.3	7.2	6.8	6.2	5.9	5.9	7.0
	Night	8.5	7.7	7.7	7.6	7.1	6.7	6.7	6.6	7.1
R5	Day	6.9	6.2	5.9	6.0	5.9	5.9	6.3	6.5	5.7
	Eve	7.9	7.0	6.6	6.6	6.4	6.4	6.8	7.0	6.4
	Night	8.8	7.7	7.1	7.0	7.2	7.4	7.5	7.6	6.9

Table 26: APD dataset population statistics, $L_{AN,TOD}$, vs LSC, dB

LSC	TOD	L_{Amax}	L_{A1}	L_{A5}	L_{A10}	L_{A50}	L_{A90}	L_{A95}	L_{Amin}	L_{Aeq}
R0	Day	73.2	59.1	47.6	42.9	32.1	23.3	21.6	16.6	46.8
	Eve	58.3	52.1	44.6	39.2	29.4	16.0	15.1	13.4	37.1
	Night	60.5	43.9	36.4	32.1	20.7	15.2	14.4	13.3	36.7
R1	Day	75.0	60.9	54.3	51.9	44.6	31.8	28.3	18.3	50.4
	Eve	100.0	60.4	54.0	51.6	43.8	28.6	21.7	13.7	47.8
	Night	73.2	56.6	51.9	49.6	38.1	22.1	18.1	13.4	45.5
R2	Day	100.0	74.5	62.7	58.5	47.1	39.8	38.0	30.1	57.5
	Eve	100.0	70.9	60.1	56.2	45.7	39.0	37.1	30.2	53.5
	Night	100.0	67.8	53.4	49.9	49.8	32.3	30.9	26.7	48.4
R3	Day	85.4	74.0	67.8	64.8	56.1	49.3	46.7	34.0	61.8
	Eve	83.6	72.0	66.0	63.3	55.1	47.7	43.6	33.3	60.1
	Night	100.0	67.7	61.3	58.5	51.3	42.2	38.4	32.1	56.5
R4	Day	100.0	75.1	68.4	64.4	56.5	47.9	45.7	37.8	62.0
	Eve	100.0	75.6	68.9	64.8	55.0	46.3	44.2	37.3	64.5
	Night	100.0	71.7	64.1	61.5	50.5	41.8	40.1	33.0	59.8
R5	Day	100.0	79.3	75.2	73.4	65.5	55.1	52.4	42.2	68.5
	Eve	100.0	79.2	74.1	71.8	63.8	52.3	50.0	40.7	67.7
	Night	100.0	78.7	71.9	69.0	49.8	48.1	46.0	36.2	65.3

The values summarised in Table 26 represent the statistical sound pressure levels that would have been found for the recreated full level-based dataset considered as one sample. That is, the statistics refer to the full 'n' samples obtained for each of the 'N' sites contributing data to each population dataset, represented also by Figure 19 and Figure 20. It is relevant to note that a level-ceiling limit of 100dB was applied for this analysis.

The following observations can be made, associating typical subjective observations with the evidence of the measurement summaries:

1. The equivalent energy level shown in the final column of Table 26 is distorted due to each location sample being of differing sample size and should be, largely, ignored.
2. For this very small dataset of LSC 0 area sampling, daytime level distribution is dominated by many apparently disparate sources distributed around 30dB(A), evening levels dominated by modally distributed sources at 20dB(A) and less and a remnant of daytime activity – almost certain to have been birds - with night mostly very low activity levels and apparently localised sources.
3. For this small dataset of LSC 1 surveying, the level PDF shows the diversity of conditions commonly experienced in rural areas. Daytime and evening level distributions are dominated by multiple sources

overlaying discrete modal sources at quite low levels more obvious in both evening and night. Night periods appear to have been affected by two modally distributed sources at around 35dB(A) and 40dB(A) – perhaps distant traffic.

4. The level PDF for LSC 2 areas suggests a generally quiet activity level at around 35dB(A) overlaid by comparatively louder events modally distributed around 45dB(A) with occasional events up to 80dB(A). The modal events are almost certainly transportation noise.
5. The level PDF for LSC 3 areas suggests somewhat homogeneous multiple sources being present, with a reduction at night periods of the louder sources – almost certainly road vehicles. Occasional events up to 80dB(A).
6. The level PDF for LSC 4 areas suggests a common activity level around 45dB(A), regular daytime and evening traffic around 55dB(A), and regular events at or near 60dB(A). The presence of some data sites affected by heavy transportation noise at around 70dB(A) is also identifiable.
7. The level PDF for LSC 5 areas is consistent with experience in CBD locations, where the presence of building services noises around 50dB(A) is common, general pedestrian activity noise around 60dB(A), general traffic noise events around 65dB(A), and both loud vehicle events and construction noise from 70-80dB(A).

4.2.3 Analysing Data – Typical and Worst Case Assessment Benchmarks

4.2.3.1 Data distribution aspects

Current NSW EPA regulation procedures utilise a background noise rating level (RBL) mentioned earlier as an impact assessment benchmark, being the 5th percentile value of the sequence of ranked L_{A90} survey samples. This approach can be understood as a regulatory procedure consistent with a policy objective of "worst case" analyses. A traditional statistical approach would likely involve calculation of a lower bound value, say, of a 90 percent confidence interval for an area L_{A90} level. This is derived from the mean value of the group of samples minus a margin calculated from the standard deviation of the individual values of those samples. This approach is conceptually similar to the RBL though not identical. The validity of such the traditional confidence interval calculation above depends on whether the range of the statistic – it could be a population of instantaneous sound pressure levels, or a sequence of L_{A90} sample values – conforms with what is known as a normal distribution, the familiar bell-shaped curve.

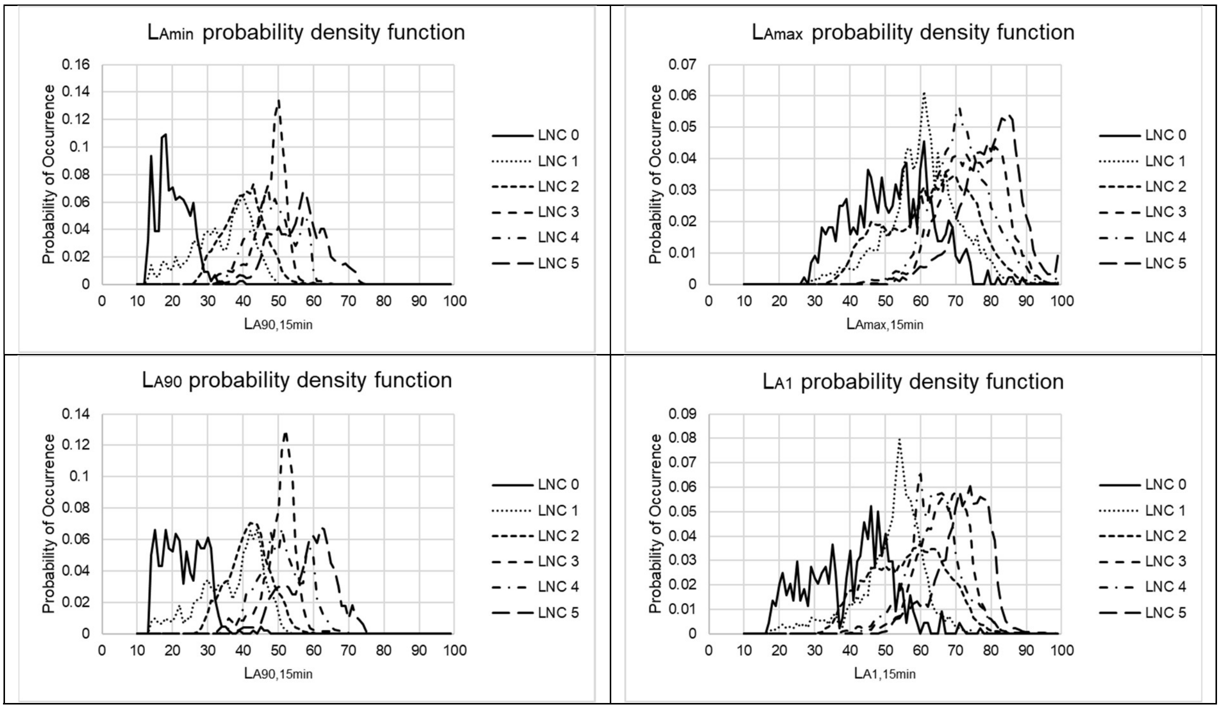


Figure 21: Density functions for statistical metrics

The level distributions shown in Figure 19 suggest some components contributing to instantaneous levels may well be normally distributed, however the overall distribution involved in stochastically varying acoustical environments is clearly not simply a normal distribution. Examining the distribution of the L_{A90} statistic for the APD dataset shows that this parameter is, in fact, negatively skewed. That is, the modal level of a set of level minima parameters - L_{A90}, L_{Amin} - is likely to be lower than the mean value of the statistic from that set. Similarly, the modal behaviour of a set of level maxima parameters – L_{Amax}, L_{A1} - is likely to be positively skewed. These features are apparent in Figure 21.

These distribution characteristics have important implication when estimating population statistics based on the results of a series of period samples. The true value of a population statistic is not represented by, simply, the mean value of that statistic determined from the set. It may be possible to conclude a value for the mean magnitude of impact in an impact assessment scenario based on the mean value of the ambient acoustic environment statistics. However it is clear, by the simple evidence of variation of the statistics between sequential samples, that a "worst case" impact assessment scenario requires a more sophisticated assessment basis than simply the mean background sound statistics.

Each set of statistical data – e.g. L_{A90}, L_{A1} etc – can be considered to represent an independent parameter associated with the ambient sound environment. The value for each sample L_{AN} must be always equal to or greater than the value of sample L_{AN+1}, however providing the data collection process has been valid the data can be examined independently. If the number of data samples is large <u>and</u> if the distribution of the sample values consolidates to what is termed a normal distribution, the statistical confidence for the value of a further sample of that statistic can be estimated from the mean value and standard deviation for the set of sampled statistics using Equation E4.

$$L_{N,CI} = L_{N,sample\ mean} +/- \boldsymbol{t} * L_{N,SDsample} \qquad \textbf{E4}$$

where
$L_{N,CI}$ is the confidence interval of the true value for the population statistic
$L_{N,sample\ mean}$ is the mean value of L_N obtained from the survey sample set
$L_{N,SDsample}$ is the standard deviation of L_N for the survey sample set
and
***t** is the critical value of the t-statistic for the number of degrees of freedom.*

If the sample size is larger than 30 the value of ***t*** for a confidence interval of 90 percent equals 1.645. The APD data provides a convenient set of samples and populations that can provide a context to the application of Equation E4, using the statistics summarised in Table 24 to Table 26 using Equation E5:

$$\boldsymbol{K} = \frac{L_{N,population}}{L_{N,sample\ mean} * L_{N,SDsample}} \qquad \textbf{E5}$$

where
***K** is the test statistic multiplier for L_N*
$L_{N,population}$ is the "true" value of the population L_N statistic
$L_{N,sample\ mean}$ is the mean value of L_N obtained from the survey sample set
$L_{N,SDsample}$ is the standard deviation of the survey sample set

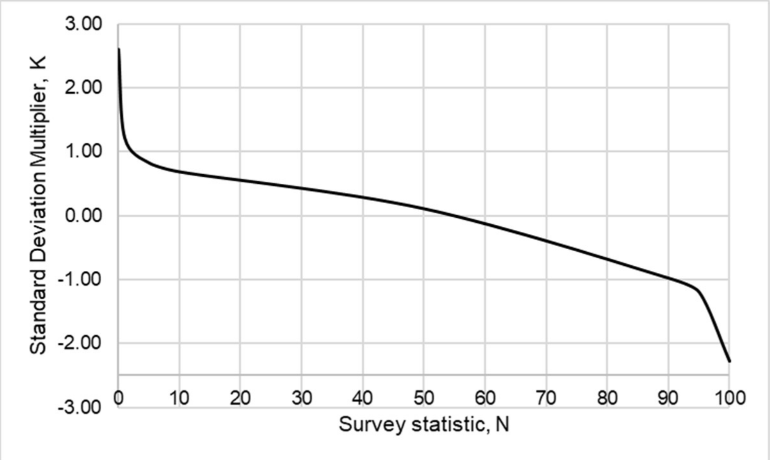


Figure 22: APD data variance test statistic, K

Values for ***K*** found for the APD data are shown graphically in Figure 22. For a 90 percent confidence interval the critical value ***t*** for the test statistic ***K*** will be found to be less than an absolute value of 1.645. Figure 22 therefore suggests that a traditional statistical analysis approach using Equation E4 cand be expected to provide reliable findings for population value statistics from nominally 1 percent level-exceedance (L_{A1}) to approximately 95 percent level exceedance (L_{A95}).

4.2.3.2 Ensuring valid data samples and associated impact simulation

These are important analytical considerations in deciding how fundamental input data should be processed when applied to regulations. For clarity, background sound levels used for assessment should be identified as "Assessment background sound levels", source levels identified as "Assessment source sound levels", and the basis of the assessment should be explained. Terms in relatively common use professionally include both "typical case assessment" and "worst case assessment". These terms are meaningless unless the input conditions associated with an assessment can be appropriately described, for which the consideration of joint probability of the input assumptions is required. This thesis proposes the statistically based approach summarised in Table 27:

Table 27: Qualifying impact assessment input data

Parameter	Worst Case Assessment benchmark	Typical Case Assessment benchmark
Assessment source levels	Upper bound 90th percentile confidence level for source statistical parameters	Upper bound 68th percentile confidence level for source statistical parameters
Assessment ambient sound levels	Lower bound 90th percentile confidence level for ambient sound level statistical levels	Lower bound 68th percentile confidence level for ambient sound level statistical levels
Critical value for ***t*** (n>=30)	1.645	1.0

In the same manner that the results of survey measurement of source emission levels must be processed to ensure the use of appropriate source level input conditions, so do the results of sound level surveys conducted to evaluate ambient site sound level conditions. It should also be recognised that the probability of occurrence of the source input and the existing ambient condition are mutually independent, both of which jointly influence the probability, productively, of any expected outcome. That is, where a probability that the source level may be exceeded is 10%, and the probability is also 10% that the ambient masking condition may be lower than adopted, the joint outcome probabilility that the impact will exceed that of the prediction is (1-(0.9*0.9). That is, the confidence level of the outcome is the product of the confidence level of the input conditions.

Among other possible outcomes, if average (or mean level) conditions are adopted for source input levels and for ambient sound level conditions, there could be a 75 percent chance that the actual impact will be higher than the expected impact level predicted by the impact assessment.

4.2.4 Planning assessment using hypothetical ambient sound levels

In a circumstance where survey measurement is either not available or inappropriate a hypothetical ambient sound level must be used. This could be carried out in different ways, however for planning applications it is likely that the aspect of most interest will be how ambient sound pressure levels might be hypothesised on the basis of the subject land planning categories. Current NSW EPA policy documents do not provide a sufficient basis for estimating area ambient sound levels as they consider only the L_{A90}.

Land use classification has been discussed earlier in 4.2.1. Analysis using the APD data suggests a benchmark model for LSC all day L_{A90} could be described in a format such as Equations E6 and E7. Equation E6 is a linear, model developed by linear model analysis of the APD data, predicting the mean L_{A90} value that would be expected for a 24-hour period set of 15 minute sampled surveys. Equation E6 shows that, for the APD data, raising the category of land usage by one level corresponds to an expected increase to the overall background noise level ($L_{A,90,24hr}$) of 6.5dB.

$L_{A,90,24hr} = 6.5\ (LSC) + 27dB + TOD$ $[R^2=0.94]$ **E6**

where

$L_{A,90,24hr}$ *is the predicted mean 15 minute* $L_{A,90}$ *for 24 hour survey period data s vs LSC area.*
LSC is the Land Sound Category Number (Table 21),
and
TOD adjusts $L_{A,90,24hr}$ *for time of day (Table 29) to estimate* $L_{A90,day}$, $L_{A90,eve}$ *and* $L_{A90,night}$.

Table 29 presents modelled LA,90,24hr values from the APD dataset for each land use type compared with the population L_{A90} determined from the aggregate bin counts from the dataset for that land use. Also included are time-of-day (TOD) parameters calculated by deducting the mean $L_{A90,24hr}$ sample value from the mean $L_{A,90,TOD}$ sample value for each land use classification. Comparing the assessment principles recommended long ago by Kosten & Van Os (Table 1), the APD dataset summarised in Table 29 concurs with a typical daily range in L_{90} for each land area of the order of 5dB(A), although the inter-classification step generated by 6.5dB in Equation E6 is slightly larger than the 5dB steps proposed in Table 1.

Mean values are stationary metrics. To include the considerations described in Table 27 for an impact model it is necessary to include expected sample level-variance. This has relevance in processing both measurement survey results and for ambient level prediction stochastic simulation for generic land classification, discussed further below. The standard deviations in Table 28 are the standard deviations from the mean $L_{A90,TOD}$ value for each array of sample values representing each land classification dataset. This table shows that the inclusion of variance when estimating an expected L_{A90} statistic for a land area is as important as is the allocation of a land category number. One observation is that ambient sound levels are sufficiently variable that it is not possible to predict hypothetical ambient sound levels considering solely a land area category. A further qualification, such as the transportation relationship descriptors referenced historically in AS1055 (Table 21) may be a necessary addition before using this approach to refine to robust predictive formulae. For any impact assessment study, analysis based on measured ambient sound levels should always be the priority.

Table 28 summarises the variation of the statistical L_{A90} parameter derived using the APD data for each land category when considered on a time-of-day basis.

Table 28: APD data $L_{A90,TOD}$ *standard deviation vs Land Category Number*

Land Sound Category	Day	Eve	Night	Mean
0	4.6	7.8	4.3	5.6
1	7.4	8.8	8.7	8.3
2	5.1	4.8	5.8	5.2
3	4.2	4.5	5.2	4.6
4	5.7	6.7	6.7	6.4
5	5.9	6.4	7.4	6.6
Overall mean SD	5.5	6.5	6.3	6.1

Table 29: Modelled $L_{A90,24h}$*, TOD parameters vs Land Category Number*

Land Sound Category (LSC)	N, sites	n, samples	TOD Day	TOD Eve	TOD Night	APD dataset mean $L_{A,90,24hr}$	Eqtn E6 Model mean $L_{A,90,24hr}$
0	1	439	1.4	0.8	-3.9	23.2	27.0
1	8	2911	0.8	1.3	-3.8	36.8	33.5
2	13	29619	0.5	1.4	-3.4	41.6	40.0
3	10	12033	-0.3	0.7	-2.3	50.1	46.5
4	22	20570	0.1	1.0	-2.8	51.1	53.0
5	26	17902	0.7	0.9	-3.6	58.6	59.5

To expand the statistical estimates generated by Equation E6 to L_{AN} ambient sound level statistics offset functions, obtained using linear analysis of the APD data, described by Equation E7 are suggested.

$$L_{A,N,TOD} = L_{A,90,24hr} + (K_1, K_2, \text{ or } K_3) + VAR \qquad \textbf{E7}$$

where

$L_{A,N}$ is a stationary statistical level (parameter N=0 - 100, plus L_{Aeq})
$L_{A,90,24hr}$ is determined from Equation E6,
$K_{1,2\&3}$ are mean $L_{A,N,TOD}$-$L_{A90,24hr}$ parameters from tables 30, 31 or 32 for Time of Day and LSC, and
VAR is the L_{A90} standard deviation (Table 28) incremented in accordance with Table 27 .

The statistical unit parameters described by Tables 30 to 32 for the L_{AN} and L_{Aeq} columns are the mean parameter value vs mean $L_{A90,24hr}$ for each land category determined by simple parameter subtraction from the APD dataset.

Table 30: $K_1 = L_{AN,TOD}$-$L_{A90,24hr}$ parameters for Daytime

LSC	L_{Amax}	L_{A1}	L_{A5}	L_{A10}	L_{A50}	L_{A90}	L_{A95}	L_{Amin}	L_{Aeq}
0	37.3	25.6	21.0	17.0	8.6	1.4	1.7	-0.1	15.6
1	29.4	19.0	13.7	11.3	6.0	0.8	1.1	-0.4	9.9
2	27.4	19.8	14.8	12.1	5.3	0.5	0.6	0.2	9.3
3	27.1	19.0	14.3	12.1	5.8	-0.3	-0.3	-1.5	9.5
4	22.7	12.7	9.1	7.5	3.1	0.1	-1.7	-2.9	5.2
5	23.2	15.3	11.6	10.1	6.1	0.7	0.7	-0.6	7.8

Table 31: $K_2 = L_{AN,TOD}$-$L_{A90,24hr}$ parameters for Evening

LSC	L_{Amax}	L_{A1}	L_{A5}	L_{A10}	L_{A50}	L_{A90}	L_{A95}	L_{Amin}	L_{Aeq}
0	26.1	15.7	12.5	9.9	3.9	0.8	-0.9	-2.8	7.8
1	21.8	14.5	11.1	9.3	4.9	1.3	-0.3	-2.0	7.2
2	22.4	16.6	12.4	9.8	3.9	1.4	0.4	-0.1	7.4
3	25.6	17.3	12.6	10.4	4.3	0.7	-0.8	-1.9	7.9
4	21.4	12.7	9.0	7.4	3.1	1.0	-1.7	-2.9	5.2
5	21.0	13.4	9.7	8.2	4.3	0.9	-0.9	-2.2	6.0

Table 32: $K_3 = L_{AN,TOD}$-$L_{A90,TOD}$ parameters for Night

LSC	L_{Amax}	L_{A1}	L_{A5}	L_{A10}	L_{A50}	L_{A90}	L_{A95}	L_{Amin}	L_{Aeq}
0	21.7	8.9	5.6	2.9	-1.4	-3.9	-4.6	-5.7	2.1
1	18.7	10.7	7.0	5.1	0.0	-3.8	-5.0	-6.3	3.0
2	12.7	7.0	3.7	2.1	-1.5	-3.4	-4.3	-4.7	0.1
3	19.5	11.5	6.7	4.6	-0.1	-2.3	-3.5	-4.5	2.8
4	16.6	12.1	8.2	6.6	2.5	-2.8	-1.3	-2.4	4.7
5	17.6	10.5	6.6	4.9	-0.3	-3.6	-5.1	-6.2	2.5

Finally, in considering the application of variance when simulating levels for all statistical parameters, instead of solely those associated with the L_{A90} and described above in Table 28, the findings of the APD dataset suggest variance could be further scaled as set out in Table 33. This confirms the intuitively obvious expectation that level variance increases as the statistical percentile of interest rises from minimum to maximum levels.

Table 33: Mean value APD dataset L_{AN} standard deviation, dB(A)

LSC	L_{Amax}	L_{A1}`	L_{A5}	L_{A10}	L_{A50}	L_{A90}	L_{A95}	L_{Amin}	L_{Aeq}
All	8.6	7.7	7.2	7.0	6.5	6.1	5. 9	5.8	6.8

In the absence of one or more available site measurement surveys, hypothetical ambient sound levels used in planning applications should consider a lower bound confidence level for predicted ambient sound level conditions based on the land use category. For example, using the APD dataset would involve prediction of the mean expected L_{A90} level predicted by Equation E6, minus the incremented sample standard deviation from Table 28 to adjust VAR to accord with Table 27, plus factors K_1 to K_3 from Equation E7 to populate all percentiles. An obvious benefit in using site survey measurement when the actual site is known is that the sample standard deviation for a single sample will almost certainly be smaller than the values of Table 33.

Apart from describing a procedure having application to the estimation of stochastically varying ambient sound pressure levels, the APD findings reported in this section have useful application to benchmarking against the range of L_{A90} and L_{Aeq} values incorporated in current NSW EPA policy documents.

4.3 ORIGIN OF DATA VARIANCE

4.3.1 Stochastic Variance

Stochastic, or random, events are events for which observations cannot be predicted with certainty [Mendenhall et al,1981], however for which, in general, the behavioural statistics tend to emerge over time.

The origin of stochastically varying immission levels at an observation position may be due to systemic changes in source location relative to an observer, systemically variable operating sound power emission by those sources or source-elements, or a combination of both location changes and emission changes. These systems are extremely common and represent the types of source systems most likely to be encountered in any acoustical environment.

An acoustical system is almost always comprised of multiple sources and fluctuating levels. Rarely experienced exceptions would be one in which one source is so dominant as to render all other signals permanently inaudible, or a system in a closed or isolated environment. A closed receiving environment is relatively common in the built environment, however quite rare in open space. In many circumstances, the perceived acoustical environment is comprised of so many sources that many are rendered unnoticeable.

Predicting statistical emission levels for a source involves estimating the probability that source components will be operating, together with knowledge of the source emission levels associated with each operational stage. Superficially, this is not greatly different from current environmental acoustic assessment methods, however consideration only of the aggregate averaged energy level throughout an assessment interval discards recognition of the probability of actual aggregate energy levels experienced at any instant.

For a simple system, involving a steady-state source that operates for the first ten minutes of every hour, within an otherwise steady state ambient environment – e.g. a large exhaust fan operating intermittently in a large mill - the expected acoustical emission levels at any time of the day can be fairly simply predicted. This example can be extended by considering a similar system, but for which the emission from the intermittently operating source is stochastically variable, requiring a similar but more complex assessment using the sampling methods described in 3.2.2 to predict the likely statistical emission levels. By extension, both the ambient acoustical environment and the intermittent source may require sampling. This is the circumstance commonly encountered in environmental acoustical systems. Predicting statistical sound levels from a source requires knowledge of the probability that the source will operate in a particular way.

4.3.2 Chaotic Variance

Acoustic chaotic events are those for which, at the current state of the art, there is no practical and identifiable pattern of behaviour. Examples include weather events, abnormal behaviours such as erratic patterns of road use, anti-social behaviours, unsystematic local factors such as occasionally encountered road surface irregularity, and the like. Technically, chaotic events describe outcome events that are highly sensitive to the input conditions but for which it is impractical to identify or predict those input conditions. Chaos theory has application in the fields of risk management prediction for chaotic but usually catastrophic events – economics, health and safety, terrorism – however the objective of such risk assessments is usually to predict the probability that the event of concern will occur at all, using Bayesian statistics, or that the event may occur within a specific time frame. Significant acoustic chaotic events – an easy example is thunder - are usually excluded from the analysis of emission for an acoustical system due to their infrequency and the fact that, with a few exceptions, are associated with effects that are neither dangerous nor damaging. Levels associated with chaotic acoustic events would generally have affected level statistics falling outside the 90 percent confidence interval relating to Figure 22 above.

4.4 STOCHASTIC MODELLING VS STATIONARY MODELLING

Stochastic modelling involves the fundamental recognition that many aspects of impact are level dependent. Some source emissions can and have been modelled to reproduce the level waveform of typical associated transient events – vehicle pass-by, aircraft flyover, etc. However, while these models may competently reflect the temporal patterns of a specific source, impact assessment involves the interaction of the stochastically varying source with the stochastically varying ambient environment. It is not practical to generate a meaningful level waveform for the range of ambient sound levels in that ambient environment. Hence, a numerical simulation of impact compares the new or superimposed sources to the existing ambient conditions on a statistical basis, aggregating the probabilistic instantaneous levels from all contributing components over an appropriate time interval. This requires that the statistical distributions representing the range in sound pressure levels of the source and ambient conditions can be compared for equivalent evaluation periods.

Statistically, source sound emission relationships need to be treated as both operationally independent and phase-incoherent, however there may be an operational correlation. For example:

1. In a motor vehicle sound generated by propulsion is independent of sound due to interaction of the tyres on the road, having no influence on one-another and being able to occur separately - one component active whilst stationary and the other active during vehicle coasting;
2. Propulsion sound and sound from the interaction of tyre-on-road are incoherent as they have no phase relationship;
3. Sound from each of the two sources is, however, independently predictable as a function of the same vehicle transit speed in normal use. [Sandberg,2001],[NTRC,2001],[De Coensel et al,2015].

The presence of multiple stochastically varying component sources within a system tends to compress the variance of the aggregate operating sound levels. As the number of concurrently operating components making up a sound generating system increases, the statistical emission characteristics of that system trend toward a steady-state, or stationary, acoustical system (Figure 60). Under such conditions the operating status of the system can often be resolved to an equivalent characteristic source. An important example is the consideration of road traffic noise as a stationary line-source, having been characterised so since the earliest of environmental acoustic assessment work following a seminal paper discussing the characteristics of sound propagation from sources of finite dimension by Rathe [Rathe,1969]. Rathe's proposals are valid for a sequence of incoherent sources each roughly equal in spacing and level emission, when observed from the far-field. However characterising sound emission from the types of transport corridors frequently associated with land-use planning as a line source fails two important tests – lack of uniformity in source spacing and differing sound propagation from those sources to locations likely to be of interest being in the nearfield.

The parameters affecting sound propagation from a source of finite dimension A x B with A larger than B, as summarised by Rathe, resolve into three regions:

1. at distance $x \geq A/\pi$; the geometric far field: A region in which the source propagation behaves as a point source for which the energy dispersion rate is 6dB per distance doubling,
2. at distances for which $B \leq x \geq A/\pi$; a transition zone in which the source propagation behaviour is that of a line source for which energy dispersion rate is 3dB per distance doubling, and
3. for locations for which $x \leq B/\pi$; The geometric nearfield, in which energy dispersion rate is zero per distance doubling.

Even for a freeway, a section of road for which a vehicle flow rate is 100 kilometres per hour over an assessment interval of 1 hour involves vehicles affecting the aggregate noise level that could be located along a carriageway section 100 kilometres in length, or for a 15 minute interval, a length of 25 kilometres. Even for the shorter assessment interval, nearfield conditions exist to a distance of $25/\pi$ kilometres from the road, or approximately 8 kilometres.

The characteristics of a free-flowing sequence of vehicles on a road is not a sequence of uniformly spaced equivalent events but, instead, a randomly spaced sequence of independent stochastic events. The distribution – arrival spacing – of events of this type are identified statistically as a Poisson Process [Banks&Carson,1984] the probability of occurrence for which can be defined as a Poisson Probability Distribution [Mendenhall et al,1981]. The average number of events conforms with the classical model, however the actual spacing and therefore number of instantaneously contributing sources may vary substantially during a sequence of observation periods. This fundamental modelling discontinuity due to uneven event spacing is aggravated by the fact that the individual sources are operationally independent and generate stochastically variable individual emission levels. The critical conditions for the line-source model – uniformity of component source event level, uniformity of physical spacing and propagation conditions within the far-field – fail from three perspectives. These issues are more pronounced at lower flow rates as the vehicle events become more sporadic and disconnected, as is often the case for common land-use activities – mine haul roads, site access roads and the like.

In contrast to the road example, sound from an industrial conveyor belt is likely to be validly modelled as a stationary line-source equivalent, as it passes the fundamental tests of uniform source spacing, relatively uniform and stationary source level emission, and propagation to a receiver usually in the geometric far-field.

A railway may present as either a mobile stationary system or a moving stochastically varying system, depending on the source to receiver distance.

The corollary to a system with many sources trending to a stationary system (Section 8.5) is that a system has relatively few concurrent source elements is likely to be more variable. These characteristics are observable in the ambient sound level statistics for different land-use areas in Figure 19. It is also a fundamental characteristic contributing to the common community noise problem of loud noise events. Loud events are a relative-level phenomenon and tend to be more apparent during periods when fewer contributing sources are present. The significance of loud events is aggravated by the observation that isolated events appear to be more noticeable when compared with a regular sequence of the same events occurring at the same level [Botteldooren et al,2008]. These scenarios can be modelled statistically using a stochastic variance-based system model.

4.5 MODELLING LAND USE ACTIVITIES

4.5.1 Simple Time-of-Day Activity Models

The fundamental difference in a stochastic model compared with a stationary model is inclusion of time as a modelling parameter, whether a temporal stochastic model or a statistical stochastic model. The stationary model may be identified with a specific time period – e.g. daytime or night – but is only able to identify a single outcome value. This is an insensitive model unable to determine any characteristics throughout that period that might be associated with specific or varying impact conditions.

A temporal model can be used to predict, for example, a time sequence of vehicle pass-by sound level events thereby emulating a real time level waveform such as road traffic [De Coensel et al,2015]. This requires knowledge, among other things, of the instantaneous vehicle sound emission, passing speed and distance from an observer. The resultant level history can then be examined in any manner of interest and, for the analysis of a specific condition of interest, can be a powerful method. However this approach is computationally intensive for the range of outcome conditions to represent sufficiently the range of input conditions occurring during an assessment period that is likely to be relevant to environmental acoustics. An effective way to model time related aspects is to model time indirectly as the probability of occurrence associated with each of the major input conditions. Using this modelling principle, temporal variation can be incorporated relatively simply through by identifying the probability that a source will be present together with the probability, when present, that the source emission sound power level will be any particular value.

This general approach is familiar, being the basis of statistical sound pressure level measurements. The origins of stochastic variance - Table 34 – provide the structure required for the stochastic model. For a stochastic system that is physically stationary the stochastic variation of the system can be directly expressed using emission power values derived from statistical measurements. For a system where the cause of stochastic variation is the physical movement of the source, or the intermittent operation of the source, the model includes those operational and physical movement parameters.

Table 34: Factors affecting stochastic variance of sound pressure immission levels

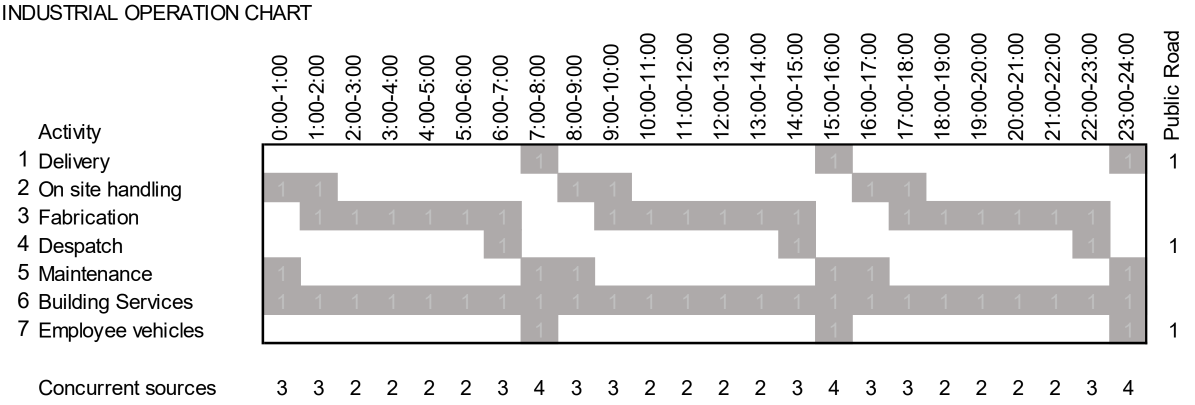
	Type of Stochastic Level Variation Source emission	Propagation
Source Presence	1=present; 0=not present	
Source emission	Varies from Lmin to Lmax	
Energy dispersion		Varies from shortest to longest propagation distance

Statistical modelling involves the randomised sampling algorithm described previously in Figure 5. The conditions that define the stochastic model and under which the algorithm is applied are therefore important, however the level of detail can obviously be varied. A model necessarily involves:

1. Identification of the sources contributing to the system
2. A description of the operational behaviour of the sources. In its simplest form this is an operating probability table such as the examples given in Figure 23 and Figure 24.
3. Source data, being statistically based level emission data, for each source, and
4. Location data representing the operating location probability for each source.

The most important content of a stochastic model, in fact of any impact assessment model, is an unambiguous description of how the sources combine as a system. Figure 23 and Figure 24 are simple Gantt charts identifying each source or activity having an operational probability of 1 during the time periods identified by shading, and a probability of zero when unshaded. This format enables a reviewer to understand what elements contribute to the system acoustical output and to consider aggregate system emission characteristics on a time-of-day basis, recognising which sources operate and, at any time of day, how many.

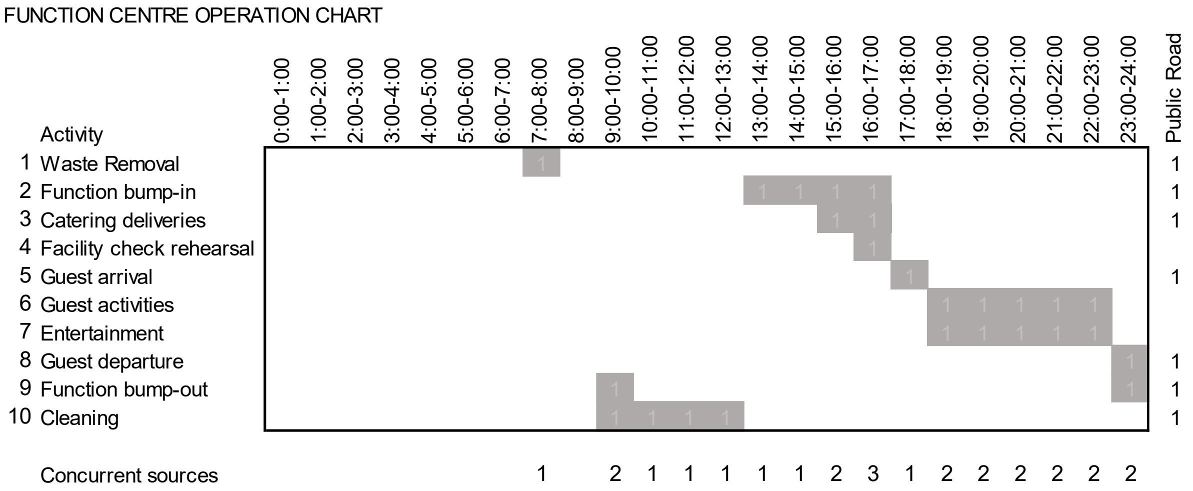
Using current assessment methods, aggregated sound pressure immission levels for each hour of a day could be derived using stationary source sound power emission levels based on these same source-operation charts with outcomes then compared with background sound levels at the same times-of-day using typical time-dependant background sound levels such as the L_{A90} data shown in Figure 25. These impact assessments would remain stationary metric impact assessments. This type of analysis can be quite straightforward, is likely to inform a stakeholder far more effectively than current "worst-case" and day / night assessment methods, and will plainly identify the sources and conditions contributing most to impact.



INDUSTRIAL OPERATION CHART

	Activity	0:00-1:00	1:00-2:00	2:00-3:00	3:00-4:00	4:00-5:00	5:00-6:00	6:00-7:00	7:00-8:00	8:00-9:00	9:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	Public Road
1	Delivery								1								1								1	1
2	On site handling	1	1							1	1							1	1							
3	Fabrication		1	1	1	1	1	1			1	1	1	1	1	1			1	1	1	1	1	1		
4	Despatch							1								1								1		1
5	Maintenance	1							1	1							1	1							1	
6	Building Services	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
7	Employee vehicles								1								1								1	1
	Concurrent sources	3	3	2	2	2	2	3	4	3	3	2	2	2	2	3	4	3	3	2	2	2	2	3	4	

Figure 23: Industrial Site Source Operating Probability Chart



FUNCTION CENTRE OPERATION CHART

	Activity	0:00-1:00	1:00-2:00	2:00-3:00	3:00-4:00	4:00-5:00	5:00-6:00	6:00-7:00	7:00-8:00	8:00-9:00	9:00-10:00	10:00-11:00	11:00-12:00	12:00-13:00	13:00-14:00	14:00-15:00	15:00-16:00	16:00-17:00	17:00-18:00	18:00-19:00	19:00-20:00	20:00-21:00	21:00-22:00	22:00-23:00	23:00-24:00	Public Road
1	Waste Removal								1																	1
2	Function bump-in														1	1	1	1								1
3	Catering deliveries																1	1								1
4	Facility check rehearsal																	1								
5	Guest arrival																		1							1
6	Guest activities																			1	1	1	1	1		
7	Entertainment																			1	1	1	1	1		
8	Guest departure																								1	1
9	Function bump-out										1														1	1
10	Cleaning										1	1	1	1												1
	Concurrent sources								1		2	1	1	1	1	1	2	3	1	2	2	2	2	2	2	

Figure 24: Function Centre Source Operating Probability Chart

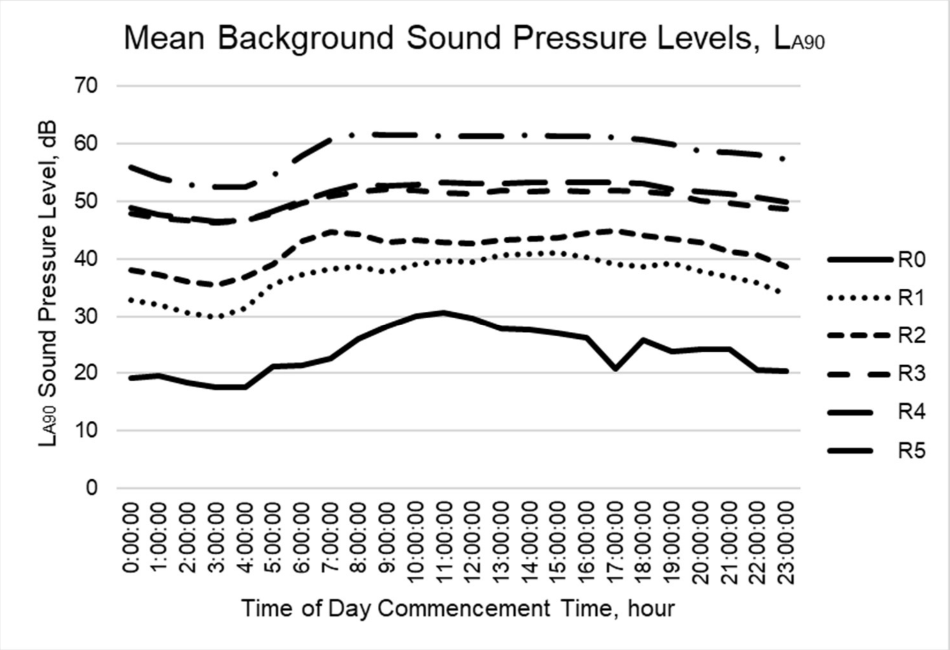


Figure 25: Example 24 hour Background Sound Pressure Level Statistics, dB

4.5.2 Proportional Representation and Conditional Probability

When one or more system components is present only part of the time it is necessary to co-ordinate appropriate model sampling and summation. Mathematically, this involves the product of two independent probability functions - the conditional probability specifying the presence of the component and the operational probability of that component when running. Statistically this is termed a joint probability function and is the basis of simulation sampling.

If source 2 is operational only when source 1 is silent, a two-stage sampling procedure would be required determining, first, if source 1 is operational after which sampling for source 2 would occur only if source 1 is silent. Source interactions require definition.

In a simple model, if a component is known to operate one-third of any given period, summation modelling could simply sample for that component at each third *Lsum* iteration. More practically, a set of N presence functions will be required for a noise system involving N contributing components. Each presence function is simply a fraction representing the probability of 1 for the condition present, and zero for the condition absent, applied at each summation using a uniform random number [0,1]. For environmental applications the probability that ambient sound is present is always 1, though this may often not be the case for the components to be imposed.

Table 35: Conditional Operating Probability for a given time period

Source		Presence probability	Operational probability	Joint Probability
Ambient sound		100%	100%	1.0*1.0=1.0
New source 1	Operates one-third of the time, otherwise silent.	33%	100%	0.3*1.0=0.33
New source 2	Operates half the time during which a starting state applies for 10 percent of the time and a run-down state for 30 percent.	50%		
	Source 2 starting up		0.1*50%	0.1*0.5=0.05
	Source 2 running		0.7*50%	(1.0-0.1-0.3)*0.5=0.3
	Source 2 shutting down		0.3*50%	0.3*0.5=0.15

Conditional probability is an important element in the assessment of multiple-component noise systems, allowing for multi-stage sources, intermittently operating sources, and overall influence factors that may be present such as systematic diurnal source or ambient variation. The underlying assumptions described by conditional probabilities should be documented and provide an unambiguous framework describing the impact assessment for the project.

4.5.3 Generating Reliable Statistics

The statistical noise level parameters used to produce relevant source level data must be robust. The survey and analytical procedures used to obtain raw input data must be appropriately rigorous. It is important to consider the sources of potential for error arising from the data sampling and modelling processes.

Many statistical analyses rely upon the Strong Law of Large Numbers. Essentially, this states [Ross,1976] that the average of a sequence of random variables having a common distribution will converge, with a probability of 1, to the mean value of that distribution. That is, provided a sufficiently large number of values is examined, the mean of those values will be statistically repeatable. This presents something of a dilemma in the field of physical and environmental acoustics as it is the outlier values that are, frequently, values of considerable interest. Loud events automatically involve outlier statistical values. The approach used in current environmental impact analysis has been to concentrate on an energy equivalent mean value, which has obvious origins in the statistical behaviour mentioned above. This in part explains the inconsistency often observed in findings based on energy equivalent metrics [Mestre et al,2011], as the level distributions associated with the source elements are rarely, if ever, the same. Indeed, if they were the same, the sources would often be operationally indistinguishable.

The implication to numerical simulation of the Strong Law of Large Numbers is that many simulations of a multiple-source stochastically variable acoustical system must be carried out to reliably model the statistics of interest. It is axiomatic that an interest in a statistic representing the extremes of outcome conditions means that sufficient iterations of a model must be conducted to ensure that many examples of those extreme conditions will occur. This requires an increasingly large number of simulated conditions, or iterations, as the statistics of interest approach the extreme percentiles.

This requirement to examine a finding based on numerous data points is neither special nor unusual. In applying a simple student T-test, the statistical test is verifying that the experimental conditions produced a sufficiently large dataset to ensure that conclusions based on the measure under test, usually of central tendency and represented by the mean, are reasonable. It is noted earlier that the endpoints associated with the normal statistical distribution are undefined – the L_{max} and L_{min} are never truly known. The determinant of a suitable run size requires, therefore, a decision about what is an acceptable level of “error”. To identify a reasonable simulation run size, bin counts have been examined for known linear cumulative level distribution inputs, determining a 90 percent confidence interval for each statistical bin across a range of run sizes.

An acceptance condition of an error of 15% was used, arbitrarily, being mathematically comparable to the 0.7dB measurement error associated with a Type 1 sound level meter (10*log(0.85),10*log(1.17)). Using known input and output conditions and modelling based on the Matlab RAND function, the run sizes summarised in Figure 26 are recommended.

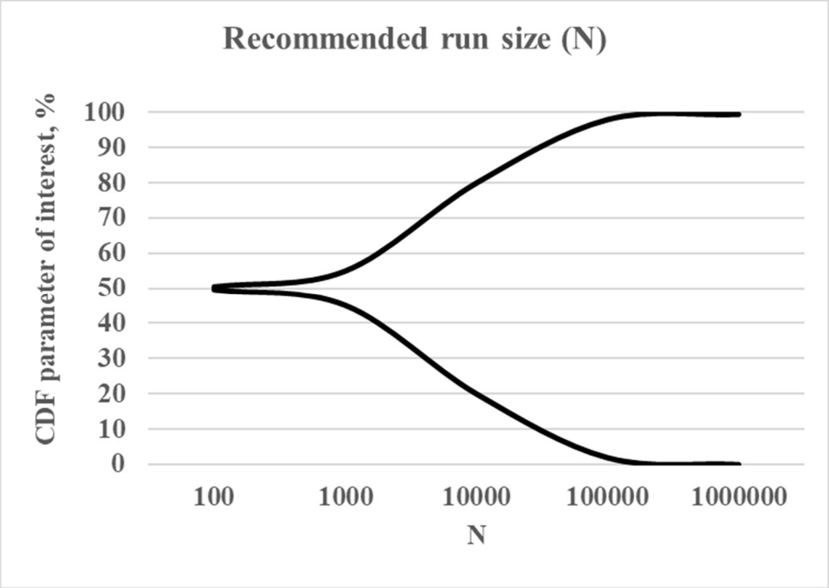


Figure 26: Recommended Simulation Run Size

Figure 26 shows that, if a simulation model for an acoustical system is planned and the results of interest include outlying value such as the L_1, a run size of up to 100,000 iterations may be required. If, say, statistics up to only the L_{10} are of interest, a run size of about 30,000 iterations is likely to be sufficient. The findings presented in this thesis were obtained using Matlab-implemented algorithms using a resolution of 1000 point sampling of the cumulative distribution function for level values, and iteration run sizes between 10000 and 100000 simulations to examine the system operating conditions. It is critical to test the accuracy of any uniform random number generator used for a simulation process and to adopt appropriate model run parameters accordingly.

Sampling errors, rather than simulation errors, arise if the resolution of the input data exceeds the number of iterations of a simulation run, however in practical terms this source of error can be ignored.

It is worth noting in closing that running fewer model iterations than the runs suggested by Figure 26 does not preclude a calculation of any statistic of interest. In such an implementation, sequential application of the model will produce a larger range of output values for that statistic wherein more than +/-0.7dB of that variance will be due to inconsistency in the random number generator alone. When modelling to test sensitivity of input conditions or evaluating concept systems, smaller run sizes are likely to provide useful and more than satisfactory findings.

4.6 TYPICAL SYSTEM EXAMPLES

Typical system model outlines are described as examples in Table 36. The objective of the table is to demonstrate that relatively simple input data is required for quite large and complex systems and that a range of different operating and output conditions can and should be modelled. The sound level emission properties and their numerical simulation as an environmental acoustic system involves identifying fundamental aspects of both source operation, emission and of the outputs having importance to potential impact:

1. What are the operational characteristics associated with the source – i.e, how many sources are fundamental to the operation of the system and how do they operate both independently and in aggregate?
2. What aspects of potential impact require consideration?

For each answer to the above either different input data or different system operating associations will almost certainly be modelled.

Among many detailed and complex system examples for which impact from changes can be examined by these procedures are changes as discretely complex as the introduction of a short new slip lane on a highway, or a re-configuration of a road section from two lanes to three. Using current methods, a change as operationally minor and specific could not be described.

Table 36: Stochastic System Outline Models

Model	Description	Main inputs	System 1	System 2	System 3	System 4	State 1	State 2	State 3	Likely outputs
1	Single Road	Flow rates, design speed, vehicle classes	Traffic flowing daytime				Running			Statistical levels daytime
				Traffic flowing night				Running		Statistical levels night
2	Multiple Roads : e.g main and cross road	As above	Main Road running / Cross road stationary				Running 60%			
				Main road stationary / Cross road running				Running 35%		
					Both roads stationary				Running 5%	Statistical levels at observer
3	New lane added to existing road		Road				Running			
				New lane section			Running			Emergence of sound from sources located in new lane
4	Carpark, Depot	Entry / departure rates	Entry and public road				Heavy morning	Light Day	Heavy Evening	Statistical levels at observer
		Design rule - Proportion vehicles moving		Vehicles moving within site			Heavy morning	Light Day	Heavy Evening	
		Equipment details / operating load vs capacity			Ventilation system		Heavy morning	Light Day	Heavy Evening	
5	Construction site	Vehicles per hour	Materials handling on public roads							Statistical levels at observer Emergence of specific sources
		Site activities schedule		Site work						
		Site activities schedule			Special site conditions - e.g. concrete pumping					
6	Extractive Industry	Site activities schedule	Material extraction processes				Running			
		Site activities schedule		On site material handling - crushing etc			Running			
		Vehicle movement schedule			On-site haulage		Running			
		Vehicle movement schedule				Site to market haulage	Running			

Table 36: Stochastic System Outline Models (continued)

Model	Description	Main inputs	System 1	System 2	System 3	System 4	State 1	State 2	State 3	Likely outputs
7	Railway	Train noise data and rail coordinates	Trains in transit				Running			Statistical levels at observer Emergence of specific sources
8	Aircraft flight corridor	Aircraft noise data and corridor coordinates	Flight corridor 1				Running 60%			Statistical levels at observer Emergence of specific sources
		Aircraft noise data and corridor coordinates		Flight corridor 2				Running 40%		

Table 37: Detailed Stochastic Model Elements - a Road Project

Input Variables for each direction (N,S)	Data Processing	Modelled parameter	Algorithm	Discrete modelling input variable	Units	Propagation rules
Required Assessment Interval					Day / Night Time of Day (hour)	
Expected traffic aggregate flows (AADT,hourly etc)	*For each vehicle class (up to 12 classes)*	Expected mean directional flow for each vehicle class for required assessment interval	Linear function (class flow input data scaled to assessment interval)	Aggregate flow data	Mean vehicles vs time per class	
Lane location coordinates		Locate segment lengths			x,y,z	
Design speed limits	*For each direction & each segment*	Determine lane position probability	(Speed x segment) / ∑(speed x segment)	Transit speed Segment length Total carriage length	Km/hour	
		If multiple lane carriageway: Expected mean flow per lane per class	Lane distribution rule	Lanes per carriageway	integer	
	For each class:	Expected mean passing speed	Linear function	Design speed limit	Km/hour	
	For each iteration (N=1:10000)	Actual number of vehicles on each carriageway	Poisson variable	Expected mean flow	Integer	
	For each vehicle	Actual vehicle location	Random location based on lane position probability	Actual number of vehicles on carriageway	Location x,y,z	
		Actual passing speed	Random variable	Expected speed + variance	Km/hour	
		Expected source emission	Linear function	Actual passing speed	Lw, dB(A) re 1pW	
		Actual source emission	Random variable	Expected emission + variance	Lw, dB(A) re 1pW	
		Sound level at receiver		Distance, source to receiver Air and ground absorption Barrier Diffraction	Lp(A)	Point source dispersion
	For aggregate of all vehicles			Each vehicle immission level	$L_{A,N}$	

4.7 CONCLUSIONS

4.7.1 Informed assessment foundations

The need for a land classification in managing land-use impact decisions has been demonstrated, as have the major elements required of assessment methods to describe impacts for stochastically varying systems within those land areas. Planning instrument classifications do not provide this capability.

Inspection and elemental description of the ambient acoustical environment should be deemed mandatory for any legislative assessment procedure. Only by inspection of the ambient condition can an assessment of potential for impact be made possible.

Processing of field survey data is described, recommending methods that are traceable and systematic. Presentation of survey results as probability density functions is shown to be both informative and preferable. This facilitates a link between survey technical data and observations described from site inspections.

Methods of describing the stochastically varying acoustic systems associated with a land-use on a time-of-day basis have been shown to be both relatively simple and informative.

4.7.2 Regulatory benefits enabling more informed development consent

The primary purpose of an impact assessment is to communicate the findings to a range of potential stakeholders. Acoustical terminology alone is a substantial barrier to the ability of many community members to understand the outcomes of a reported assessment. However, this is not the only concern expressed by many involved in the review of development and planning studies. The conditions for which a reported finding is valid are frequently unclear and developments are, at times, approved and found to operate in different and unforeseen ways. The title attached to a development does not guarantee its method of operation, yet the basis of approval under current NSW Model LEP land use planning regulations is strongly title-focussed [NSW Govt,2006]. Clarity of description is not unique to an assessment carried out using numerical simulation, however such modelling necessarily provides a framework that concisely documents the operations and activities to which an approval extends.

1. Input conditions are defined – the operating conditions of the system that has been modelled are clear.
2. Assumptions are clarified – approved operating conditions are unambiguous.
3. Input variables are disclosed leading to more appropriate management options – sources are clearly disclosed and the nature of impact that has been considered is unambiguously identified.
4. The relative significance of sources is disclosed – modelled outputs describe the relative significance of the contributory sources using linear terms (probability of being audible) able to be understood by non-technical readers.

The requirement for clear definition of valid operating conditions is one of the powerful benefits of assessment based on the numerical simulation procedure, as these operational aspects should inform conditions under which a land-use is approved. Subsequent operating conditions can be readily verified in contrast to verifying operating sound pressure levels which may be difficult, expensive and time consuming. From the perspectives of both the local authority and an affected neighbour, approved site activities can be reviewed post-consent with less reliance on technical expertise.

In combination with the magnitude of impact concepts summarised in section 3.5 this method of analysis supports traceable, robust and informative approval procedures relating to land-use applications.

5 A STOCHASTIC ACOUSTICAL MODEL FOR A ROAD

5.1 PREAMBLE

Modelling a road as an example of the application of statistical simulation to a detailed stochastic system is chosen because it is a difficult and complex example. Most planning level noise models will be substantially simpler.

The prediction and management of noise from road traffic is a field of major collective endeavour, involving policy, legislation and community. Numerous road noise prediction models have been developed. Work at an international level has been directed to the identification of desirable management criteria, while road construction at a national and state level is of major economic importance. This chapter demonstrates that the prediction of accurate statistically based noise levels from road traffic can be obtained using numerical simulation techniques, based on relatively simple input data. These outcomes for the example of road traffic interface with the discussion of the magnitude of impact from any stochastic system outlined in Chapter 3.

Chapter 5 describes a method of prediction of road traffic based on the mathematical simulation of a sequence of instantaneous conditions, each such condition representing a statistically reliable random arrangement of discrete omnidirectional emission sources located according to the defined lane corridors. The objective of the technique is to enhance prediction of road noise impact assessment through the mechanism of statistically based sound levels. These permit greater insight into factors contributing to community complaint, such as the occurrence of loud noise events. The modelling detailed discussed in this chapter can be scaled up to prediction for a freeway, and down to prediction for an occasionally trafficked minor road. It is hoped that the superior prediction from this type of modelling will contribute to improved regulatory and design standards associated with road traffic noise.

The modelling procedure describes the stochastic emission characteristics of both individual and the aggregate sources with more flexibility than current international road noise models. A number of parameters affecting the propagation and attenuation of sound from a source to a recipient – e.g. barriers, temperature gradients – are not the subject of this work, as the use of these parameters is both reasonably well documented [ISO 9613,1993], [Concawe,1981] and not controversial. An outcome of this work could, however, be that a review of the methods of implementation of some attenuation parameters may be warranted.

5.2 CURRENT ROAD NOISE MODELS

Following the publication by the UK Department of the Environment of a formal method of calculation, CoRTN [HMSO,1975] road traffic noise impact assessment in Australia has been calculated by treating a roadway as a line source, attenuating at a nominal rate of 3dB per distance doubling perpendicular to the lane axis. The CoRTN assumptions predicting noise impact for a daytime (0700-2200) and night (2200-0700) have continued, with a relatively minor modification to amend the output assessment parameter to an L_{Aeq} in place of the original CoRTN use of L_{A10}.

Internationally, more analytically complex models are in widespread use [Steele, 2001],[Quartieri et al,2009],[Guarnaccia et al,2011],[Guarnaccia,2012] and offer more flexible computation of both noise propagation and input source characteristics. However, assessment using these models continues to be based on the prediction of energy equivalent metrics, or variants thereof [Garg & Maji, 2014] based on stationary conditions. In one or two instances, an estimate of the maximum passby level may be derived. Overall, an expectation for prediction accuracy is considered to be in the order of +/- 3dB(A) [Gulliver et al, 2015],[Prezelj&Murovec,2017] for relatively elementary situations based primarily on discussion of equivalent energy level predictions.

Many criticisms of the limitations of traffic noise models (TNMs), even under relatively stationary conditions are noted. The application of TNMs is usually applied to areas where road traffic is already dominantly present [Guarnaccia,2012] with the outcome that TNMs in application are calibrated and adjusted to site conditions using experimental survey measurements to modify calculation algorithms. This has the effect that the process of generalising TNMs is compromised [Guarnaccia,2012].

Almost all models distinguish between vehicle types – cars, light and heavy trucks, buses [Quartieri et al,2009]. All models predict an energy equivalent (L_{Aeq}) metric, with some also providing L_{A10} and L_{A50} [Quartieri et al,2009]. Many TNMs do not take into account the intrinsically random and variable nature of vehicle flow [Quartieri et al,2009].

The differential between predicted levels using 6 internationally common models, based on normalised conditions is reported to be within a range as little as 2dB(A) [Quartieri et al,2009], however found by measurement in field applications for those same models to be in error as much as +10dB/-15dB [Guarnacci et al 2011] due to inability of the models to take account of random traffic variation. The accuracy, for L_{Aeq} alone, of the CoRTN model most commonly used in Australia has been found to generate a standard deviation, or error, of nominally 5dB(A) [Alam et al,2021]

In an important conclusion to their 2009 paper [Quartieri et al], Quartieri states:

> *"In our opinion, an ideal model should reproduce the random feature of the traffic type, with a well defined distinction between vehicles (also in the same categories, due both to the vehicles conditions and to conductor attitudes) and without any assumption of collective speed."*

Guarnaccia adds to this comment, concluding that:

> *"This approach fails especially in 'not standard' conditions, i.e. when the flow is not fluid or when the number of vehicles is very low (or very high).*
>
> *A dynamical approach, able to evaluate the emission of the single vehicle by considering its position and speed, is needed to better model the road traffic noise phenomenon".*

Responding to the above criticisms a number of researchers have developed a modelling approach designed to simulate sound pressure level-time waveform generated by a passing vehicle flow. This approach facilitates the calculation of equivalent energy levels for an aggregated period of vehicle flow as well as statistical level parameters. In particular, the modelling approach includes provision for the effects of variance in a number of important input parameters [Brown & Tomerini,2011],[DeCoensel et al, 2012],[Iannone et al,2013],[De Coensel et al,2016]. The statistical levels derived using these models have obvious application to the assessment of Emergence-based impact discussed in previous chapters, however models are computationally difficult to scale to more complex situations when compared with statistical simulation methods. The intuitively desirable aspect of modelling vehicular pass-by sound level profiles to consider Emergence is made less attractive when the fact that the background level is non-stationary is recognised. It is also important that level waveform modelling tends to be more informative where loud sound pressure level events are the focus, whereas in many planning conditions it is the cumulative impact affecting lower level statistics, occurring at times of very low vehicle flow, that may be an equally or more important feature of interest – for example the feature noted above in 3.4.3.

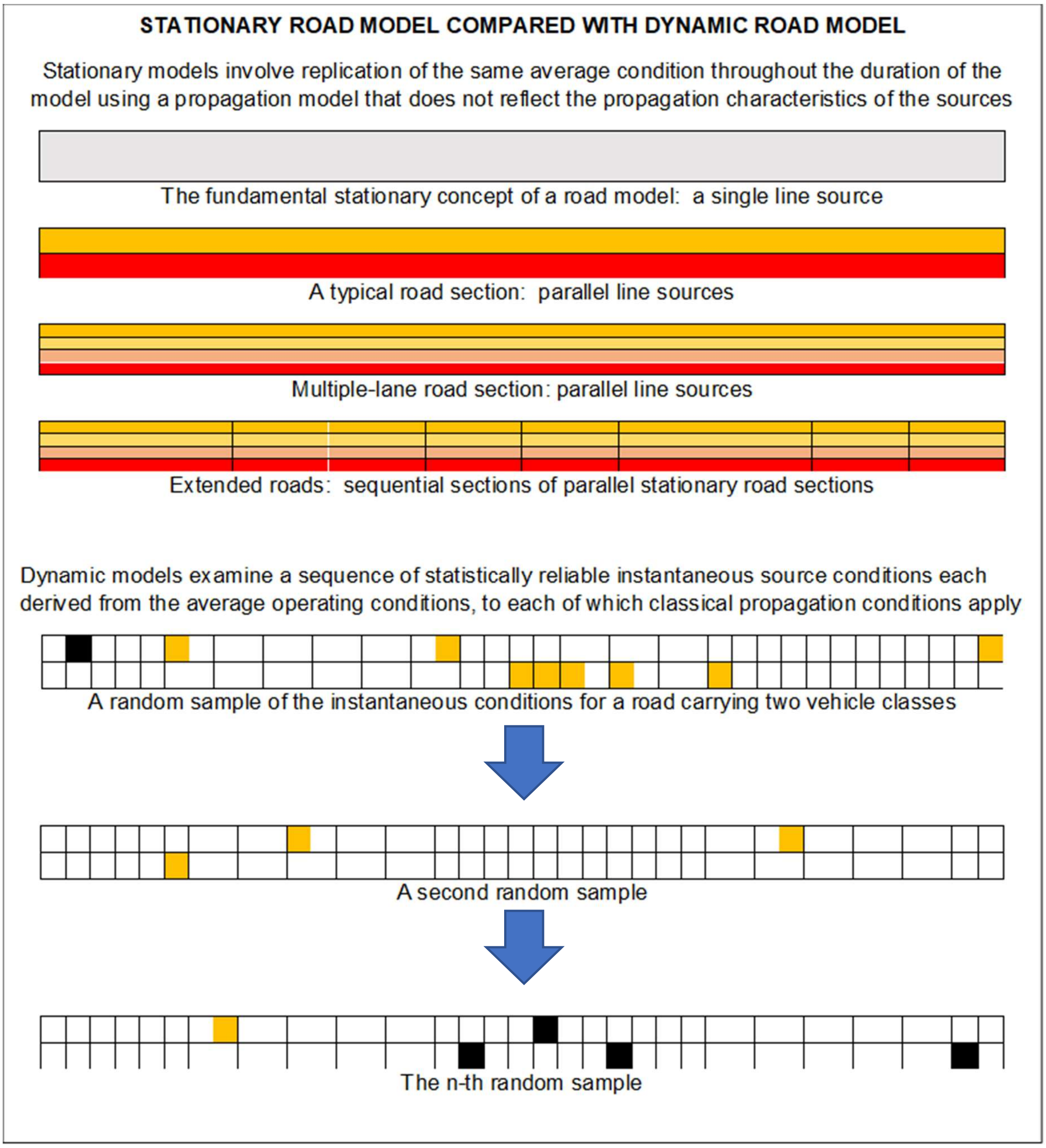
From a slightly different perspective, Iannone et al have recognised that traffic flow is influenced by flow density due to driver safety reactions, observing relationships between vehicle passing speed and vehicle-per-hour flow density [Iannone et al,2011].

The road noise model currently in most common use in Australia is the CoRTN method, which pre-supposes that the sources of road noise may be characterised on a unit-length of carriageway and is predicated on fixed vehicle speed and noise emission. This configuration has some validity where equivalent-energy outcomes are the only metric of interest.

In fact, road traffic noise is both a stochastic and, at times, chaotic noise generating system. In many cases the normal conditions relevant to a land use that constitute road use are entirely impractical for the TNMs mentioned above. In land-use planning investigations, a road has many meanings – a highway, major road, minor road, lane, track, service road, or a carpark. The operational parameters associated with such a range of conditions is vast, for many of which the most critical conditions affecting impact are conditions that are operationally extreme and frequently intermittent. A mine haul track is a classic example. Stationary and energy-averaged conditions are almost universally invalid as a descriptor for impact in these circumstances. Stochastic statistical modelling principles are scalable to the range of situations relevant to land-use planning where current road noise models are not.

5.3 MODELLING A ROAD AS A STOCHASTIC SYSTEM

A road is a system with moving sources, the emission from each of which is likely to be stochastically varying. Stochastic variance arises with both source-distance variation and source emission properties. A road could involve a primary carriageway with a signalled side-road, involving a mobile stochastic system – the main carriageway – and a second stationary system – the vehicles waiting in the side road, as described above in Table 36.



STATIONARY ROAD MODEL COMPARED WITH DYNAMIC ROAD MODEL

Stationary models involve replication of the same average condition throughout the duration of the model using a propagation model that does not reflect the propagation characteristics of the sources

The fundamental stationary concept of a road model: a single line source

A typical road section: parallel line sources

Multiple-lane road section: parallel line sources

Extended roads: sequential sections of parallel stationary road sections

Dynamic models examine a sequence of statistically reliable instantaneous source conditions each derived from the average operating conditions, to each of which classical propagation conditions apply

A random sample of the instantaneous conditions for a road carrying two vehicle classes

A second random sample

The n-th random sample

Figure 27: Road Model Concepts

5.3.1 Fundamentals

The fundamental principle in statistical simulation is that each simulated condition represents an instantaneous collection of point sources operating in aggregate. A vehicle may be modelled as one or more concurrently operating individual point sources representing the vehicle propulsion system, vehicle exhaust and a tyre/road interaction component. The outcomes of the verification modelling for this thesis project found that the use of separate tyre and propulsion sources appears necessary for heavy vehicles, but only of minor importance for cars. In any case the importance of modelling the variance of source location on the carriageway is more important than distinguishing tyre and propulsion components. Assumptions and input constraints to enable statistical modelling are:

- Contributory noise sources are individually identified;
- Sources are mutually incoherent, acoustically, with respect to both frequency and phase;
- Sources are operationally correlated only where the operation of one source may be associated with the operation of another source, but has no effect on the emission level of that other source;
- The statistics (cumulative distribution function) describing the sound power emission characteristics for each source are defined, either analytically or from measurement;

- Operating characteristics of each source – times of operation, location, velocity, can be defined;
- The modelled assessment period is longer than the operating cycle of any input source;
- The statistical parameters describing each source represent a stochastically variable source, but not a chaotically variable or chaotically operational source.

5.3.2 Algorithm

```
For each simulation $(i=1:X)$
For each carriageway (e.g. north / south)  $(1:\phi)$
  For each lane of each carriageway $(1:\varphi)$
      Compute expected mean number of vehicles ($\lambda$) for each class (each carriageway $\varphi$, each lane $\phi$)
         Define actual number (poisson variable) of vehicles ($\beta$) for class for each simulation ($i$)
         Determine, randomly, the position for each of the $\beta$ vehicles
         For each vehicle $(1:\beta)$
            Compute actual transit speed for vehicle
            Compute actual sound power emission
            Compute propagation to recipient $k$
            Compute incident sound pressure level $L_{,\beta,k}$ at recipient $k$
Compute aggregate incident noise level at $k$ from all vehicles $L_{,\varphi,\phi}$ across all lanes
```

With incident sound pressure level at receiver (k) from vehicle (β):

$$Lp_{\beta} = \sum (Lw_{,\beta,k} + N_{DIVERG,\beta,k} + N_{EXTRA,\beta,k} + N_{GROUND,\beta,k} + N_{AIR,\beta,k} + N_{DIFF,\beta,k})$$

where

Lw_{β} is the sound power level emitted by the β-th vehicle

$N_{DIVERG,\beta,k}$ = divergence attenuation $10*\log(Q/4\pi R^2)$ from β to the k-th receiver

$N_{EXTRA,\beta,k}$ = additional attenuation due to atmospheric effects from β to the k-th receiver

$N_{GROUND,\beta,k}$ = attenuation due to ground absorption, from β to the k-th receiver

$N_{AIR,\beta,k}$ = attenuation due to air absorption from β to the k-th receiver

$N_{DIFF,\beta,k}$= attenuation due to diffraction shielding from β to the k-th receiver

Figure 28: Road Noise Model Algorithm

The stochastic road noise model involves the iterative (i.e. *1:X*) application of the algorithm described in Figure 28. A propagation matrix is required for each receiver, the outcome array of *X* aggregate incident noise levels of which enables the determination of immission level statistics at a receiver. The basis of modelling an array of valid aggregate vehicle noise emission conditions – an example of a condition being the vehicle arrangement captured in Figure 29 - is to determine the probability that each vehicle will be in the observed position and the probabilistic sound emission level for each vehicle based on the further probabilistic instantaneous operating condition for each vehicle.

5.3.3 Source Location Probability

A fundamental input parameter is the number of vehicles likely to be situated within a road section at any time. The arrival of a vehicle at a nominated observation point on a road can be considered a Poisson process.

A process is said to be a Poisson Process [Law & Kelton,1991] if:

1. Each event arrives one at a time.
2. The number of arrivals (N) in the time interval (*t,t+s*) is independent of the number of arrivals in the preceding intervals (0,t).
3. The distribution of arrivals in each interval is independent of *t*.

Condition 1 for a poisson process requires an independent calculation to be carried out for each lane and for each vehicle class. Conditions 2 and 3 may break down for periods of congested traffic flow while condition 3 may require a more sophisticated modelling assessment for roads on which traffic flows vary systematically during the day – e.g. distinct peak hour flows. A process for which only condition 3 is not satisfied is termed a ‘nonstationary poisson process’ [Law& Kelton,1991].

It can also be shown [Law&Kelton,1991] that the inter-event time for a poisson process is an independent and identically distributed exponential random variable with mean value $1/\lambda$.

Figure 29: Road traffic source locations are discrete and vary constantly

Mathematically [Mendenhall et al,1981] a poisson process is described by equation E8:

$$P(y) = \frac{\lambda^{y} e^{-\lambda}}{y!} \qquad \textbf{E8}$$

where P is the probability of an event of magnitude y occurring in the interval
λ is the expected (average) number of events in the interval

That is, Equation E8 can be used to determine the probability of *(y)* vehicles being observed on a section of a road carriageway at any time, knowing the mean value *(λ)* that is expected to be on that section of carriageway at that time.

There are convenient properties of a poisson function for the simulation application, one being that the mean value and the variance are numerically equal. This has implications in selecting the assessment interval over which simulation modelling should be carried out.

The value of *λ* may be calculated from the average expected traffic flow for the period of interest for each direction of flow. The vehicular flow on each lane of a multiple-lane road is, theoretically, an independent variable, as is the flow for each class of vehicle within each lane, so it is necessary to establish a modelling rule from which to determine *λ* for each vehicle class flow across multiple lanes.

For roads on which free-flowing traffic cannot be assumed – e.g. a service road - an empirical distribution based on either physical observation at other similar road sites, or determined analytically, may be required. This is also the case for traffic flows within urban areas, at intersections, car parks and the like. While discussion of empirical distributions is beyond the scope of this work, the use of an empirical or logical distribution function is a simple substitution for the poisson distribution in the simulation procedures discussed below. For example, if an access road is known to systematically carry one haul truck every 30 seconds, between the hours of 07:00 and 10:00, a linear sampling rule may be set up accordingly in place of the poisson distribution sampling.

5.3.4 Managing Model Size and Resolution

Resolution of the statistical model is determined by the resolution of the spacing of vehicles along each carriageway. In most cases, vehicles will travel at a substantial speed throughout the duration of the assessment period, so the range of possible contributory locations is inevitably large. For a road with an average posted speed limit of 100km per hour vehicles contributing to statistically based noise levels evaluated over an assessment period of, for example, 1 hour will travel approximately 100 kilometres. This generates specific modelling considerations:

1. The maximum immission sound pressure levels associated with passing vehicles are likely to be generated from locations where those vehicles pass closest to the receiver point – most likely at or near the orthogonal junction projected from the observation point to the carriageway. It is therefore optimum to implement source location modelling to include a position at or near this junction.
2. The source locations from which the lowest immission sound pressure levels are generated – e.g. levels representative of the L_{min} and L_{90} – are likely to be those at the greatest operating distance from the receiver. This translates to a lane modelling requirement comparable in length to the distance travelled by the contributing vehicles over the duration of the assessment interval. These lengths can be very large for a freeway.
3. The problem of large carriageway length increasing computation time can be compensated by assessment over shorter intervals, followed by summation of those shorter period statistics to generate longer assessment intervals, however most approaches result in similar computation burden.
4. In terms of impact, the contribution of road traffic noise to statistical sound pressure levels representing the background is significant. Modelling only the higher occurring noise levels is insufficient to determine the magnitude of impact on a land area from road traffic noise.
5. An efficient model requires sufficient source locations points to ensure the statistics of interest are valid. If a modelling resolution is constrained to, say, 1000 uniformly spaced source locations over 100 kilometres, the first adjacent location from the observer is removed by a distance of 100 metres and, aside from a potentially valid L_{max}, the next lower predictable sound pressure level is of the order of 20 decibels lower. If the interest is in the resultant L_{A90}, the model may be both valid and useful, but potentially of no value for prediction of an L_{A1}.
6. The overall modelling objectives should take account of the simulation run sizes recommended in Figure 26.

The relative proximity of adjacent location points, mentioned in point 5 above, along the carriageway affects the resolution able to be achieved by the model for sampling of the higher sound pressure level extremities, while the overall carriage length affects the validity of the model for the lowest sound pressure level extremities.

$$x \geq \frac{0.1}{RN} \qquad \textbf{E9}$$

where

x is the shortest distance from observer to carriageway, metre
R is the required prediction accuracy in dB $(0.1 - 0.5dB)$, and
N is the lowest percentile required $(N > 0)$

The limit to validity for the highest L_{AN} percentile levels (i.e. N<1) is a function of the laneway-to-receiver distance and of the resolution intended for the calculation accuracy. This relationship resolves to the relatively simple limit relationship of equation E9 for carriageway locations determined to the nearest one-metre. Checking compliance with equation E9 is unlikely to be necessary unless modelling of $L_{A0.1}$ is contemplated.

5.3.5 Time and Frequency Compression

Because the velocity of sound (c) is finite, sound arriving at the observer from the furthest vehicle will have left the source earlier than the sound from the nearest vehicle. This has the effect of skewing the location of the vehicle at the instant of noise immission from the vehicle actual emission location toward the direction of travel. This compresses time and distance in the case of vehicles travelling toward the observer and extends time and distance when vehicles are travelling away – the origin of the familiar doppler effect. While this effect may have some influence on the A-weighted sound levels of vehicles that may warrant further consideration, it is ignored for the purposes of this study on the basis that any shift in A-weighted level is anticipated to be small.

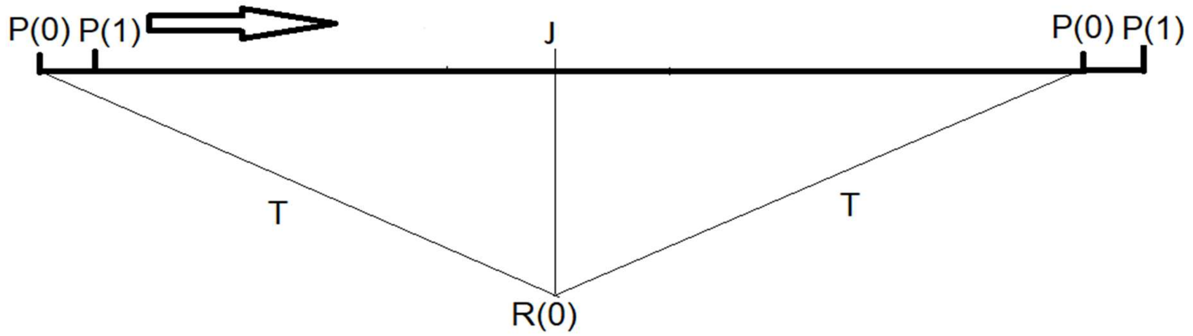


Figure 30: Source-Receiver space-time relationship

At the commencing instant of an assessment interval the event horizon for sound arriving at the receiver is determined by the elapsed time (T) equal to the speed of sound (c) multiplied by the distance from the source to the receiver at the instant of emission. During the elapsed time of the sound transmission interval, the source will have moved from the position of emission shown in Figure 30 as P(0) to position P(1). A snapshot of the source configuration contributing to the aggregate instantaneous immission sound level is progressively displaced, with the approaching vehicle sources appearing to be closer together than they actually were acoustically, and the departing vehicle sources appearing to be further apart than they actually were at that instant of emission.

It is apparent from Figure 30, however, that the carriageway length over which the contributing sources are distributed remains constant, but displaced. Providing the locations and therefore distance between two sources concurrently located on a carriageway are independent variables, which they are by definition of the poisson variable, there is no statistical reason to adjust the location of sources to account for distance distortion due to these compression effects. Furthermore, skewing effects are opposed for most road sections due to the presences of both northbound and southbound carriageways, usually operating at equivalent or similar vehicle passing speeds. Distance compression effects can be ignored, for practical carriageway lengths, as the sensitivity of immission sound pressure levels to incremental distance declines exponentially as distance increases.

5.3.6 Statistical Foundation

For a straight section of carriageway in a free-field environment, the effect of carriageway length on the validity of statistical sound pressure levels is symmetrical about the perpendicular junction from the observation location to the carriageway, marginally skewed as above. That is, if source vehicles are expected to travel X metres during the assessment period – e.g. 100km at a speed of 100km per hour – the locations of the sources contributing to the lowest immission sound levels are locations at or near the beginning or end of the carriageway. An ideal model configuration will involve approximately equal carriageway sections either side of a mid-point, at or near the junction of an orthogonal projection line from the observer to the carriageway.

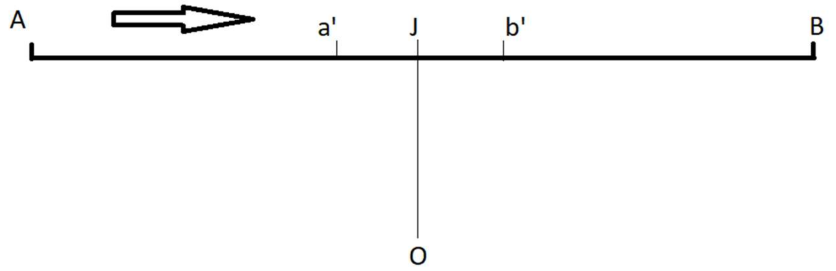


Figure 31: Carriageway Schematic

For the general free-field propagation case, the highest immission sound pressure levels at observer (O) will be generated by vehicles at, or near, location J. For an interval a'b' positioned symmetrically about position J, the event horizon generating immission sound pressure levels equal to or higher than L_N will be described by the probability that vehicle x lies within the interval a'b'. Notwithstanding that the probability that a vehicle (*x*) will be located within an interval a'b' at any time is less than or equal to 1, the number of vehicles passing A, a', J, b' and B per unit of time will be a constant (Q).

For the carriageway AB, where AB is determined as the product of the mean vehicle speed and the assessment period (T), the probability that a vehicle will be located on the carriageway is described following, to deduce Equation E10:

$$AB = V \times T$$

$$a'b' = V \times t$$

$$P(A \leq x \leq B) = 1$$

$$P(a' \leq x \leq b') = \frac{a'b'}{AB} \qquad \textbf{E10}$$

Under lower flow conditions the inequality of Equation E11 is progressively more important– e.g. a mine haul road - as it describes the length of carriageway that should be modelled to determine the statistics of interest.

$$a'b' \geq \frac{AB*N}{100*C} \qquad \textbf{E11}$$

where

a'b' is the modelled carriageway length
AB is the carriageway length determined in Equation E10
C is the statistical compression as a function of number of events per period and
N is the statistical percentile exceedance level of interest.

The statistical compression factor, C, used in Equation E11 is described in Figure 32.

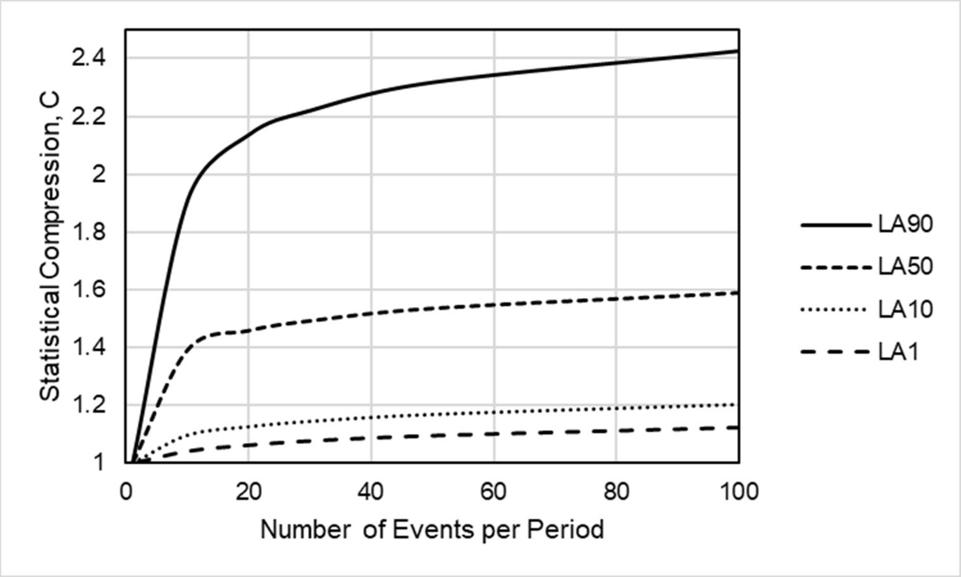


Figure 32: Statistical Compression due to Number of Events

For example, a carriageway designed for a 100km/hr passing speed, the recommended modelling length is suggested by Figure 33 for a range of statistical parameters. Obviously, modelling a road carrying 50km/hr traffic will require half these lengths, while modelling for shorter intervals would reduce the carriageway length but would correspondingly reduce the number of events per period.

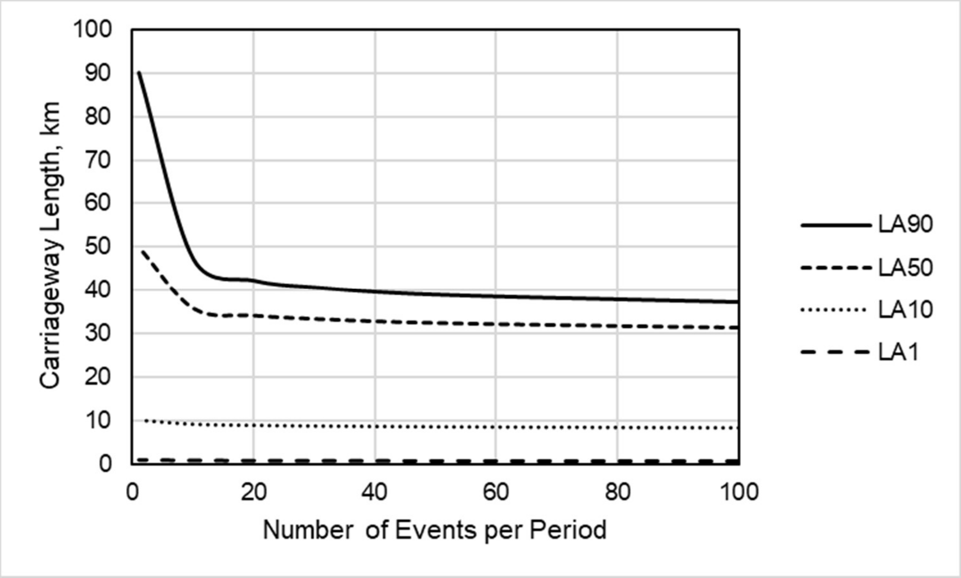


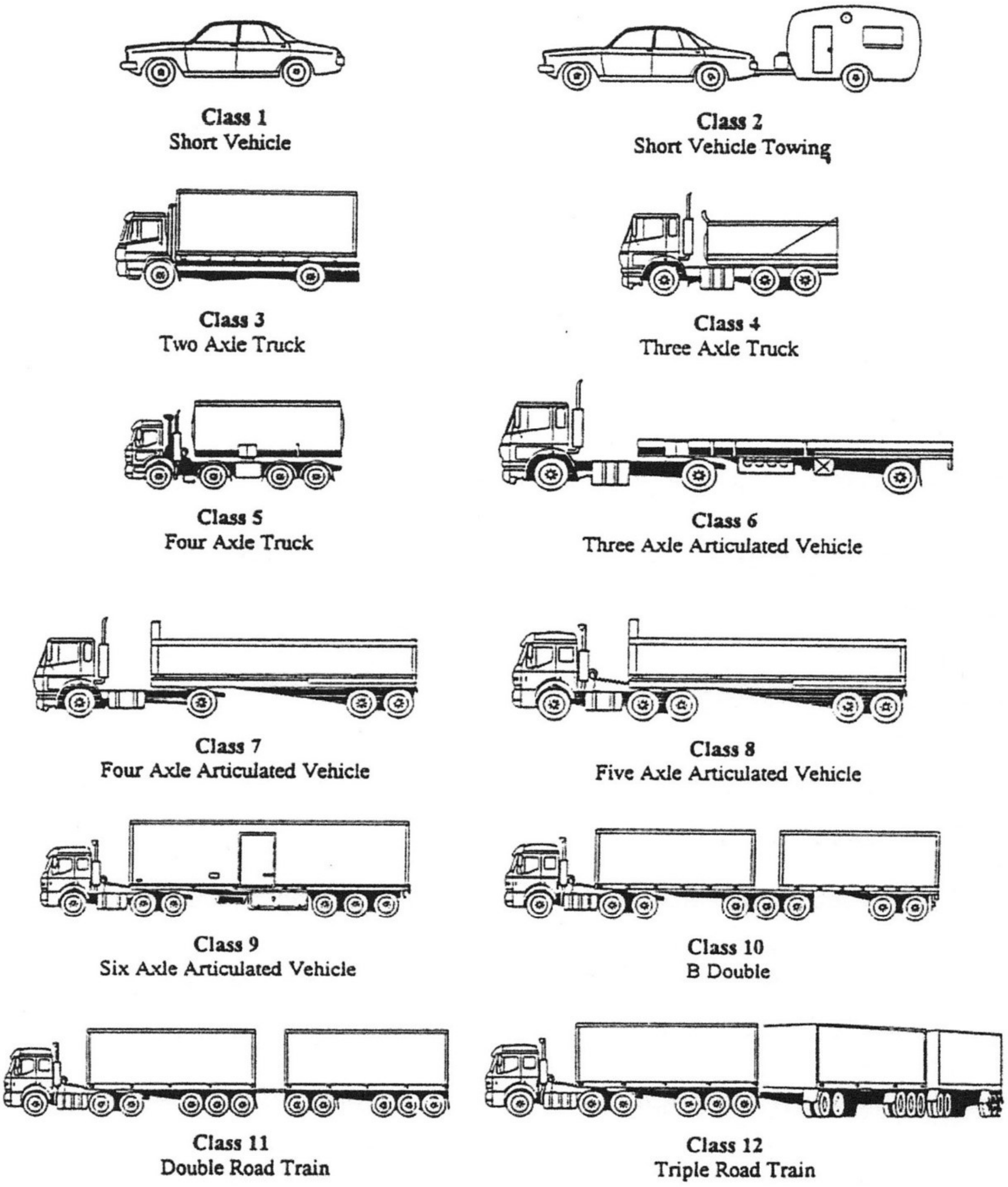
Figure 33: Carriageway modelling length for 100km vehicle speed

Finally, If the subject of interest in a road impact-modelling investigation is primarily level maxima, such as may be relevant during design of a new built environment project, the necessary modelled carriageway length may be quite short. For environmental impact assessment, for which lower percentile levels are as or more important than passing maxima, it is necessary to model quite long lengths.

5.3.7 Vehicle Types

Automatic vehicle counters are in widespread use in Australia, from which vehicle flow data for existing roads classified according to the Austroads vehicle classification system [Austroads,2006]. Sophisticated flow data can be compiled, identifying grouped or individual vehicle information typically including average flow rates, vehicle classes with speed distributions, and inter-vehicle spacing. These types of data provide reliable input data for road noise modelling purposes.

For this project, vehicle classifications were restricted to two classes of input data, being classes 1 and 2 combined representing cars, and classes 3-12 combined representing trucks.



Class 1
Short Vehicle

Class 2
Short Vehicle Towing

Class 3
Two Axle Truck

Class 4
Three Axle Truck

Class 5
Four Axle Truck

Class 6
Three Axle Articulated Vehicle

Class 7
Four Axle Articulated Vehicle

Class 8
Five Axle Articulated Vehicle

Class 9
Six Axle Articulated Vehicle

Class 10
B Double

Class 11
Double Road Train

Class 12
Triple Road Train

Figure 34: Austroads Automatic Vehicle Classification – Part 1

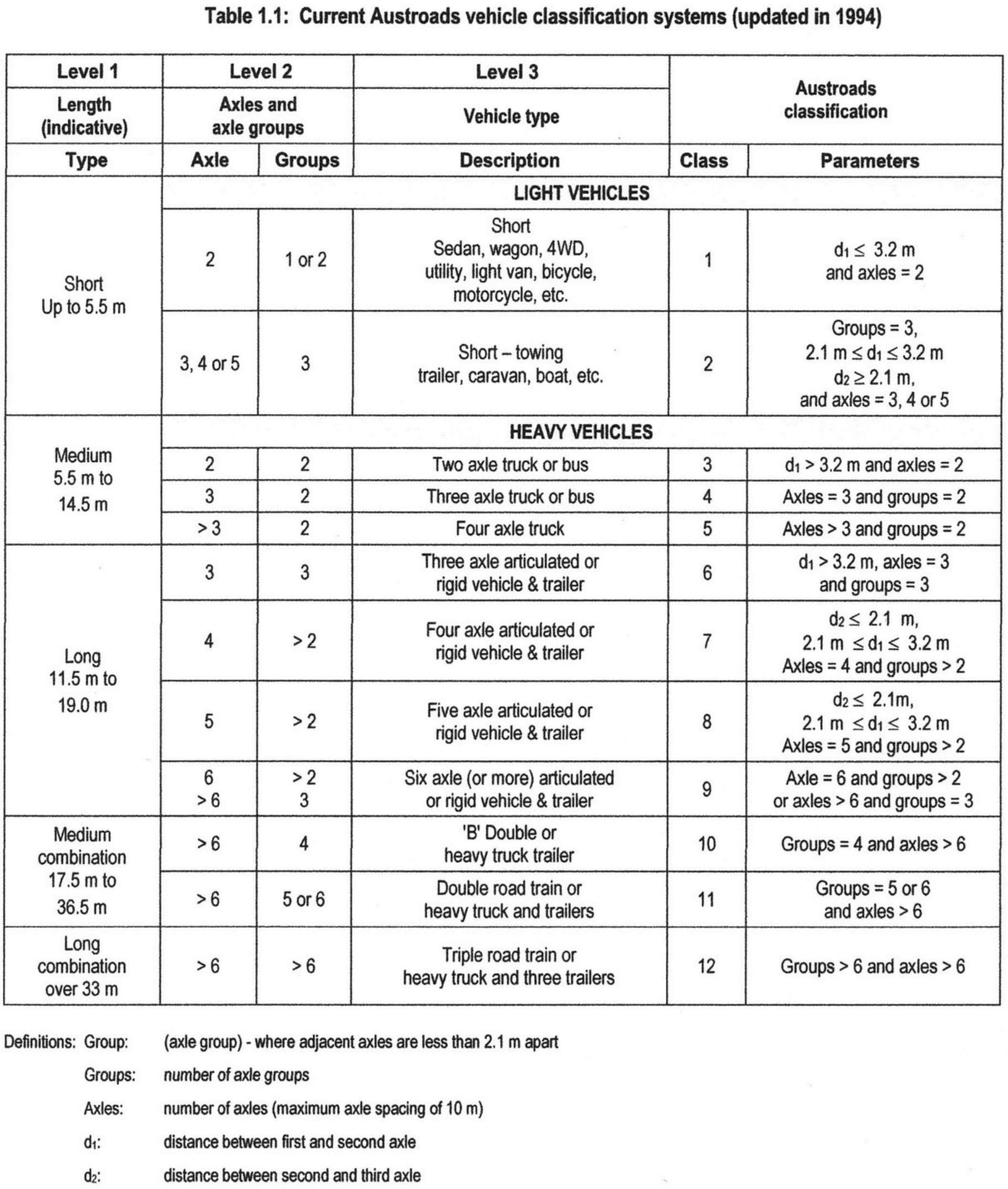


Table 1.1: Current Austroads vehicle classification systems (updated in 1994)

Level 1	Level 2		Level 3	Austroads classification	
Length (indicative)	Axles and axle groups		Vehicle type		
Type	Axle	Groups	Description	Class	Parameters
	LIGHT VEHICLES				
Short Up to 5.5 m	2	1 or 2	Short Sedan, wagon, 4WD, utility, light van, bicycle, motorcycle, etc.	1	$d_1 \leq 3.2$ m and axles = 2
	3, 4 or 5	3	Short – towing trailer, caravan, boat, etc.	2	Groups = 3, $2.1 \text{ m} \leq d_1 \leq 3.2$ m $d_2 \geq 2.1$ m, and axles = 3, 4 or 5
	HEAVY VEHICLES				
Medium 5.5 m to 14.5 m	2	2	Two axle truck or bus	3	$d_1 > 3.2$ m and axles = 2
	3	2	Three axle truck or bus	4	Axles = 3 and groups = 2
	> 3	2	Four axle truck	5	Axles > 3 and groups = 2
Long 11.5 m to 19.0 m	3	3	Three axle articulated or rigid vehicle & trailer	6	$d_1 > 3.2$ m, axles = 3 and groups = 3
	4	> 2	Four axle articulated or rigid vehicle & trailer	7	$d_2 \leq 2.1$ m, $2.1 \text{ m} \leq d_1 \leq 3.2$ m Axles = 4 and groups > 2
	5	> 2	Five axle articulated or rigid vehicle & trailer	8	$d_2 \leq 2.1$m, $2.1 \text{ m} \leq d_1 \leq 3.2$ m Axles = 5 and groups > 2
	6 > 6	> 2 3	Six axle (or more) articulated or rigid vehicle & trailer	9	Axle = 6 and groups > 2 or axles > 6 and groups = 3
Medium combination 17.5 m to 36.5 m	> 6	4	'B' Double or heavy truck trailer	10	Groups = 4 and axles > 6
	> 6	5 or 6	Double road train or heavy truck and trailers	11	Groups = 5 or 6 and axles > 6
Long combination over 33 m	> 6	> 6	Triple road train or heavy truck and three trailers	12	Groups > 6 and axles > 6

Definitions:		
Definitions:	Group:	(axle group) - where adjacent axles are less than 2.1 m apart
	Groups:	number of axle groups
	Axles:	number of axles (maximum axle spacing of 10 m)
	d_1:	distance between first and second axle
	d_2:	distance between second and third axle

Figure 35: Austroads Automatic Vehicle Classification – Part 2

5.3.8 Summarising model inputs

The inputs and the associated statistical variance required to model the noise from a roadway include:

1. Carriageway definition – a sequence of x, y and z coordinates defining each segment
2. A receiver location – z, y, z coordinates;
3. Posted speed limit – for each segment of the road carriageway;
4. Vehicle classes to be modelled – In Australia, 12 classifications are used following the AUSTROADS classification system, classes 1 and 2 combined identifying light vehicles, and classes 3 to 12 heavy vehicles [Austroads, 2006];
5. Average expected vehicle flow for each vehicle class – commonly estimated for design purposes as an average annual daily transit (AADT) but can refer to any appropriate interval of interest. Traffic flow data is used to calculate the expected vehicle flow for a period of interest (e.g. 1 hour). The number of vehicles arriving at a given location is a poisson variable, using which an instantaneous vehicle flow is calculated for each simulation calculation.
6. Vehicle passby speed – estimated empirically, based on observed vehicle passby speed. This has been modelled as an expected mean passby speed, derived from field observation, with an associated standard

deviation. Using these parameters, an actual vehicle transit speed is calculated for each vehicle for each simulation calculation.

7. Individual vehicle noise generation characteristics for each vehicle class. For this project, source sound power levels are modelled using empirical formulae for each vehicle class, also derived from field surveys and including an expected standard deviation in emission level. Using these parameters, an actual vehicle noise emission is calculated for each vehicle for each simulation calculation.

Modelling sound transmission from the source to receiver may also involve stochastic processes, such as wind or temperature gradients. These aspects are not examined here, however, attenuation parameters could be modelled as an expected average statistical condition, with an allowance for variance, if required.

5.4 VALIDATING STATISTICAL MODEL INPUTS

Input data for road noise models in current use require, generally, input data relevant to an equal-energy model output “calibrated” to a reference distance [Bartolomaeus,2012], [Bernhard & Wayson,2005], [Can & Aumond,2018], [Gulliver et al,.2015], [Steele,2001]. A source of error is the assumption that vehicle transit speed is both uniform and constant [Iannone et al,2013]. Other researchers have examined individual source sound power levels including measures of source emission variance [DeCoensel, Brown & Tomerini,2016], [Pamanikabud, Tansatcha & Brown,2008], [RWTUEV,2005], [Schruers, Brown & Tomerini,2011]. In preference to utilising published source emission formulae of potentially uncertain origin, field surveying has been used in this thesis project as it was considered the role of input emission modelling on the outcome statistics would be better understood. This has informed appropriate allowance for variance in both vehicle vehicle flow numbers, individual vehicle passing speed and individual source emission, in preference to simply an overall source emission level.

For the statistical modelling algorithm described by Figure 28 classical Newtonian ISO 2613 calculations are involved, based on energy dispersion originating in a source emission sound power level. In addition to the ability to model statistical outcomes, this principle has other benefits – source ranking and contribution to an eventual outcome prediction is unequivocal, while projection of outcomes from changing source types, such as electric vehicles, is possible.

Field surveys were undertaken to determine reasonable input parameters for both magnitude and variation of expected vehicle passby speed and of source emission sound power levels as a function of both speed and vehicle class. The locations selected for input data surveys, largely due to convenience, were sections of the Princes Highway and at one location on Bolong Road, NSW, between the townships of Berry and Nowra. Data was obtained at six survey locations, for measurement distances ranging from 6.5 metre to 15 metre from centreline of the nearest lane on road sections with posted speed limits from 50 to 100 kph. Instrumentation used a Rion NA28 precision meter and pocket speed radar. Road sections involved single northbound and southbound carriageways, with vehicle class, passby speed and maximum passby sound pressure level being recorded. This data was subsequently analysed to provide source noise generation parameters discussed below in Equations E12, E13 and E14. Importantly, source level survey locations were different from the locations subsequently selected for the verification model surveys. The source input data and the subsequent modelled output findings were therefore mutually independent.

Validation of the statistical road noise model involved:

1. Gathering verified input data, by field survey, for vehicle source sound power levels as a function of vehicle type and passby speed. This data was, in turn, verified by comparison with independently reported source level data.
2. Establishing the likely range of vehicle passby speed compared with posted speed limit, again as a function of vehicle type.

5.4.1 Modelling Vehicle Pass-by Speed

Modelling of expected vehicle pass-by speed could either be deemed to be the posted speed limit on the chosen section of road, or the expected individual vehicle speeds making up the traffic flow, depending on the specific dispersion algorithm adopted for a model. The modelling for this project used the latter. When surveying, it is desirable to record both the vehicle pass-by speed and the posted speed limit, as either may be appropriate for future modelling.

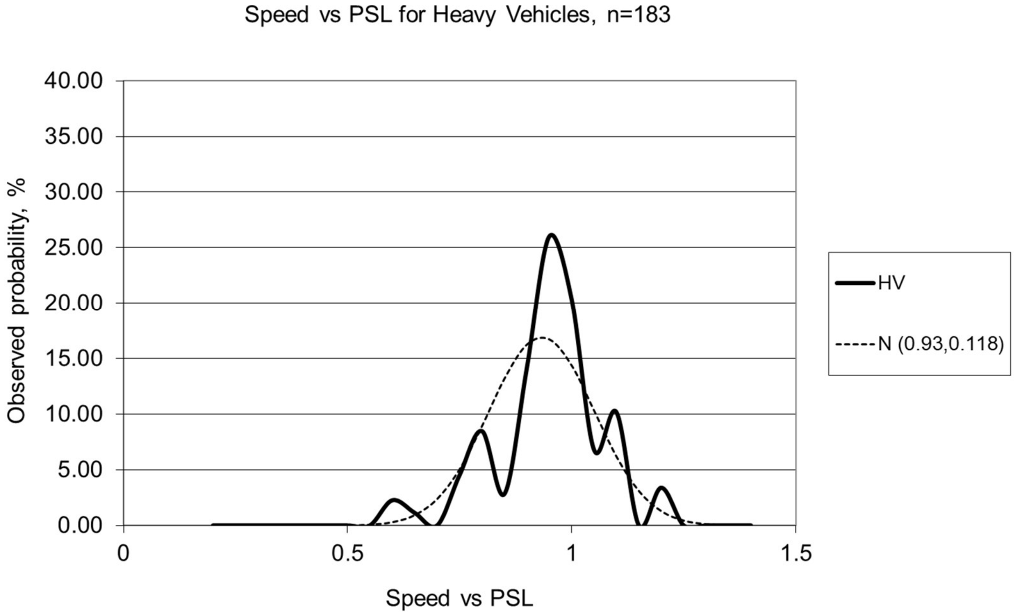


Figure 36: Observed Speed vs Posted Speed Limit for Trucks

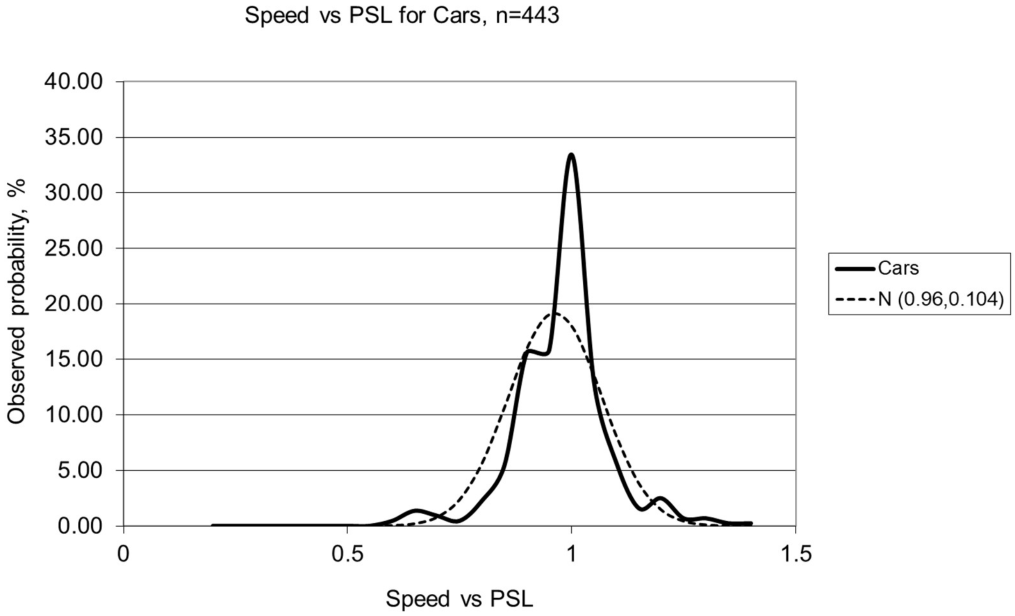


Figure 37: Observed Speed vs Posted Speed Limit for Cars

Figure 36 summarises the survey results for heavy vehicle speed as a ratio of posted speed limit, together with a normal distribution defined by the equivalent mean and standard deviation. Vehicle pass-by grouping effects are apparent, while the use of the normal distribution in modelling can be expected to generate a slightly wider spread of simulated data than was observed in the field. The range of simulated and field data are quite close. Figure 37 summarises similar field data compiled for cars. Both figures suggest that flow saturation affected the traffic flow, with vehicles tending to move in groups at a group speed. The use of a normal distribution is considered satisfactory, predicting comparable individual vehicle variance from the expected mean speed within a bound of +/- 1 standard deviation.

Using the field survey observations, average and standard deviation vehicle speed for light and heavy vehicles is summarised in Equations E12 and E13:

EPS(light) = 0.963PSL with a standard deviation of 0.104PSL **E12**

and

EPS(hv) = 0.932PSL with a standard deviation of 0.118PSL **E13**

where

EPS(cars) is the expected average passby speed for cars, kph

EPS(hv) is the expected average passby speed for heavy vehicles, kph

PSL is posted speed limit for the road section in kilometres per hour

5.4.2 Vehicle Sound Power Level Emission

No effect of gradient on vehicle noise emission could be identified for the road inclinations at sites available for field survey work, none of which exceeded 2 degrees,. The standard error of the estimated sound power emission level vs speed compared with the modelled emission was found to be lowest for regression models in which road inclination effect was set to zero.

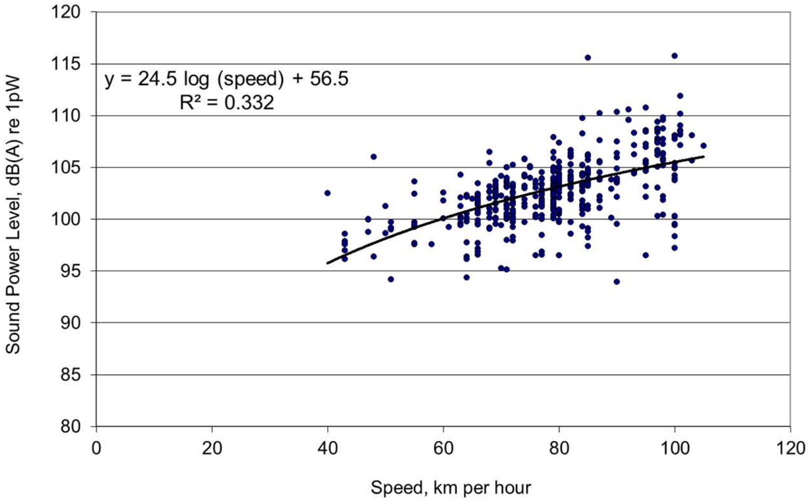


Figure 38: Sound Power Level vs Speed for cars

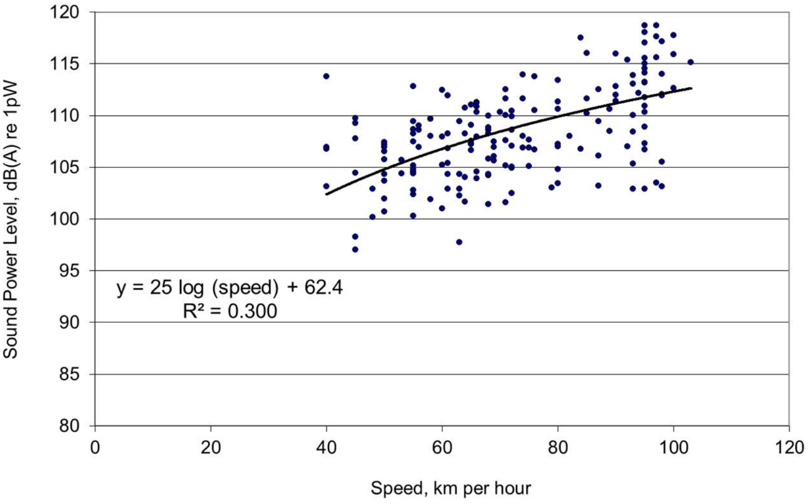


Figure 39: Sound Power Level vs Speed for Trucks

More unexpectedly, the highest correlation between sound power level and passby speed ($R^2=0.36$) for cars was found to be for a polynomial model. The correlation for sound power level vs Log(speed) was found to be almost equal ($R^2=0.33$) and was adopted for reasons of industry convention.

$$Lw_{i,j} = M*\log(V) + K_0 + VAR \quad dB(A)\ re\ 1pW \qquad \textbf{E14}$$

where

$Lw_{i,j}$ is the sound power level of the j'th vehicle, class i, dB(A) re 1pW
V is the vehicle transit speed in km/hr
Input parameters M and K_0 are listed in Table 38 for the class, and
VAR is the standard error in sound power emission for the class.

The parameters used in Equation E14 and summarised below in Table 38 have been derived from surveyed (N samples) maximum pass-by sound pressure level, converted to sound power level based on Q=2, for a theoretical source and microphone height of 1.1m and a source to microphone distance measured perpendicularly from lane centre to microphone position.

Table 38: Vehicle sound power level emission parameters

Vehicle class i	M	K_0	N	Std Error, dB
Cars – single source	24.5	56.5	443	2.62
Cars – tyre component	10	82		
Cars – propulsion component	100	-95		
Heavy Vehicles single source	25	62.4	177	4.03
Heavy Vehicle tyre	10	89		
Heavy Vehicle propulsion	100	-89		

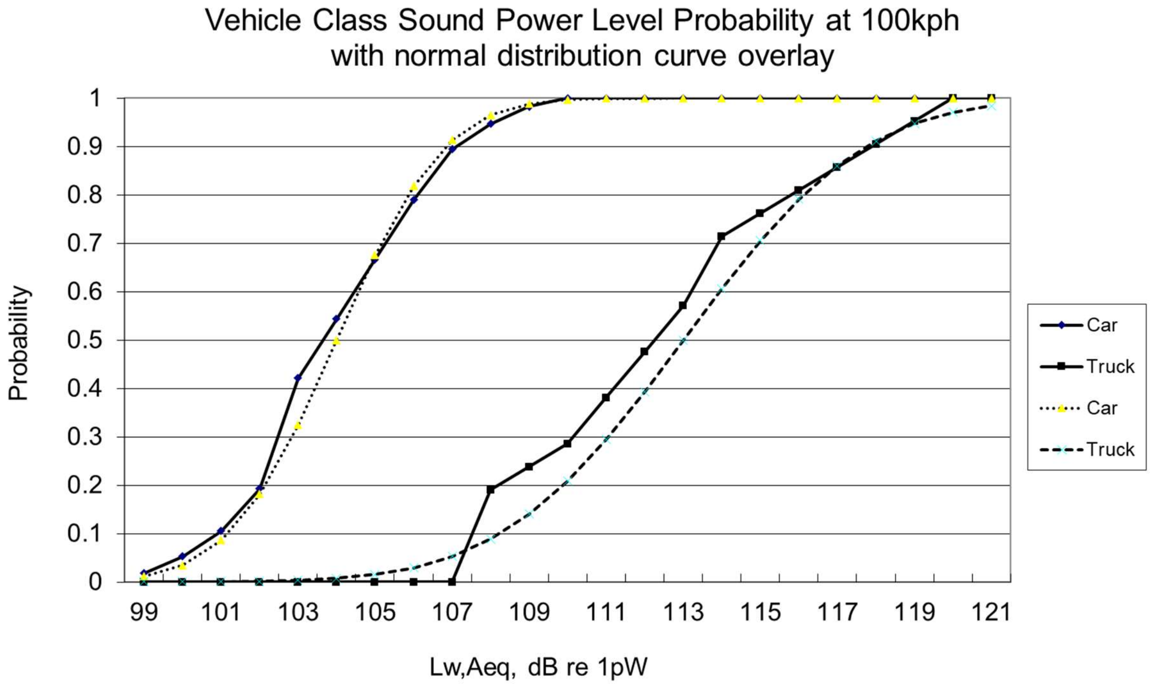


Figure 40: Source Surveyed Level Distribution

Before application of Table 38 parameters to a model, the survey level findings were benchmarked by comparison with independent literature findings [Schreurs et al,2011] with the findings summarised in Table 39 for cars, and Table 40 for heavy vehicles.

Table 39: Sound Power Levels for Cars vs Speed

Vehicle Speed, km/hr	60	70	80	90	100
Mean Survey Level this project	100	101	103	104	106
Separate tyre & engine model cars	100	101	102	104	107
Single source model cars	100	102	103	104	106
Schreurs, Brown & Tomerini paper	102	104	103	106	107
Imagine	101	102	104	105	106
Harmonoise	102	103	103	104	105

Table 40: Sound Power Levels for Heavy Vehicles vs Speed

Vehicle Speed, km/hr	60	70	80	90	100
Mean Survey Level this project	106	108	108	110	114
Separate tyre & engine model trucks	107	108	109	112	115
Single source model trucks	107	109	110	111	112
Non-Articulated Trucks					
Schreurs, Brown & Tomerini paper	104	107	109	110	110
Imagine	107	108	109	110	110
Harmonoise	108	109	110	111	112
Articulated Trucks					
Schreurs, Brown & Tomerini paper	109	111	112	115	114
Imagine	110	111	112	113	113
Harmonoise	114	115	115	117	118

5.4.3 Input Data Survey Observations

A large data scatter is observed. This is typical of road traffic noise level variances reported elsewhere [Alberola et al, 2005]. Survey observation was that chaotic operational parameters commonly affect noise generation in otherwise similar situations - driver behaviour, vehicular speed grouping, slower vehicle flow impediment, unstructured changes to engine operating load, road wear and surface imperfections. Some aspects of road noise variation show stochastic variance, while others are chaotic and unpredictable. Modelling procedures based on variance determined from field surveys is strongly recommended, rather than under controlled or laboratory conditions such as vehicle certification or labelling surveys.

In recognition of convention, log-linear data models for noise generation were used based on the logarithm of vehicle speed, despite log-linear relationships not being the best fit. Relatively poor R-squared model variance was obtained for all model regression analyses.

Vehicle speed variation was observed to conform, reasonably, to a normal distribution, though a secondary factor probably relating to vehicle spacing and grouping tendency was also observed, itself a function of speed and volume flow. Other speed related effects were observed to occur in the subsequent verification model analyses, particularly the factor that as vehicular flow density increases so the average pass-by speed tends to diminish.

The range in passing speed observed for heavy vehicles was approximately 40 kilometres per hour to approximately 110 kilometres per hour. The mean sound power level for heavy vehicles from the survey results in the data band centred on 40 kilometres per hour was 5dB(A) higher than the data trend otherwise applying. This survey findings suggests an addition of 5dB(A) may be required for modelling sound level emission from low speed heavy vehicles, say at or below 45 kilometres per hour, to account for the more variable throttle settings apparently occurring in such conditions.

It was also noted that the sound power level of heavy vehicles was most predictable (i.e. the modelled power level generated the lowest error vs survey) at approximately 70 kilometre per hour, above or below which the standard deviation of the observed sound power levels systematically increased. It is hypothesised that these trends of increasing variability arise from the progressively more variable throttle settings thought to apply at progressively lower speeds, and perhaps more vehicle body noise and road surface irregularity interaction noise at progressively higher speeds.

It was also noteworthy that no trend of increasing variability was observed at low speeds for cars, however a similar increasingly variable trend above approximately 70 kilometres per hour was evident.

Both of these aspects warrant further investigation – adjustment to propulsion sound power emission as a function of lowering speed, and introduction of an additional vehicle body noise parameter at speeds above 70 kilometres per hour. None of these potential factors have been applied for the modelling studies reported in this chapter.

Sources of potential error in the application of this input data to other road situations should, however, be noted:

1. Vehicle and driver composition drew from a relatively small region and types of vehicles and driver behaviour could differ from that of other regions.
2. The surveyed road sections service a mix of metropolitan, industrial and rural areas.
3. The dataset applies to a generic and non-special road surface type. Surveying included areas for which recent sprayseal bitumen had been laid together with locations at which worn graded asphalt was typical for a road having had a number of years usage.
4. Pocket radar speed measurement error was unknown and speed records may have included influence from unobserved sources – wildlife, concurrent vehicles etc.

5.5 MODEL OUTPUT VALIDATION

5.5.1 Survey and Model Methods

Two site surveys were carried out, each of nominally one week duration, during which classified vehicle counts were conducted, together with statistical noise level surveying. Noise levels were monitored and hourly statistical noise levels ($L_{A,N,1hr}$) were compiled. Using input data from the classified vehicle counts, statistical noise levels were then predicted using the modelled algorithm and compared with the surveyed noise levels. The prediction error outcomes were then examined. Importantly, road surface type was not included as a parameter for the validation modelling. Further, each vehicle was modelled as a single point source at a nominal height of 1 metre. Analysis showed that the influence of statistical variance in both vehicle speed and source sound power was orders of magnitude more important than changes likely to arise from discrimination between individual vehicle source component locations. For the objective of this project – to accurately model the variable source–to-receiver relationships – these parameters are not important. They could, however, be readily included.

Two independent surveys were carried out, each involving a road section with single carriageway in each direction and a posted speed limit of 100 kilometres per hour. Inputs obtained from the classified vehicle counts and required for the two verification test models included average passby speed together with the poisson variable parameters relating to each vehicle class and each sample period using the methods discussed above and in Equation 4-1.

The survey locations were:

- Survey 1: Bolong Road, Seven Mile Beach, approximately 1 kilometre south of Beach Rd. This is a secondary road with a load restriction and carries primarily light vehicle flows. Traffic patterns include a small proportion of motor cycles that are not distinguished in the light vehicle traffic count system.
- Survey 2: Picton Road, Cordeaux, approximately 9.5 kilometres south of Wilton. This is a major thoroughfare carrying a large proportion of heavy vehicles. Survey was carried out at one of a small number of remaining sections of undivided single carriageway.

5.5.2 Measurements and Model Input Data

Each survey gathered the following data:

1. Statistical noise levels determined over consecutive periods of 15 minutes and 1 hour duration, over a period of nominally five days each, for two microphone positions at one site and a single position for the second. Data was obtained using an ARL Ngara noise level logger, and a Rion NA28 sound level meter.

2. Concurrent classified vehicle counts, using the MetroCount logging system to record vehicle classification and passby speed for each carriageway. Data was then analysed to provide aggregate flow for each class, mean vehicle speed against class and mean vehicle speed against flow rate, for each observation period.

The traffic flow data was consolidated to aggregate light and heavy vehicle flow for each 1-hour period. These data were then used as input to the numerical model described above, with incident noise modelled at the microphone positions used for each survey. The input parameters used for each predictive model were:

3. Vehicular flow for each class (light and heavy) and each direction for each sequential period, modelled to an expected flow for each iteration randomly located along each carriageway
4. Pass-by speed for each individual vehicle modelled according to Equations E11 or E12.
5. Noise emission for each individual vehicle modelled according to Equation E13.

Figure 41: Bolong Road Survey Site

Figure 42: Picton Road Survey Site

5.5.3 Technical modelling aspects

A number of technical aspects adopted for the modelling are summarised below:

- Where variance is incorporated into the modelling –actual vs expected pass-by speed and actual vs expected source sound power level – the variance was modelled using a normal distribution and a multiplier of +/- 1 times the standard deviation for the relevant input data. Experimentation using higher multipliers – e.g. 1.645 for a 90% confidence interval – produced essentially unchanged mean predicted outcomes however the standard deviation of the errors increased, particularly for L_{Amax}. It was concluded that a larger multiplier was unproductive.
- Individual source energy divergence is calculated using the inverse square propagation rule.
- Q for dispersion modelling was investigated at a range of values between 1 and 2. A value of 2 for Q would reflect a fully reflective ground plane, while a value of 1 represents a fully absorptive ground plane. The most reliable modelling outcomes appeared to involve Q=2, particularly when the effects of ground absorption are included in the model. Furthermore, conversion of field survey data for source input was processed on an assumption of Q=2.
- Extra attenuation due to ground effects, forest vegetation scattering, shielding and the like was initially investigated using a linear function ranging in value from 0-0.2dB(A) per 100 metre but discarded.
- Ground absorption was modelled by fitting a curve to the mean frequency curves presented in Concawe [Concawe,1981] according to Figure 43 for distances of 100m and greater
- A number of experimental runs incorporating shielding due to intervening ground contour or dense forestry obstruction were modelled according to a generic shielding rate described in Figure 45, for source to receiver distances greater than 1 kilometre. Ultimately, it was decided that results for modelling with no provision for shielding would be documented.
- Air absorption was applied according to Figure 44. Figure 44 was derived using air absorption rates recommended by Concawe [Concawe,1981] in air at 15°C applied over a number of distances to a range of octave band vehicle noise emission spectra, then consolidated to A-weighted attenuation rates.
- Wind effects were set to zero
- To reduce the uncertainty of vehicle location, field studies were carried out on two-laned road sections only. Modelling can, however, be based on any number and configuration of lanes.
- Modelling was carried out comparing predicted results with survey results for sequential hourly periods. This was, in part, necessary to match the reporting format of the commissioned independent vehicle flow surveys, but also so as to make optimum use of the number of sample periods able to be compared. There was insufficient data to enable a reliable comparison of modelling vs survey for the typical L_{day}, L_{eve} and L_{night} parameters also used in road design criteria.
- Modelling of carriageway coordinates was reasonably careful to distances of approximately 1 kilometre from the survey measurement point, thereafter being modelled as relatively simple and long straight extensions. This simplification may have had consequences to the lower percentile levels as discussed later.

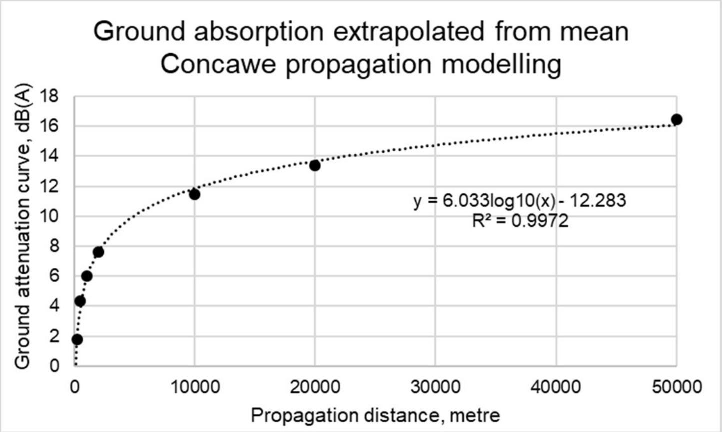


Figure 43: Modelled ground absorption, dB(A) (estimated from Concawe)

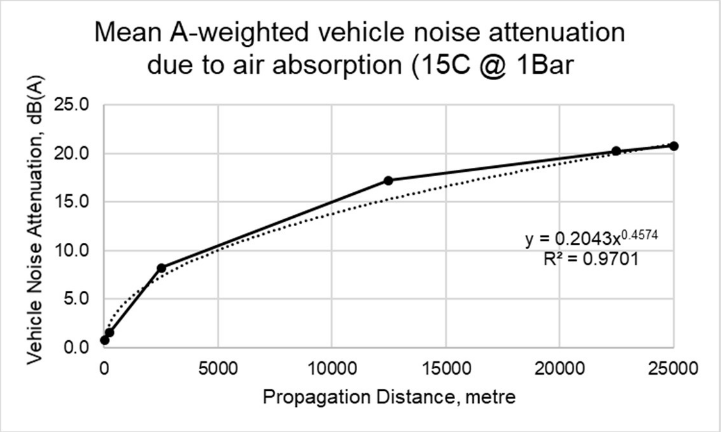


Figure 44: Modelled A-weighted Air Absorption vs Distance for Traffic

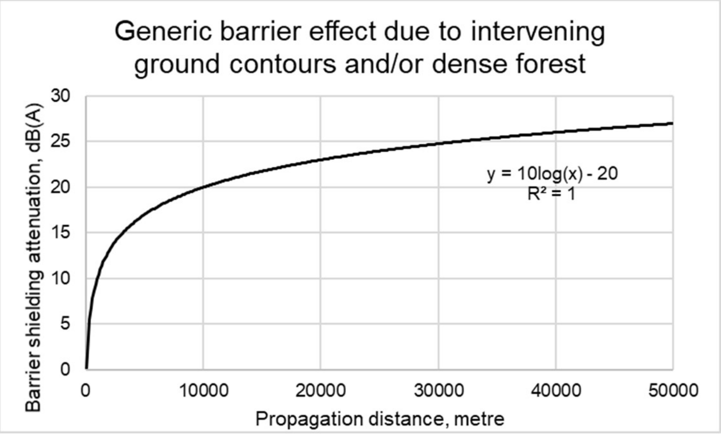


Figure 45: Modelled barrier attenuation Effects, dB(A)

5.5.4 Model issues and outcomes

It was found that the standard deviation (variance) of predicted statistical levels is uniformly larger than that of the survey measurement. This is expected, as each vehicle is modelled as independently variable, whereas vehicle flows in practice tend to show periods of speed grouping (Figure 36).

For initial review at site model 1 (Bolong Rd), co-ordinates for a section of road 7km in length were used corresponding to a transit duration of less than 5 minutes. This limited the validity of statistical level predictions to percentiles ranging from L_{Amax} to approximately L_{A10}. For site model 2 (Picton Rd), a longer modelled section of road 12.5km length was used, though still sufficient for valid percentile levels only to approximately L_{A20}. Both models were enlarged using simple straight extensions to allow investigation of statistical levels from L_{A50} to L_{Amin}. These lower percentile levels will often be masked by ambient sound, however for quieter areas, analysis of immission levels and of impact should be based on more extended carriageway sections.

Survey results showed that modelling of the stochastic physical properties of the source alone, based on Q=2, gave good results across statistical noise levels, but suggested a restriction on calculation of L_{Amax} as the 99.95%-th value would be appropriate. This is an empirical recognition of the fact that modelling 10000 examples of instantaneous pass-by levels including variance is intuitively more likely to include a higher proportion of extreme upper levels than can occur in practice in a field survey involving vehicles numbering in the hundreds only. Prediction of unexpectedly high L_{Amax} arose almost exclusively with truck passes and, whereas vehicle speed is modelled as a normal distribution, observed speed variation shown by Figure 36 is truncated at higher speeds approximating, perhaps, a Beta density function.

Severe storms limited valid noise survey data for the Picton Rd survey to the 32 hourly periods only. Whilst traffic flow data was collected for a period of a week, only the first portion of the data was able to be used for validation of modelling outcomes.

5.5.5 Results

Table 41: Bolong Rd, prediction error, dB (N=10000, n=144, Q=2, Nair, Ngrnd)

	L_{Amax}	L_{A1}	L_{A10}	L_{A50}	L_{A90}	L_{Amin}	L_{Aeq}
Mean Measured	81.2	68.9	56.7	44.4	39.2	35.2	58.6
Mean predicted	80.4	67.5	49.9	32.2	21.7	11.0	57.7
Prediction vs Survey	**-0.8**	**-1.4**	**-2.3**	**-1.0**	**-3.5**	**-13.3**	**-0.9**
Stdev Error	5.2	3.8	5.3	6.0	3.4	3.8	2.7

Table 42: Picton R, prediction error, dB (N=10000, n=32, Q=2, Nextra=0)

	L_{Amax}	L_{A1}	L_{A10}	L_{A50}	L_{A90}	L_{Amin}	L_{Aeq}
Mean Measured	92.2	85.4	78.2	65.0	49.6	34.8	75.0
Mean predicted	92.7	85.2	76.0	63.7	52.9	38.4	73.8
Prediction vs Survey	**0.5**	**-0.2**	**-2.2**	**-1.3**	**3.3**	**5.7**	**-1.2**
Stdev Error	2.7	2.0	1.2	1.6	2.3	3.9	0.8

The results in Table 41 and Table 42 represent the predicted vs measured outcomes. The Bolong Rd model outcome is obviously affected by the presence of background sound masking the lower percentiles, particularly the L_{Amin} level - The measurement location was approximately 400m from a beach. In the case of Picton Road the minor over-prediction at L_{Amin} and L_{A90} is almost certainly due to ground contour shielding effects excluded from the modelling algorithms.

For both validation models it was necessary to exclude from the error analysis predicted levels lower than a threshold of the order of 25dB(A), as the disparity (pseudo-error) due to difference between the predicted and observed outcomes was a meaningless measure of masking by sound from sources other than the road. Noting also the maximum vehicle-observer propagation distance affecting a 1-hour sampling period is approximately 50 kilometres, extra attenuation factors are beyond the scope of normal extrapolation rules. Simplification to the more distant sections of carriageway may have affected accuracy of the longer propagation distances, perhaps systematically, in the manner discussed in later error discussion. Shielding, almost certainly significant for Picton Rd, is also entirely ignored.

A modelling strategy managing periods of very low flow, and of very large propagation distances, appears to warrant further development, in much the same manner as the empirical restriction to sampling found to be effective for the opposite extreme condition for the highest occurring sound levels.

5.5.6 Error analyses

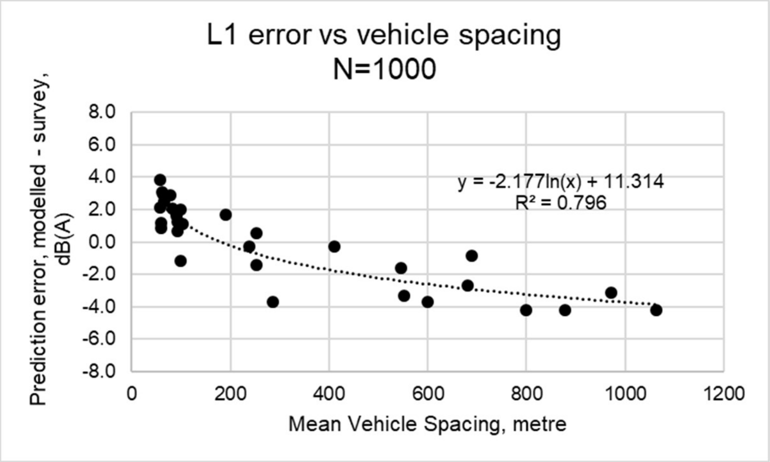


Figure 46: Picton Road error analysis, L_{A1}, 1000 simulations, dB

It was recommended in Figure 26 that stochastic modelling for the extreme percentile values – L_1 for example – should be carried out over 10000 iterations and, potentially, 100000 iterations. Figure 46 and Figure 47 suggest that for road traffic as few as 1000 iterations may be sufficient for relatively dense traffic flows, but for more widely spaced traffic 10000 iterations is almost certainly required.

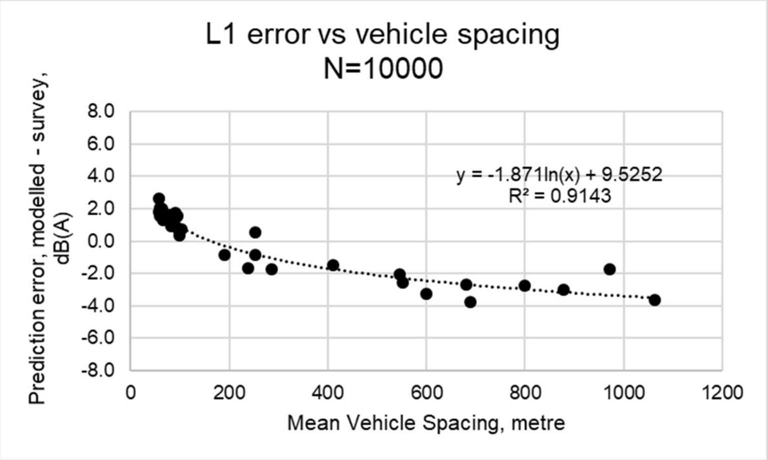


Figure 47: Picton Road error analysis, L_{A1}, 10000 simulations, dB

Both Figure 46 and Figure 47 modelling outcomes show a systematic trend in prediction error that can be explained, at least in part, by a systematic flow behavior observed in vehicle pass-by.

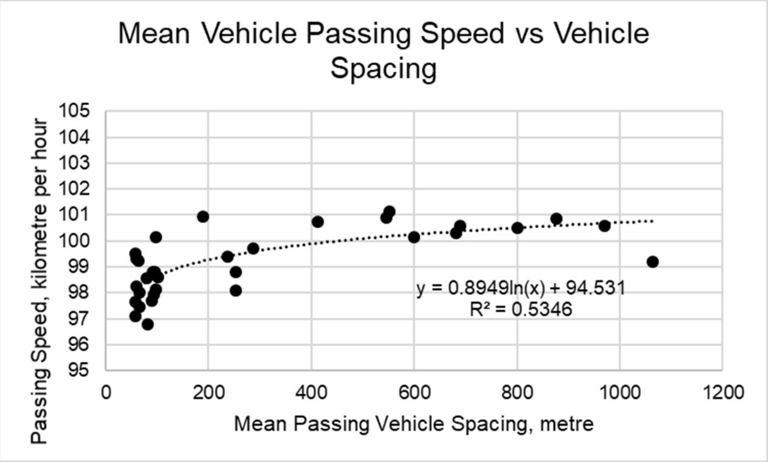


Figure 48: Picton Rd, Vehicle Pass-by Speed vs Vehicle Spacing

Vehicle pass-by speed is modelled according to Equations E11 and E12 as a function of the posted speed limit, so the modelled variance is symmetrical about the modelled mean relative to the posted speed limit. Actual mean pass-by speed for each hourly sample was observed to be a function of the vehicle flow rate, in the manner shown in Figure 48, with the logical outcome that as vehicle spacing increased and the actual mean passing speed increased, so the predicted outcomes showed a relative decrease and trend toward a systematically negative error. A congestion adjustment function for pass-by speed could be a worthwhile modelling addition. As regards overall vehicle speed related error, the mean vehicle pass-by speed observed at Bolong Rd was 94.3 kilometre per hour, composed primarily of light vehicle flows. Compared with the modelled mean expected passing speed for light vehicles from Equation E11 this disparity would introduce an overall error of approximately -0.2dB(A). For Picton Rd, where roughly half of vehicle composition involved heavy vehicles, the mean passing speed of 99.2 kilometre per hour could have resulted in an overall prediction error as high as +0.7dB(A) when compared with modelling based on Equation E12.

Figure 49: Stochastic model error analysis

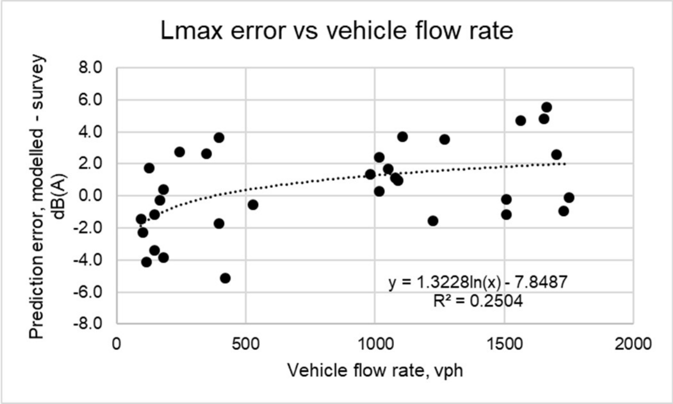
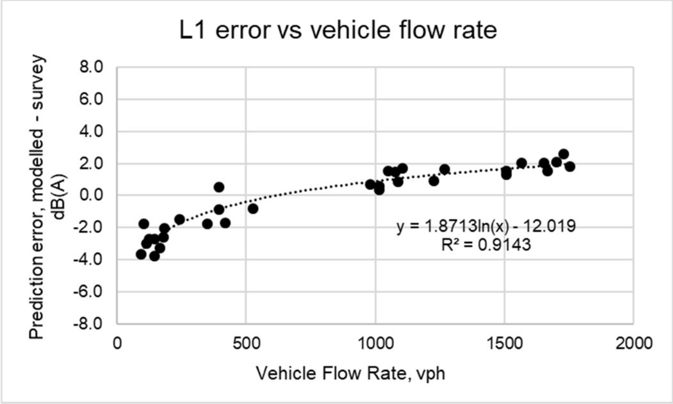
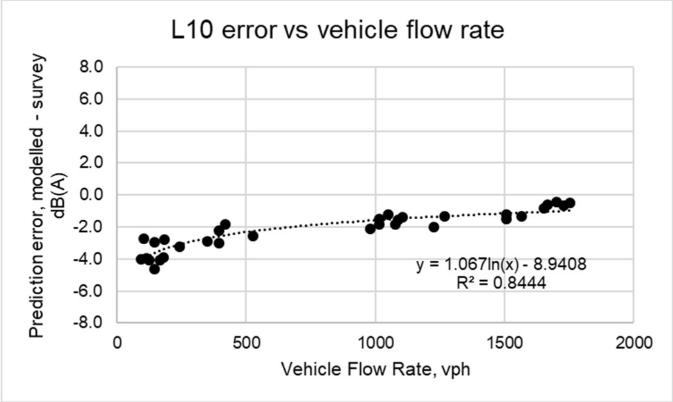
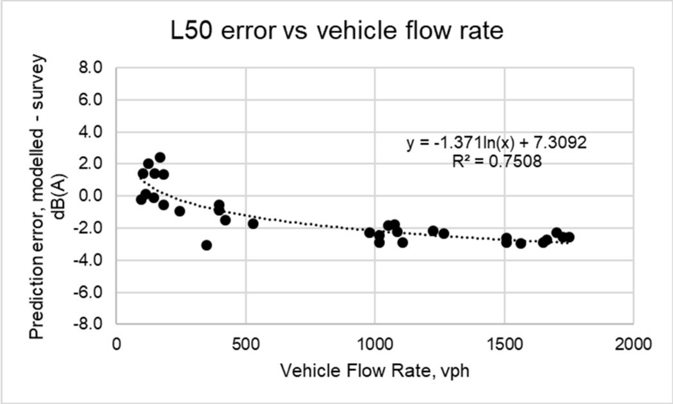
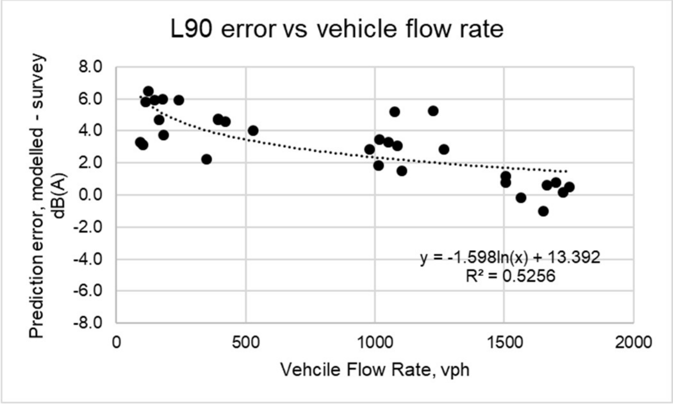
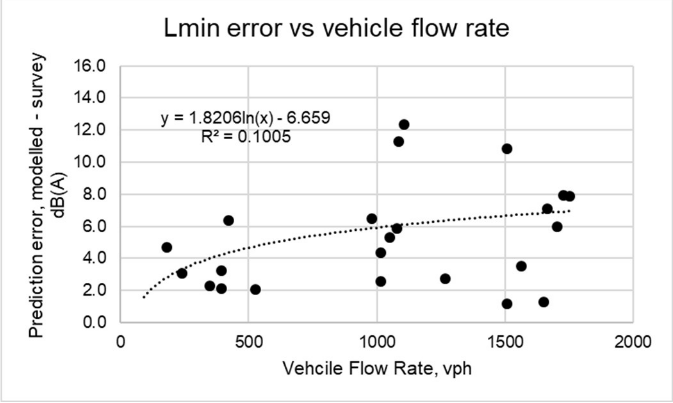
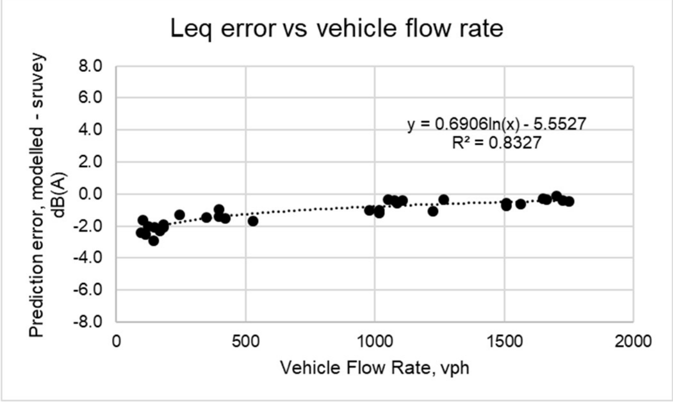
	For LAmax, a scatter of more than 2dB is a predictable result of differential distance between carriageways and the measurement location. An observed systematic error is inversely correlated with the vehicle flow rate and possibly related to trend in vehicle passing speed Figure 48.
	The observed systematic error inversely correlated with the vehicle flow rate is possibly related to trend in vehicle passing speed Figure 48.
	Similar observation to Lmax
	These errors apply to a simulation model ignoring shielding due to ground contours. Lowest vehicle flow leads to a model with a proportionally higher presence of sources at more distant locations. The incorporation of ground contour modelling would be expected to reduce the systematic trend to over-prediction of the percentile levels from $L_{A,50}$ to $L_{A,min}$. at lower traffic flows.

Figure 49 continued

	The most obvious relationship between L_{A50} error and L_{A90} error is an overall shift in scale, with otherwise somewhat similar trends. This suggests a uniformly more significant influence from unaccounted ground contour shielding affecting the lowest percentile levels.
	A number of predicted level results lower than 25dB(A) for LAmin were excluded to avoid invalid error assessment based on measurement including background sound. Consequently, low traffic flow samples are reduced and an overall error in LAmin of the order of 6-8dB is accountable by the absence from the model of shielding effects for more distance sources.
	The error trend for predicted equivalent energy level appears largely explained by the observed trending variation in actual passing speed vs flow rate whereas modelling utilised a fixed passing speed. Speed vs flow rate is a parameter worthy of further investigation.

The exponential error trend observed in both Figure 46 and Figure 47, and for most statistics summarised in Figure 49 can be part explained by congestion related effects on pass-by speed. Somewhat opposing systematic trends apply for percentiles above and below the mean energy level statistics. Possible causes of the observed error trends are:

1. Over-simplification of the carriageway coordinates leading to errors in progressively distant carriageway-observer distance relationship.
2. The statistical symmetry may also imply a distributive function is involved, either individually or in aggregate, associated with variance modelling – normal distributions for speed and sound power level, poisson distribution for source location.
3. More pronounced progressive attenuation of higher frequencies may have occurred over longer distances distorting the A-weighted attenuation modelling more than is estimated by Figure 44.
4. Modelling of vehicle flow as a poisson variable may not accurately reflect flow characteristics such as vehicular grouping, evident indirectly in Figure 36 and Figure 37.

5. It is a characteristic of decibel addition (Section 8.1,Equation E15) that levels will trend toward the higher of the contributing components, therefore any departure from the true distribution of source locations is likely to bias resultant level toward higher, rather than lower, outcomes.
6. The commissioned traffic count system does not distinguish vehicle speeds on a vehicle-type basis, reporting the mean transit speed for all vehicles for the sampling period. This is a source of prediction error if actual heavy vehicle flow characteristics differ from those of light vehicles.

The relationship between mean vehicle pass-by speed and vehicle flow rate for the two sites were found to be similar, though far from identical. Models for both sites were tested with expected vehicle pass-by speed modelled as a function of flow rate. Whilst there was improvement in linearity of error vs flow rate, the mean predicted L_{AN} percentile values were not greatly altered. This is an important finding as it indicates modelling using independent input data achieved similar outcomes to a model based on flow characteristics data derived retrospectively for the actual site itself. Not only is independent generic modelling therefore robust but, in any case for planning applications, independent input data is the only practical modelling basis.

5.5.7 Fundamental Modelling Constraints

1. The length of carriageway required for a study is affected by both the intended statistics of interest and by the relative magnitude of traffic sound levels compared with the ambient sound.
2. For longer carriageway sections, where lower level statistics can be more valid, the conflicting influence of uncontrollable factors such background noise and of factors affecting attenuation bias will increasingly interfere with the experiment.
3. The presence of, and influence on measurement of, ambient noise needs to be considered as part of the analysis of modelling and survey outcomes.

5.6 MODELLING DISTANCE ATTENUATION RATES NEAR ROADS

Current noise prediction paradigms for road traffic are based on stationary models utilising a fixed attenuation rate vs distance, many being a nominal rate of 10 times the logarithm of the distance ratio based on the premise that road noise can be modelled as a stationary and simplified source. Recalling that most road traffic prediction models are concerned with outcomes measured in L_{Aeq}, the findings of an investigation using stochastic modelling reported below suggest such an extrapolation rule is reasonable. However, where statistics other than L_{Aeq} are of interest, as is often the case in prediction of loud noise events, current methods generally involve attempted adjustment factors added to the modelled L_{Aeq} immission level.

Results summarised in Table 43 and Figure 51 show attenuation rates for statistical sound level parameters determined through the application of stochastic modelling, using vehicle flows similar to those from the Picton Road survey, but modelled as a simple straight two-laned carriageway 100 kilometres in length. Immission levels were predicted for distances from 12 metre to 800 metre from the nearest carriageway.

Two conditions were examined – modelled attenuation rates including attenuation from ground absorption and air absorption, and modelled attenuation rates excluding the “extra” attenuation effects thereby considering primarily source configuration influences only. The latter arrangement could be considered one extreme condition with the former, probably, the more likely condition.

To validate these theoretical findings, the calculated attenuation rates were compared with independent data from survey records at sites adjacent to roads. The data was a part of a larger dataset from which the APD dataset referenced in 4.2.2.1 was drawn. The road-affected records involved 42 generally urban sites, for distances ranging from 5 metre to 400 metre from the nearest carriageway and comprised of approximately 20,000 statistically based samples each of 15 minutes duration. The data were sorted into periods representing day, evening and night data, and statistically analysed using a simple single-order regression analysis to determine each attenuation rate parameter (Z_N).

$$L_{AN} = Z_N * \log(r) + C_0 \qquad \textbf{E15}$$

where

L_{AN} *is the immission statistical sound pressure level, dB*

N is the statistical percentile of interest (0-100)

Z_N *is the attenuation rate observed for the percentile N*

r is the distance from the nearest carriageway to the observation point,

and

C_0 *is a site-specific constant.*

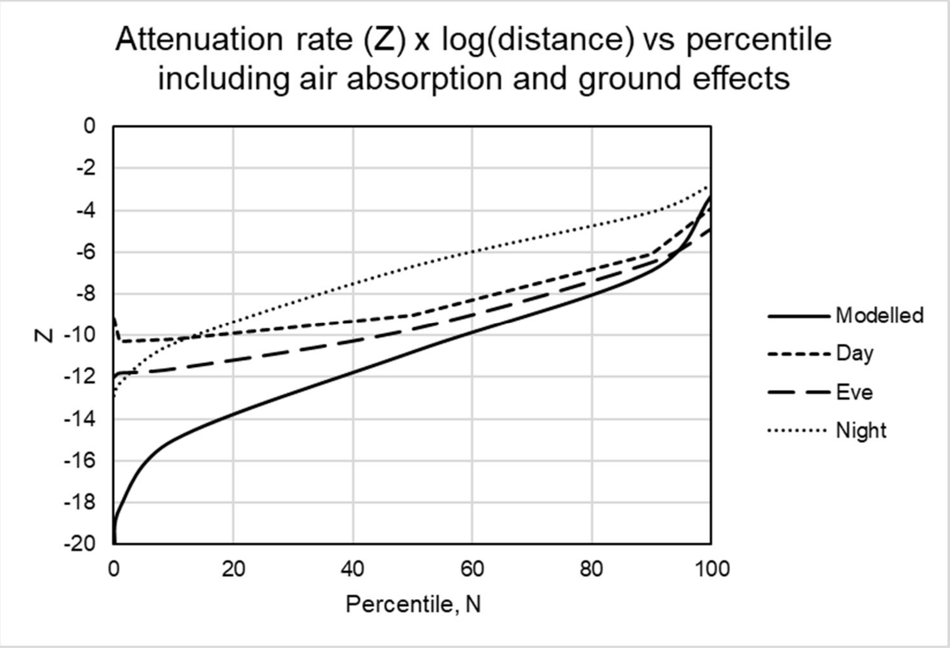


Figure 50: Percentile level attenuation rates including air and ground absorption effects

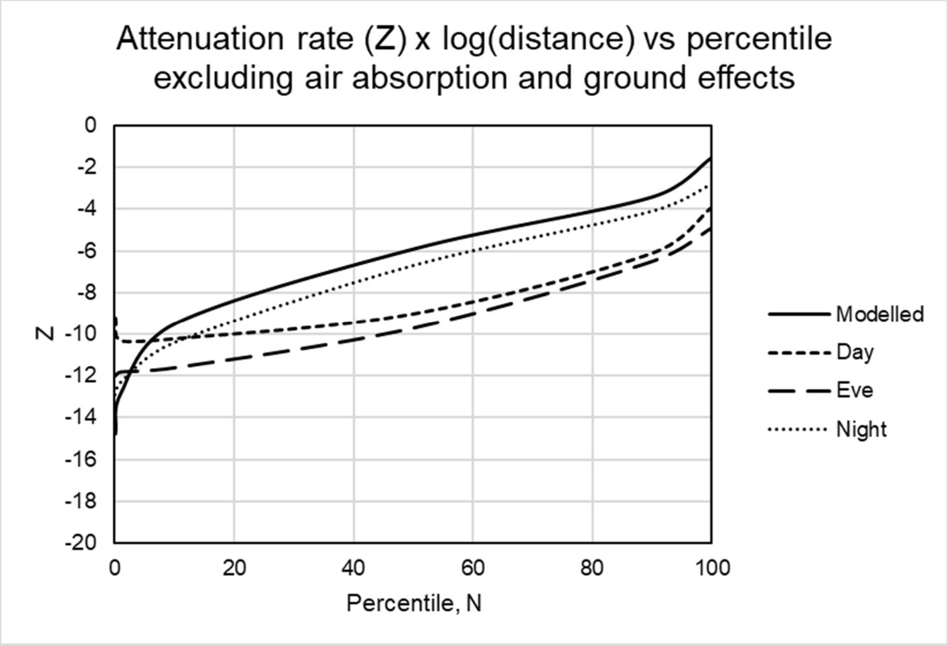


Figure 51: Percentile level attenuation rates excluding air and ground absorption

Table 43: Statistical level attenuation rates (Z) adjacent to roads

	Model with ground/air	Model without ground/air	Day	Eve	Night	Mean D,E,N
L_{Amax}	-20.4	-14.8	-9.2	-12	-12.9	-11.4
L_{A1}	-18.2	-12.8	-10.3	-11.8	-12.3	-11.5
L_{A10}	-15	-9.5	-10.2	-11.6	-10.4	-10.7
L_{A50}	-10.8	-5.9	-9	-9.7	-6.7	-8.5
L_{A90}	-6.9	-3.4	-6.1	-6.5	-4.1	-5.6
L_{Amin}	-3.3	-1.5	-3.9	-4.9	-2.8	-3.9
L_{Aeq}	-15.6	-9.7	-9.4	-10.7	-10	-10.0

Z_N in Equation E15 describes the observed attenuation rate for the statistical sound pressure level of interest. This parameter can be used to predict the statistical noise level immission for an observer when that level is extrapolated from a statistical level observed at a different location. Comparing theoretically modelled attenuation rates with those observed in the analysis of survey measurements, Table 43, shows a higher correlation between night survey results and modelling, when the influence of other non-traffic sound sources influencing the survey would be expected to be low. During daytime and evening periods, the influence of other conflicting sound sources is more apparent, merging almost all attenuation rates from L_{A10} and higher, however the observed attenuation rates are generically consistent with the values calculated from modelling.

The difference between the attenuation rates found to apply for systems with and without the inclusion of ground and air effects is both significant and fundamental. The presence of more attenuation factors would be expected to generate higher attenuation rates, as is the case. It is not so obvious that, as extra attenuation factors diminish, so the relative contribution from the more remote elements of the system expands. That is, the distributed capacitance and inductance in the system network changes. The fact that this effect influences all statistical parameters is not automatically obvious, demonstrating how significant is the overall magnitude of a road and its' surroundings when properly considered as a system, compared with the current approach to road impact assessment based on relatively small segments. Large scale effects occur at the lower percentile levels, affecting ambient sound pressure levels at great distance. This also has significance to urban areas where, not only is ground absorption likely to be low, multiple reflections will amplify the effect of system sources.

The findings summarised above show that prediction of a universal L_{AN}-L_{Aeq} relationship is a flawed objective, as the magnitude of intra-percentile adjustment is automatically a unique function of distance, and the range of the site specific constant (C_0) applicable to each circumstance is both unique and unknown. Statistical sound levels can be determined only from direct measurement, or through application of a stochastic model able to emulate the range of source configurations occurring over time.

5.7 EXAMINING IMPACT

To examine impact of traffic from Bolong Road at a more distant receiver, ambient sound levels were recorded at a location 550 metres from the Bolong Road carriageway, during the week immediately prior to the Bolong Road study. Weather conditions during both periods were observed to be similar. The location is known, from personal experience, to experience occasional loud vehicle noise events from Bolong Road traffic but a relatively low presence of road noise most of the time. Sound levels from traffic were then predicted using the Bolong Road survey period traffic data to this same location and the magnitude of impact examined. This utilised the inverse transformation sampling algorithm described in Figure 57, comparing the predicted hourly traffic noise immission levels with the average existing hourly ambient sound levels. Using these findings, average maximum emergence levels were able to be determined on a time-of-day basis. An alternative comparison could have been restricted to average daytime traffic sound levels vs average daytime ambient sound levels, however considerably less information would be gleaned regarding the nature of potential impact.

It is instructive to note that road traffic noise emergence summarised in Figure 52 is not the same quantity as passive impact shown in Figure 53, nor does it necessarily reach a maximum at the same time of day. Both Figure 52 and Figure 53 show the mean expected levels of both emergence and impact together with associated 90 percent confidence intervals. These intervals were determined using the mean, lower and upper bound hourly values for the ambient sound pressure levels sampled at the reference location prior to the traffic count surveying. Conclusions able to be deduced from these analyses are that road traffic noise would, on average, be audible only in the middle of the day, being unlikely to impact more than 15 percent of any hourly time interval. On relatively rare occasions traffic noise could be audible for up to 60 percent of the time, though still only during the middle of the day.

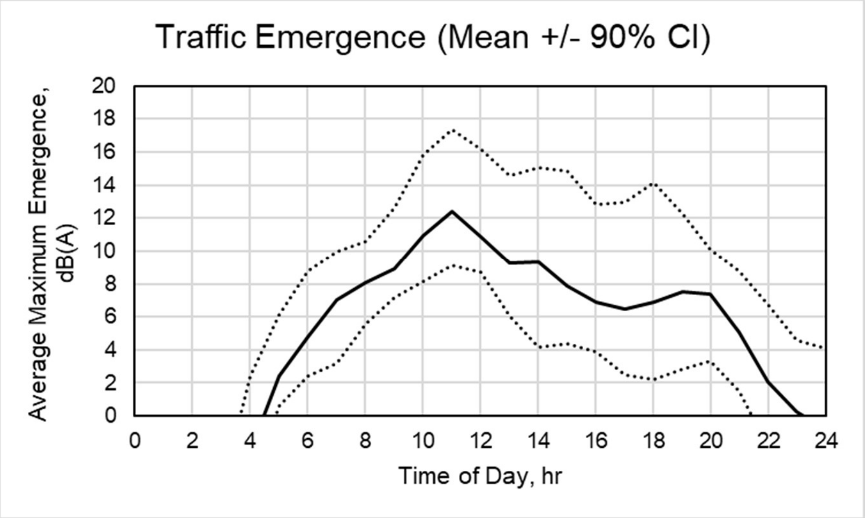


Figure 52: Bolong Road Traffic Noise Emergence at receiver location

Emergence also enables an assessment to be made of the prominence of loud noise events. Table 44 summarises the average emergence of noise from traffic for daytime and night-time periods, considering also the range of likely ambient sound level conditions.

Table 44: Emergence of Loud Noise Events, dB(A)

	Lower 90% CI	Mean	Upper 90% CI
Daytime hours	6	9	14
Night-time hours	3	5	7

Experience at the site is consistent with the above description of road noise Emergence.

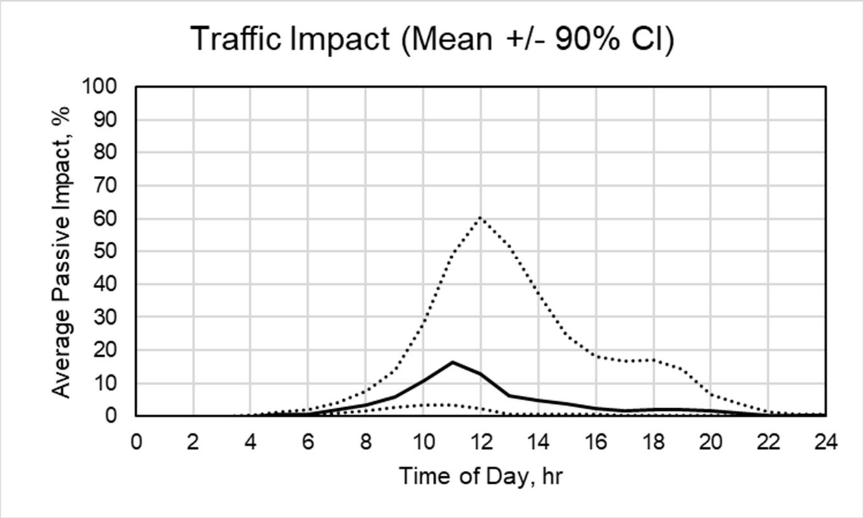


Figure 53: Passive Impact from road traffic at receiver location

5.8 CONCLUSIONS AND RECOMMENDATIONS

The studies carried out and reported in this chapter demonstrate the high level of prediction accuracy for equivalent energy levels that can be achieved using statistically based noise modelling. This is demonstrated for the complex and stochastically variable source example of a road. These procedures have ignored road surface type, vehicle height and operating conditions of the vehicles, using independently obtained input data, yet have produced a validated level of prediction accuracy at least as good as models in widespread use.

More importantly the procedures enable the modelling of statistical sound pressure levels at a high level of accuracy. These statistical levels can be calculated from other modelling methods such as level-time waveform simulation, however the statistical simulation enables quite complex multi-system situations to be modelled – signalled intersections, feed-in side roads, carparks and any similar sub-system. These sub-system behaviour models can be analytically developed and can be clearly described.

While it is likely that road surface type will remain an important parameter in modelling for new freeway projects, the parameters identifiable from this work – statistically valid source configuration and the inclusion of variance for both vehicle speed and sound power emission – appear more critical in achieving analytically useful outcomes.

The modelling procedures utilise the statistics of both source location and emission characteristics, applied using simple, classical and uncontroversial noise dispersion modelling.

When compared with other stochastically varying noise systems, roads represent one of the more complex and challenging source systems. The development and application of stochastic numerical modelling for other sources currently affecting the acoustical environment will be both simpler and more straightforward.

When used in conjunction ambient sound level data, using inverse transformation sampling to examine Emergence, outputs from this modelling procedure provide a meaningful prediction of impact due to the system under investigation, the example in this chapter being road traffic noise. These modelling procedures will address the issues of variance, source distribution, multiplicity of sources, source dynamics and source uncertainty. These long noted concerns [Lercher & Schulte-Fortkamp, 2003] have impeded informed assessment of both passive noise impact and community noise annoyance.

In relation to the prediction of sound from vehicles, error review suggests that modelling for light vehicles as a simple single-component source alone can provide very satisfactory outcomes. For heavy vehicles, the evidence is that effective modelling outcomes require consideration of, at least, a propulsion source and a tyre/road interaction source.

These modelling procedures, when allied to an assessment of the magnitude of impact, will help clarify aspects of legislative responsibility for the NSW EPA where current inconsistency can arise. In the Noise Policy for Industry [EPA, 2017] clause 2.4.1, notwithstanding an inappropriate use of the term “amenity”, it is noted that road traffic noise may often be high enough to render industrial noise sources effectively inaudible. The adoption of impact assessment using this type of modelling for both road traffic and industry can distinguish between individual and collective significance.

6 THESIS CONCLUSIONS

6.1 OVERVIEW

In Australia, and in much of the world, sound is recognised as one of a number of parameters that describe what is termed The Environment. Sound is clearly different from other environmental parameters in being sensory, and anthropogenically sensory specifically. The parameters associated with environmental impact are not simply organic, being those of a system with all its inputs and externalities, one of which is manifested sound. This thesis is concerned with the management of environmental sound and of the way in which its management affects the environment.

Early natural resources law was primarily concerned with managing the exploitation of natural resources with little regard to impacts on natural environments, however with Acts such as the NSW Environmental Planning and Assessment Act 1979 and the Commonwealth Environment Protection and Biodiversity Act 1999 the legal obligation to consider consequential environmental effects has become a foundation for development control [Farrier et al,1997]. Indeed, current scientific community focus on factors perceived to aggravate climate change may bring pressure to strengthen those obligations.

Environmental noise legislation evolved from the objectives of managing nuisance and annoyance to humans. Legislative procedures relating to sound are based primarily on measured sound levels. These have now been widely applied for some decades with a reasonable measure of effectiveness when both the legislative subject and the ambient soundscape are composed of sounds of primarily anthropogenic origin, particularly of transportation. In these circumstances, the effectiveness of decisions made based on metrics that consider annoyance have been reasonable. There are common exceptions however, where the subjective character of the subject differs from that of the local or immediate environment. Examples include sound from an entertainment precinct which may be considered to enhance an area otherwise dominated by transportation or industrial noise or, conversely, in quiet areas where a relatively low but frequent noise intrusion may significantly change the subjective character of the soundscape. Current noise impact assessment methods are unable to provide management guidelines for these relatively common circumstances and, importantly, of cumulative impacts.

It has not been concealed from the community that current legislation is founded on the management of annoyance to humans due to the activities of other humans. Instead, the passage of time has masked the actual purpose of legislation due to unintended obfuscation. This results from the arcane nature of the language and the functional complexity of the associated regulatory procedures. Much of this complexity results from attempts to compensate for shortcomings in the assessment procedures, that had been foreseen by the author of the 1978 work [Schultz,1978] from which the objective measurement criteria, endemic to regulatory procedures, evolved. This thesis considers there is widespread misunderstanding of what should be expected from environmental noise control legislation, a misunderstanding that has been nurtured by industry focus restricted to regulatory compliance with insufficient consideration of legislative purpose and objectives.

It is unsatisfactory that environmental regulation fails to impose obligation to consider the quality and integrity of an environmental parameter of the biosphere, sound, and how that may be affected by land-use activities. Changes to the acoustical attributes of land can be an early-indicator of an undesirable externality from those land uses in the form of a wider bio-diversity impact or degradation. Many areas occupied by humans present as environmentally degraded land. It is constructive to revisit remarks by Schultz [Schultz,2011], interestingly the namesake of the 1978 author of the benchmark paper on environmental noise annoyance:

> *“Most instances of deteriorating environmental conditions are caused by human behaviour.” “Drivers of phenomena such as climate change, loss of species’ habitat and ocean acidification rarely are the result of malicious intent”…* being the *…”consequence of the lifestyles of billions of humans”.*

Whilst seeking effective management, it is significant that impact – the change to the ambient environment - is not measured by regulatory procedures. The public and possibly regulatory authorities themselves construe that to be the intended purpose and the outcome of those procedures. Regulatory noise assessment metrics do not measure a magnitude of change. Instead, these metrics reference criteria providing, at best, an approximation of a wide area level of annoyance thought to be experienced by humans for the relatively specific case of transportation noise. To a Legislator, an absence of outrage under current assessment should not be mistaken as a meaningful indicator of either preference or acceptance. Occupants of a community that is adversely affected by large-scaled acoustical impacts – for example transportation corridors – “vote with their feet” and leave the area; or may consider the circumstances to be intractable and begrudgingly attempt to adapt. Significant environmental and amenity issues are potentially ignored.

While development and conservation are the extreme ends of a continuum of possible land uses, stakeholders to many development proposals believe that environmental protection legislation has an over-arching responsibility to conserve environmental aspects; furthermore, that those aspects are innately of value in a context of inter-generational equity, ecologically sustainable development, the polluter pays principle and the precautionary principle. The origin of unintended bias in some development decision-making arises from the fact that the exploitation of the natural resource – land – associates a finite value for a proposal (financial benefit, economy, jobs, trade) when many other uses for the potential development continuum of that same land are less able to be assigned formal value – recreation, community amenity, residential amenity, habitat preservation, ecology. Some situations involving carbon credits may assign monetary value to natural resources, though usually as an intrinsic retired-credit value in the circumstance that a development of a different type is approved.

Monetary value, it should be remembered, is simply an anthropogenic invention originating in the objectives of facilitating trade [Harari,2014]. Apart from the real possibility of estimation errors, the computation basis for the metric itself is frequently opaque.

Evidence that the acoustic features of an anthropogenic environment are considered both important and valuable to humans is the magnitude of investment by owners in managing the acoustics of the built environment. A building is unambiguously recognised as an asset of quantifiable cost and function. This contrasts with situations given the general title of an acoustic environment. Importantly, the technical methods associated with the acoustics of the built environment differ quite markedly from those commonly used in environmental acoustic assessment, being strongly outcome focussed for the case of buildings.

The purpose of legislation is to provide the decision-making platform to bridge the continuum of these many factors. Historically, technical development in environmental acoustic fields has trailed legislation, some aspects of which have changed little in decades. It has been shown in this thesis that greatly superior methods enabling the assessment of impact – the change to the ambient condition - are available.

The work outlined in this thesis aims to provide a platform for improved communication and technical collaboration between the sciences of Soundscapes and Environmental Acoustics, through the implications and uses of the term “Emergence”. This will also improve communication between scientists, legislators and members of the public through the role of Emergence as a surrogate for audibility.

6.2 SUMMARY

Chapter 2 of the thesis examines the history of environmental noise legislation and its objects, explaining the origin and foundations on which that extant procedures have evolved. For context, the procedures that currently devolve from NSW Legislation are discussed, however these procedures are shown to be descendent from traceable international legislative policy and standards. The inconsistency between common procedures and more recent environmental principles is highlighted, resulting in aggravation to already restricted community understanding. The technical inability of the current methods of noise assessment to identify, distinguish or respond to desirable and undesirable aspects of environmental acoustics – sound compared with noise – is also demonstrated, leading to the apparent conclusion that a fundamentally different method of assessment is required.

Chapter 3 builds from and advances the underlying terminology associated with environmental noise assessment. This chapter discusses the nature of change and contrasts the elements identifying change to an ambient environmental parameter with the limited metrics discussed in Chapter 2. Chapter 3 describes a method for quantifying impact in acoustical assessment using an objective measure of change. Using an objective definition for the commonly used term of impact, Chapter 3 describes a relative outcome assessment method able to provide both subjective and objective insight in place of simple absolute sound levels. This is achieved using a concise but effective basis for modelling emission of sound from proposed land-use activities, capable of being scaled up to the level of predicting sound emissions from major transportation. The technique provides a uniform method of assessment for physically stationary and physically moving sources, enabling the impact from either and both to be evaluated in the context of an existing ambient acoustical environment. The approach will facilitate more realistic expectation of both annoyance and environmental impact outcomes. Chapter 3 explains that impact can arise from both active and passive processes with importantly different potential outcomes.

Chapter 3 also considers the inconsistency between the objects addressed by environmental acoustic management procedures and those of the legislative hierarchy. Outcomes of assessment procedures are frequently termed “acceptable” whereas a common legislative object is to achieve an outcome that is reasonable. Procedures are shown to be incapable of distinguishing between subjects that are anthropocentric and those that are ecocentric, a situation aggravated by the use of excessively simple assessment scenarios for both land-use activities and technical assessment metrics. The absence of more rigorous procedures can lead to, sometimes, seemingly arbitrary approval decisions.

Chapter 4 examines the principles associated with stochastic acoustical systems, recognising that the prominence of simplified assessment procedures is a reaction to the complexity encountered in acoustical environments. Chapter 4 notes that procedural simplification is counter-productive to both effective management and community understanding, concealing the underlying aspects of uncertainty and risk-management when compared with the use of statistically based assessment. Technical transparency is an important attribute demonstrated by the investigative procedures described by Chapter 4. Long-standing statistical methods of statistical analysis, insufficiently recognised in acoustical assessment procedures, are discussed in the context of improved investigation of stochastically varying systems.

Chapter 4 notes that most land use planning approvals are made at a Local Government level. Uncertainties and inconsistencies in regulatory investigations are opaque to the local authority and legislators cannot expect uncertainty to be compensated by the technical expertise of the local authority. Among other issues, Chapter 4 suggests that consistent land use planning will require acoustical land classifications to distinguish environmental characteristics from the function-based local environmental planning methods used in NSW planning [NSW Govt,2006]. Chapter 4 builds on the terminologies discussed in Chapter 3 to a platform identifying legislative and procedural changes from which significantly improved land-use planning can evolve.

Chapter 5 examines the detailed implementation of statistical simulation to a complex stochastic environmental acoustic system. This example demonstrates the level of sophistication able to be achieved for the outcome sound level and ambient environmental impact using this analytical technique.

6.3 THIS THESIS – A PLATFORM FOR PRO-ACTIVE MANAGEMENT

This thesis reviews fundamental questions associated with environmental sound management, some of which may have application to the wider generic field known as The Environment. These questions contemplate both the activities and the outcomes that will result from a proposed action:

1. Will this action have an impact?
2. How significant is the impact?
3. Has the assessment of impact been reasonably conducted?

The actions of interest to this thesis are actual and proposed land uses and the associated approval processes. The scope of these fundamental questions can be difficult to address using current land and environmental management legislation, as the legislation provides insufficient guidance on the intent and interpretation of their objects. Whilst judicial arbitration can clarify this legal intent, planning decisions are too numerous to be decided by a court and are necessarily made, with best of endeavours, attempting to understand and interpret these Acts appropriately. Obstacles to effective decision-making are the absence of an unequivocal definition for 'impact' and the subjective aspects of 'significance' and 'reasonableness'. This thesis proposes an interpretative framework structured around commonly used planning terms.

Impact –

> *The environmental impact of an action is the difference between the state or condition of the environment which occurs as a result of that action being taken or withheld, and the state or condition which would otherwise occur. (after Hede)*

Magnitude of impact –

This thesis describes a method enabling prediction of the probability that outcomes (sound) of an action will dominate the sound otherwise associated with the ambient environment, thereby resulting in change to the ambient condition.

Worst case scenario –

> *The action scenario that results in the greatest magnitude of change to environmental characteristics, or environmental parameters, that otherwise describe the existing ambient environment.*

For acoustic environments, the thesis has described a method predicting the probability that an action will result in energetic masking of the ambient environment, together with the probability that such energetic masking will be audible. The function describing these joint outcomes is termed Emergence.

Reasonable impact –

> *The magnitude of impact, for either or both anthropocentric and ecocentric outcomes, that is considered acceptable to the common man.*

For acoustic environments, this thesis provides a platform for values of Emergence that are supported by historical indicators of reasonable impact, together with values around which planning policy can pro-actively provide for reasonable cumulative impacts.

No impact –

> *The magnitude of impact, for either or both anthropocentric and ecocentric outcomes, that changes none of the environmental characteristics, or environmental parameters, observed in the existing ambient environment.*

For acoustic environments, this thesis enables an unambiguous interpretation for policy requiring no impact.

Reasonable assessment basis -

> *A basis that examines the range of conditions that will be the outcome of an action and is able to consider the probability that such conditions will occur.*

For acoustic environments, this thesis establishes a platform enabling rigorous statistically based assessment.

6.4 LEGISLATIVE AMENDMENT RECOMMENDATIONS

The following are amendment recommendations. It is foreseen that these recommendations would constitute an investigation brief undertake a review to assess and refine both the content and scope suitable to specific legislation, with review outcomes consolidated in format as a Regulatory Impact Statement.

6.4.1 Legislative definition for 'The Environment'

a) Review the definition for The Environment as referenced in legislation. Where necessary, supplement or add definitions to associate Environmental Parameters in sufficient depth to clarify the target objects of the Act, either in aggregate or in its parts. Considered parameters should include, at least, environmental light, environmental sound, biodiversity, air quality, water quality.

6.4.2 Legislative definition for impact

a) Introduce a definition for impact within environmental and planning legislation. The following definition is recommended:

> *The environmental impact of an action is the difference between the state or condition of the environment which occurs as a result of that action being taken or withheld, and the state or condition which would otherwise occur.* [Hede,1993]

6.4.3 Legislative definition for amenity

b) Introduce a definition for amenity for environmental and planning legislation. The following definition is recommended:

> *The pleasantness of a place, being influenced by the environmental parameters – sound, air quality, odour, climate - describing the place. All the features, benefits and advantages inherent in the environment of the place, its social framework and its conveniences. Amenity describes the intrinsic value made available by the place.*

6.4.4 Amend Protection of the Environment Operations Act 1997 No 156

In addition to each of the above recommendations:

a) Update the objects of the Act to associate appropriate environmental parameters to identify those objects that are intended to address anthropocentric priorities – e.g. the environment characterised by dwellings, urban areas, active recreation areas – and/or those that address eco-centric environmental priorities – habitat, environmental diversity, passive recreation and the like. This will provide traceable consistency between the objects of the POEO Act and those described in Part 3 of the Protection of the Environment Administration Act 1991 No 60 and help distinguish those land uses that may affect either or both already developed land areas and less developed, or natural, land areas.
b) Replace current definitions for noise, noise pollution and offensive noise with definitions referencing sound, noise pollution and noise respectively.
c) Cross-reference objects associated with noise pollution in the POEO Act to outcomes affecting human comfort and/or annoyance.
d) Include objects that affect eco-centric environmental sound degradation.
e) Review the extent to which the amended NSW EPA regulatory assessment criteria satisfy the obligations of the Protection of the Environment Administration Act 1991 No 60, specifically clauses 7(2)(a) and 9(1)(a), in the context of these thesis findings and of the amended definitions above.
f) Review the extent to which the NSW EPA Policies satisfy the objects of the Protection of the Environment Operations Act 1997 No 156, to section 10(b) in the context of the definitions under the Act for "harm" and "waste" and identify elements of current EPA Policy that should be updated.

6.4.5 Adopt WHO policy guidelines in environmental legislative policy.

a) Review and adopt policy guidelines of the WHO [2018]. For infrastructure projects such as roads use active and passive impact assessment methods to evaluate effects on surrounding land.

6.5 LAND-USE PLANNING PROCEDURE RECOMMENDATIONS

6.5.1 Adopt active and passive impact assessment

a) Provide regulatory procedure definitions for both active and passive impact.

Passive Impact: sound from a new source that permeates an existing ambient environment, inundating like floodwater and concealing the lower ranging sounds first. Passive impacts tend to evolve and accumulate over time, are frequently not noticed but are generally irreversible. Passive impact control is commonly relevant to eco-centric legislative objects.

Active Impact: sound from a source similar to others in an existing ambient environment, overlaying and increasing the ambient sound to a louder, but otherwise similar, environment. Allowance for a Just Noticeable Difference (JND) threshold within the Soundscape is appropriate. Active impact effects can manifest rapidly. Active impact control is commonly relevant to anthropocentric legislative objects.

Utilise Table 11 (page 35) if appropriate.

b) Recognise management of cumulative environmental impacts as a priority assessment policy. An approvals policy based on the guidelines of Table 19 is recommended.

Table 19: Limit magnitude of impact criteria (from page 45)

Characteristics compared with ambient sound	Impact Criterion	Reasonable Magnitude of impact
New characteristics involved	Passive	20% (or Figure 11)
Similar to, or already existing, in the environment	Active	20 %

6.5.2 Adopt land area sound classifications

a) Introduce land area sound classifications where appropriate to planning legislation as a referencing category usable in Model Planning Instruments. This thesis proposes classifications as scheduled in Table 20.

Table 20: Land Area Environmental Sound Categories (from page 47)

Land Use Area Sound Category (LSC)	Description
0	Acoustically Pristine Land
1	Rural Land
2	Quiet Residential Land
3	Suburban Residential Land
4	Urban Residential Land
5	Central Business Districts
6	Industrial Land Uses

a) Provide classifications and descriptions for each land use area sound category (e.g. Table 21, cols 5&6)
b) Use classifications to identify the existing nature and amenity in areas potentially affected by a proposed land-use and to provide context against which to consider the findings of site assessment surveys.

6.5.3 Upgrade applicant obligations

a) Include ambient sound levels survey at a potentially impacted location unless such measurement is technically unfeasible.
b) Include description of auditory soundscape elements and associate those observations with measurement survey findings.
c) Present site survey results as a range of observed percentile levels.

d) Describe site activities and activity-based emission on both day-of-week and time-of-day basis, for both proposed and existing land-uses. Phase out application assessment procedures based on equilibrium-state conditions.
e) Define the basis adopted for impact assessment - active and/or passive – reported in an application for approval to carry out a proposed land-use. A physically extensive project may require consideration of different types of impact in different locations.

6.6 POLICY DEVELOPMENT RECOMMENDATIONS

6.6.1 Research emergence-based area preferences

a) Research the potential role for regulatory Land Sound Category / Soundscape based importance functions. These would supplement or replace existing penalty weightings used in current policies and would add positive and negative weighting factors to individual source emergence in determining their contribution to impact. These weightings should be traceable to a local area development policy recognising the relevance of zone-appropriate sources and activities in different ambient land areas.

6.6.2 EPA policy

a) Introduce land area sound classifications as scheduled in Table 20 above.
b) Define the “Ambient Acoustical Environment”:

> *“The subjective audible content of the ambient environment at a place, observed in the absence of any proposed or actual sound producing component that is the subject of an impact assessment review, together with sufficient statistically-based sound pressure level measurement and field observation based description to reasonably characterise that ambient environment”.*

c) Replace usage of the term “Background Noise” with the term “Ambient Acoustical Environment”.
d) Repeal policy permitting the assumption of a lower limit threshold to the ambient acoustical environment for assessment of impact.
e) Require all impact assessment reporting procedures to clearly describe the existing Ambient Acoustical Environment within each potentially affected area. Identify features considered to be at risk of impact, and those not at risk, within those assessment areas.
f) Except where practical issues prohibit direct measurement, require survey measurement of ambient conditions. Where direct survey is invalid or impractical, require the basis used to predict or assume ambient sound level conditions to be fully justified.
g) Require survey of ambient conditions at a site to be reported in a manner that assists communication. This should identify existing subjective aspects and should include sufficient range of statistical measurement parameters to ensure the relationship between environmental elements and ambient sound pressure level conditions can be described.
h) Require benchmark reporting of ambient conditions to explain the site context to the various stakeholders to a development so that they can make informed decisions.
i) Require determination of source levels and of ambient levels to include specification of allowance for variance according to Table 27 above.
j) Continue to use the A-weighted unit for measurement and assessment for acoustical environments.
k) Require survey findings to be presented as probability density functions.
l) Require assessment of both active and passive impact arising from all projects including road development projects.
m) Discard and remove the term “amenity” in its current context in documents issued by the NSW EPA.
n) Require land-use development projects to be evaluated using temporal and stochastically based modelling.
o) Permit the addition of subjective penalty weightings on a per-source basis providing the basis of addition is clearly explained.
p) Adopt the recommendations of the WHO Guidelines 2018 in setting regulatory assessment criteria for noise from industry, roads, railways and aircraft.
q) Review the adequacy of the procedures of The NSW Noise Policy for Industry for all land uses to which the Policy applies. Amend procedures to address impact on land areas that differ substantially from the industrial lands for which the procedures of the Policy were developed.
r) Cease recommending that the NSW Noise Policy for Industry be used as a guide to policy and procedures by regulatory authorities in their own areas of jurisdiction.
s) Prohibit definition of a measured existing equivalent energy level at a location as the sound level generated by existing road traffic without technical justification based on vehicular flow rates and speeds.

6.6.3 Interim EPA recommendations

During an interim period require reported source levels and ambient level benchmarks (background noise level, RBL or L_{A90}) to include allowance for the effects of variance as described above in Table 27.

Update EPA Noise Policy for Industry guidelines as suggested by thesis findings set out in Table 45 below. The results shown in column 4 of Table 45 in bold type distinguish land areas where the analysis of the APD dataset used for this thesis suggest more rigorous research will find deficiency, or omission, in EPA Policy criteria. The cells highlighted in bold type identify land areas that should be formally excluded from application of the Policy instruction in Fact Sheet A1.2, and elsewhere in the Noise Policy for Industry, that

> *Where the rating background noise level is found to be less than 30dB(A) for the evening and night periods, then it is set to 30 dB(A); where it is found to be less than 35 dB(A) for the daytime period, then it is set to 35 dB(A).*

Reference to this general Policy statement should be removed from the Noise Guide to Local Government cl 2.3. The Policy (NPI, section 1.4) is designed for “large industrial and agricultural sources” and it is evident that these activities are generally compatible with the EPA land usage descriptions of Table 21 for Land Sound categories higher than 3, and therefore unlikely to be compromised by the principle of an assumed background noise threshold. In section 1.1.1 of the Policy, prior to the clarification noted above from part 1.4, the policy states that “planning authorities can use the noise levels in the policy to inform decisions about the potential impacts of different types of development”. This statement is incorrect. If applied to local government, Table 21 shows that the use of a threshold limit to background noise will lead to unsatisfactory outcomes in acoustically pristine, rural and quiet suburban areas. The statistics of this study suggest that 100 percent of acoustically pristine land, approximately half of rural land and at least some portions of quieter suburban areas are being compromised where this policy principle is utilised.

Table 45: APD Ambient sound levels compared with EPA guidelines

LSC	Description	EPA NPI Category and Description[1]	L_{A90}[2] observed D/E/N[3]	L_{Aeq} observed D/E/N[3]	NPI RBL[4] dB(A) D/E/N[3]	NPI Amenity[5] L_{Aeq} D/E/N[3]
0	Acoustically Pristine Land		**22/17/15**	**39/31/25**		
1	Rural Land	Rural Residential Dominated by natural sounds; little or no road traffic, sparse settlement	**32/30/25**	**47**/44/40	<40/<35/<30	50/45/40
2	Quiet Residential Land	Suburban Residential Local traffic, intermittent flows, evening noise levels defined by natural environment and human activity	39/38/**32**	**51**/49/42	<45/<40/<35	55/45/40
3	Suburban Residential Land		48/46/42	60/58/53		
4	Urban Residential Land	Urban Residential Dominated by ‘urban hum’…aggregate sound of many unidentifiable, mostly traffic and/or industrial related sound sources…heavy and continuous traffic flows…near commercial districts	47/46/42	58/57/53	>45/>40/>35	60/50/45
5	Central Business Districts		55/53/48	66/65/61		

Notes:

1. Noise Policy for Industry Table 2.3.
2. L_{A90} values refer to the lower bound 67% confidence based on the observed mean
3. D/E/N refers to the day, evening and night period data.
4. Noise Policy for Industry 2017 rating background noise level.
5. Noise Policy for Industry 2017 amenity criteria for dwellings

6.7 AUSTRALIAN STANDARDS RECOMMENDATIONS

a) Substantially revise Australian Standard AS1055 to provide content and procedures that reflect the title of the Standard.
b) Update AS1055. Do not rely on issue of Soundscape standards to provide guidelines for appropriate description and measurement.
c) Include guidance within the standard on preferred methods for effective description and on preferred methods for coordination of description with associated measurement.
d) Consider incorporation of land sound categories as described above.

6.8 RECOMMENDED FURTHER TECHNICAL RESEARCH

a) Research the importance of appropriateness when reviewing an impacting source within a specific land area.
b) Research and develop Land Amenity Categories.
c) Research how existing soundscape work may inform planning preference weightings mentioned in 6.6.1 above - penalty and leniency – to better define significance of impact in the context of amenity of existing lands for land use assessment applications.
d) Research Table 19 and Figure 11 applications to explore limitations in validity.
e) Research commonly occurring stochastic source power levels including their level variance. Particularly examine sound generated by human activities in a range of common situations.

7 APPENDIX 1 – GLOSSARY OF TERMS

The **Acoustical Environment** identifies the components of the Environment that relate to sound.

Acoustical Impact of an action is the portion of the existing acoustical environment that is masked as a result of that action being taken. (%)

Active Acoustical Impact equals the probability that the imposed sound pressure level of an impacting source will exceed the sound pressure level of the ambient environment at any time during an assessment period by more than a just-noticeable-difference. (%)

ANEF is the Australian Noise Exposure Forecast. An ANEF is a plot of estimated noise exposure based on forecasted aircraft movements and aircraft fleet mix at a defined future date.

Anthropogenic is an adjective qualifying any condition, the origin of which can be traced to initiation by or the influence of human beings.

APD Dataset is the name used for this thesis to identify the author's project dataset, being a database of professional ambient sound level survey records.

Average Maximum Emergence equals the average maximum Emergence assessed over a sequence of assessment periods (e.g. a day, the hour-of-day average for a sequence of days, the daytime hours of each of a sequence of days). (dB)

The **A-weighting** refers to a frequency-weighting procedure in which the power or energy spectrum of a signal is progressively attenuated at the low and high ends of the audio frequency range, low frequencies being substantially attenuated and high frequencies being modestly attenuated. (dB(A))

A-weighted sound pressure level refers to the level of a sound pressure signal to which the A-weighting has been applied.

Background Noise Level is the value of the 10th percentile, also known as the L_{90}, of the cumulative distribution of ambient sound pressure levels occurring within a relevant sample period. In the case of an impact assessment, background noise usually refers to the L_{90} of the ambient acoustical environment. (dB)

Cumulative Distribution Function for a variable describes the probability that, at any instant, the value of that variable will be equal to, or less than, the value described by the function.

DNL refer L_{DN}

Emergence equals the instantaneous value of the difference between an imposed sound pressure level and the sound pressure level of the ambient environment that would otherwise be present. (dB)

Emergent Noise refers to a sound having an emergence greater than zero when compared with the ambient acoustical environment and having a character or context that is unwanted in the context of the ambient environment. (dB)

The **Environment** is defined in the Protection of the Environment Administration Act 1991 (s.3) as:

> *…components of the earth, including (a) land, air and water, and (b) any layer of the atmosphere, and (c) any organic or inorganic matter and any living organism, and (d) human-made or modified structures and areas, and includes interacting natural ecosystems that include components referred to in paragraphs (a) and (c).*

Environmental Acoustics refers to the science of outdoor sound, its sources, and its propagation in both natural and urban environments [Morfey,2001]

Environmental Impact [Hede, 1993]

> *….of an action is the difference between the state or condition of the environment which occurs as a result of that action being taken or withheld, and the state or condition which would otherwise occur.*

Environmental Noise refers to the subset of environmental acoustics associated with unwanted sound

Equivalent continuous sound level, usually of a non-stationary sound signal, defined for a specified time interval (T) is the level of a stationary sound signal that has the same energy as the non-stationary signal over that time interval.

Geometric near field refers, for a source of finite size, to the region close to the source within which the distances of different source elements from the field point cannot be treated as equal. In free-field conditions, at distances greater than the geometric near field the sound pressure level decreases 6dB for each doubling of the distance of the field point from the acoustic centre of the source.

Inverse Transformation Sampling refers to the process of randomly sampling a value from a cumulative distribution function utilising a uniform random number distribution to designate a uniform linear probability and deducing that the value of the function at that probability will be no more than the sampled value of the cumulative distribution function. Mathematically the inverse transformation function is described thus:

> *F is the integral of the distribution function of a continuous variable X.*
> *F is both continuous and strictly increasing when $0<F(x)<1$.*
> *If Y is distributed as a uniform distribution function U(0,1) then $X = F^{-1}(Y)$*

Just-Noticeable-Difference equals an amount by which a sound pressure level must be increased for that increase in level to be considered subjectively noticeable. The default value for JND is +3dB.

L_{Aeq} is the symbol used for and A-weighted equivalent continuous sound pressure level. (dB)

L_{AN} is the symbol used for an A-weighted sound pressure level, the value of which is equalled or exceeded for N-percent of the observation period. (dB)

L_{DN} is the symbol used for a day-night equivalent energy level, being the A-weighted equivalent energy determined for a period T=24 hours, during the sampling of which sound levels occurring during specified night-period hours are penalty weighted by an amount of plus 10dB.

Mathematical Simulation refers to a large sequence of mathematical models, in contrast to mechanical or analogue models, of a process or system wherein each mathematical model represents one statistically likely configuration in which the elements of the model can be expected to be arranged and, through the repetition of which, the range of statistically likely conditions expected to arise due to that process or system in aggregate may be examined.

Maximum Emergence equals the maximum value of Emergence reached during an assessment period (e.g. for a one-hour sample). (dB)

Noise is sound that, when compared with a set of objective and subjective assessment parameters, is unwanted. Noise is an undesired or extraneous signal.

Noise Rating Number is a metric determined as the highest of a family of standard reference octave band curves for which the emergence of any of a set of measured octave band sound pressure levels compared to any of the respective noise rating octave band reference levels is zero. (NR#)

Passive Acoustical Impact equals the probability that the imposed sound pressure level of an impacting source will exceed the sound pressure level of the ambient environment at any time during an assessment period. (%).

Pristine Acoustical Environment identifies an acoustical environment comprised of sounds of non-anthropogenic origin.

8 APPENDIX 2 - MODELLING THE STATISTICS OF SOUND

Environmental sound varies almost constantly and is comprised of, normally, many sources. Each of those sources may also vary constantly, so that at any instant the sound pressure level from a given component may be either higher than, or lower than, the aggregate of the sound pressure level from all other components. Emergence refers to the condition when sound generated by a source is higher than that of the rest of the ambient sources. Emergence is an instantaneous quantity – auditory emergence occurs now.

If a field-based sampling study to identify contributory sources were to be conducted within an ambient sound environment, it would be possible to determine the probability of emergence for each of the multitude of sources that comprise that overall environment from the number of times each individual source was identified. Objective measurement of Emergence in field situations is difficult given the fact that the observed sound levels are a combination of the contributing components. The origin of the current noise impact assessment paradigm did, however, evolve from estimation of Emergence using analogue measurement techniques, conditioned by concurrent subjective listening.

8.1 Decibel Addition and Manipulation of Statistical Metrics

The addition of two steady-state incoherent sound pressure levels, L1 and L2, is straightforward, being determined by mathematical manipulation using equation E16.

$$L = 10\log(10^{\frac{L1}{10}} + 10^{\frac{L2}{10}}) \qquad \textbf{E16}$$

Where a new source is introduced to an existing environment, the sound levels for both of which can be characterised as a steady-state level, predicting the outcome is mathematically trivial. An example of this case would be an empty air-conditioned office when an additional air circulation fan starts.

If the instantaneous sound pressure level observed over *X* samples varies, as is common, an equivalent energy sound pressure level (L_{eq}) can be calculated using equation E16, which is logically derived from equation E1:

$$Leq = 10\,log\left(\frac{\sum(10^{\frac{Li}{10}} * x)}{X}\right) \quad for\ i = 1 : X$$

$where\ x\ is\ the\ number\ of\ samples\ stored\ to\ bin\ i$

and

$$\sum x = X \qquad \textbf{E17}$$

A statistical expression of the same time variant sound pressure level data is:

$$Ln = i' \qquad where\ (1 - \frac{\sum x}{X}) = n\% \quad for\ i = 1{:}i' \qquad \textbf{E18}$$

The sum of two or more steady-state sound pressure levels, and of energy-averaged sound pressure levels, is straightforward being derived from equation E16. The validity of the equivalent energy level metric is dependent on the relevance of the sample size (*X*) and assessment duration to the intended purpose – e.g. one full cycle of a particular process. However the mathematical addition of two or more equivalent energy metrics is mathematically straightforward and does not require knowledge of the individual sample sizes, providing the metrics has been derived from measurement or calculation over a valid integration time interval.

The computation of L_n for each source level sample requires a similar assessment interval validity to ensure dataset describing the statistical variation in level for each of the contributing sources is reasonable. The sum of two stochastically variable level events requires a sampling process so as to determine, independently, the probable instantaneous sound pressure levels for each of the individual components.

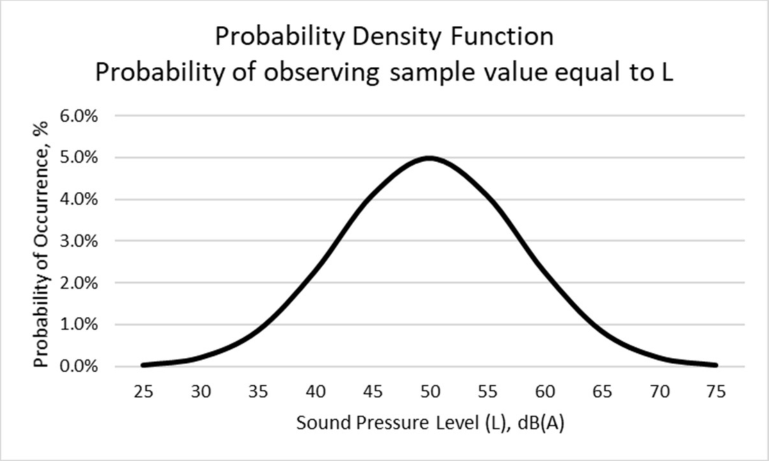


Figure 54: Probability Density Function (PDF)

For many randomly occurring and randomly sampled processes, providing the sample size is large, the observed values of a statistic – e.g. adult male height - consolidate to what is known as a normal distribution. The important parameters from which many statistical analyses associated with the normal distribution can then be derived are the mean sample value, and the standard deviation of the aggregate instantaneous sample values from that mean. These techniques are not widely used in the fields of acoustical measurement. Examples of a probability density function and a cumulative distribution function are shown in Figure 54 and Figure 55, with the latter being related to the common acoustical measurement regime using statistical noise level L_N shown subsequently in Figure 56. The probability density function (PDF) and cumulative distribution function (CDF) are different expressions of the same data and these examples are for a theoretical sample that perfectly follows a normal distribution.

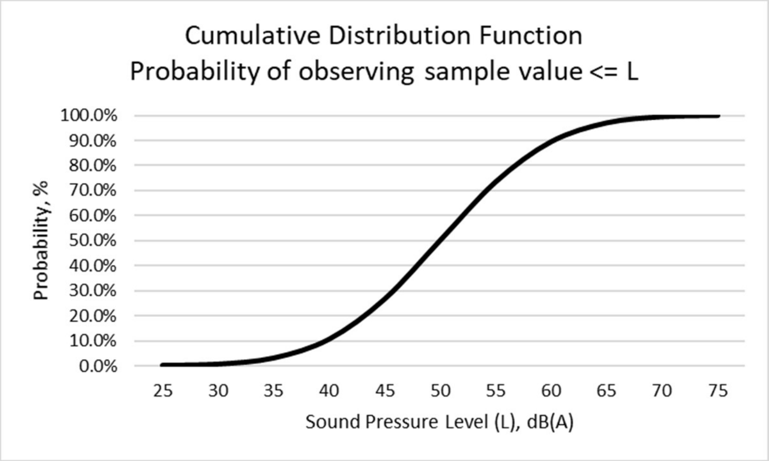


Figure 55: Conventional Cumulative Distribution Function (CDF)

Acoustical convention dictates that a cumulative distribution function derived from a noise measurement sample denotes the probability that the sound level *L* has a value greater than or equal to *b*.

$$F(b) = P\{L \geq b\} \qquad \textbf{E19}$$

This is the inverse of the conventional statistical definition for the cumulative distribution function, wherein *F* denotes a probability that a random variable *L* has a value less than or equal to *b* [Ross,1976] and can result in some unfortunate confusion. Standard statistical convention (Figure 55) can be compared with the same data transformed to acoustical engineering convention (Figure 56).

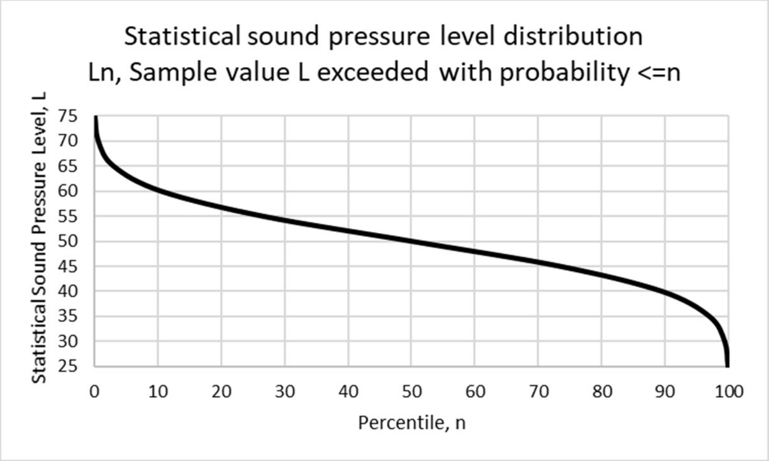


Figure 56: Statistical Sound Pressure Level distribution

As a concluding note, it should be stated that the normal distribution, mathematically, is an unbounded function and the associated cumulative distribution, therefore, can never reach a probability of either zero or 100 percent. This is no different from an important principle in statistical sound level measurement, whereby reported values apply to a finite observation period and true minimum and maximum values can never be known with certainty.

8.2 Sampling and Numerical Modelling

The statistics of sound level Emergence can be examined if the statistics of the contributing sound source components are known. For a land-use study example, the two known sources are the proposed activity and the ambient conditions.

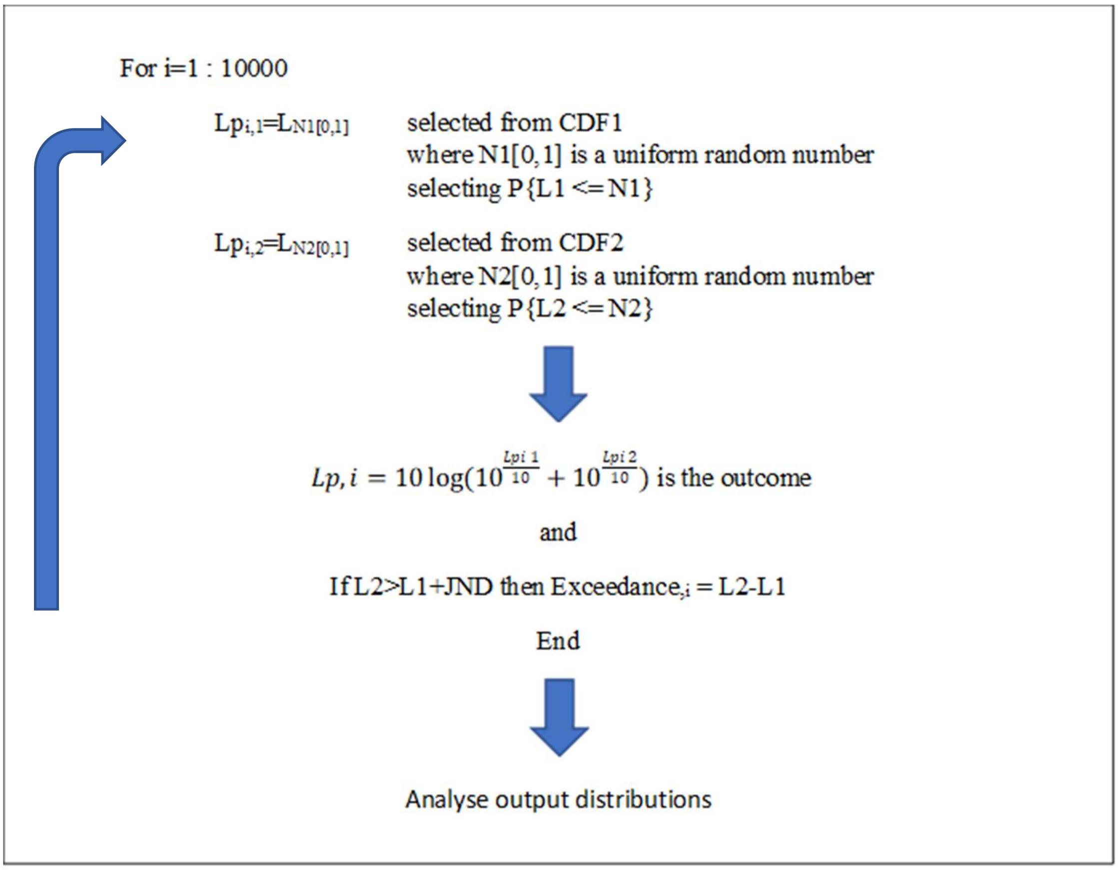
For a trivial case where one steady state sound level is to be combined with a second existing steady state sound level, equation E16 is used and the third value equalling the combined level outcome is quite readily predicted. If this condition were to be examined over a sampling period – say 15 minutes – the three values representing each of the contributing components and of the outcome combined level would be the same at each sample. This is the notional objective achieved by the measurement and expression of source components as an energy-averaged or equivalent-energy level, as the subsequent manipulation is simple.

The same observation is made more complex if one of the components is variable, as the value recorded at each observation for two of the three components will also then vary. If only one of the two component parts is variable then the instantaneous value from the variable component can be calculated using the inverse of equation E16, however the presence of concurrent variance in both source components means that there will be an infinite number of solutions and the true value of each component observation is not solvable. In almost any circumstance, the ambient sound environment will be stochastically variable, as will most sources of interest to environmental acoustic studies.

For prediction, however, this limitation does not exist and powerful planning studies examining Emergence are able to be conducted. This enables the calculation of statistical variance based on the combined condition of the existing ambient sound levels superimposed with the sound of the additional source, or sources, of interest [Fitzell, 1991].

The interaction between two incoherent or independent noise systems can be statistically modelled using iterative inverse transformation sampling. The repetitive application of the algorithm of Figure 57 enables the calculation of the probability that sound from the new source will be lower, or higher, than the ambient sound environment, as well as the distribution levels representing the existing and new sound combined. Inverse transformation sampling involves the conceptually simple process of randomly sampling concurrent instantaneous levels representing each condition of interest and computing the instantaneous aggregate outcome for each sample [Fitzell, 2019]. Through iterative summation, the statistics of the outcome aggregate level – e.g. L_{A1}, L_{A10} etc – can be determined, as well as the statistics of the differences between L1 and L2 at any instant of time. Cases such as a high level but short duration emergence are distinguished from a longer duration lower level emergence using this method, when an energy averaged metric will conclude that they are identical.

By extension, sampling of N-number of sources as well as the concurrent ambient sound pressure levels can determine the Emergence of each of the N sources individually. Where a subjective feature of a source is considered relevant, the Emergence for that source can be estimated including specific weighting factor to the contributory sound levels otherwise generated by that source. The ability to selectively apply subjective weightings to individual or discrete source components is, alone, a major impact discrimination outcome.



```
For i=1 : 10000
    $Lp_{i,1}=L_{N1[0,1]}$    selected from CDF1
                              where N1[0,1] is a uniform random number
                              selecting P{L1 <= N1}
    $Lp_{i,2}=L_{N2[0,1]}$    selected from CDF2
                              where N2[0,1] is a uniform random number
                              selecting P{L2 <= N2}
    $Lp,i = 10\log(10^{\frac{Lpi\,1}{10}} + 10^{\frac{Lpi\,2}{10}})$ is the outcome
    and
    If L2>L1+JND then $Exceedance_{,i}$ = L2-L1
End
Analyse output distributions
```

Figure 57: Inverse Transformation Sampling Algorithm

Figure 57 algorithm utilises a uniform random number and therefore involves sampling from source data expressed as a uniform cumulative distribution function. Knowing the probabilistic values of *L* represented by *F*, randomly selected instantaneous values representing *L* may be determined using a uniform random number [0,1] as a sampling key. Sampling from any distribution is possible, providing the distribution generated by the random number generator is appropriate – the uniform generator is the simplest. From an acoustician viewpoint, the need for an accurate uniform number generator is fundamental and is analogous to the use of a perfect frequency-response electronic amplifier. From a sampling perspective, a procedure designating *b* to be a uniform random number [0,1] may be used to sample from either a conventional cumulative distribution function, or its acoustically equivalent transformation. Due to this disparity between the acoustical and statistical distribution conventions, however, understanding the origin of any data being used for analysis is obviously fundamental.

Each calculation that concludes a sound pressure level from an individual is dominant represents a contribution to the Emergence of that source, and the proportion of time that the source is Emergent represents the overall probability of Emergence for that source. Emergence is a function of both level and time and may be expressed as both a probability density function describing the modal behaviour of that source Emergence, and as a cumulative distribution function showing the probability that Emergence from that source will exceed a given magnitude.

8.3 Sampling Resolution

Sampling is a procedure that involves discrete observations of instantaneous values occurring within a continuous function. Sampling describes a process that may be carried out by a digital measuring instrument, or by a data-interrogation process where values are obtained from a very significantly larger dataset. The values obtained from a sequence of instantaneous observations of a sound pressure level value, by sampling, provide an approximation of the true sound pressure level waveform. These approximations affect both the raw observation data itself obtained from a field study and the values of a randomised sampling trial using Inverse Transformation Sampling. Three overall data reference points are commonly available – L_{max}, L_{min} and L_{eq} – and the relationships between the three parameters can be described mathematically based on Equation E16 where *X* is a large number of sampled instantaneous values ($L_{,i}$) from the values of which Leq is calculated, and L_{max} and L_{min} define the maximum and minimum observed values for $L_{,i}$.

The maximum and minimum observation values from any set of field observations are uncertain estimates of the likely range of a population dataset from which the sampled dataset was drawn. Furthermore, the upper and lower bounds of the raw data range represent instantaneous extrema, whereas all other data points making up the sample represent values falling within a finite interval. The finite interval in the case of the equivalent energy level value is likely to be the duration between each data sample - the sampling rate of the instrument gathering the physical observations (Total time divided by X in equation E16). In the case of statistical data, the portion of the overall observation time period corresponding to a selected statistical value will be a more complex finite period affected by the aggregate number of samples stored to the corresponding storage bin accruing observation data at the required level reporting resolution. If a measuring instrument is designed to report data to the nearest 0.1 of a decibel, each instantaneous observation value is stored to a data storage bin 0.1 decibel wide, with the selected statistical parameter then reported as the N-th percentile of the overall dataset represented by a datapoint somewhere within the group of observation values stored in the relevant raw-data storage bin. The true value of the N-th percentile value is somewhere within the 0.1 decibel width bin. If the probability of occurrence of the maximum and minimum data values is treated, mathematically, as equivalent to that of each of the statistically based values – when one represents a single point and the others are a set of points - distortion of outcomes occurs.

For practical sampling, a probability interval [0:100%] at a resolution of N% can be considered as a sequence of 100/N+1 bins, the first and last bins of which are 0.5N% wide.

The solution to the sampling dilemma lies in the inequality described by equations E20 and E21 from which a sufficiently discrete sampling resolution can be determined. The sampling error will still occur, however the potential effects are adequately minimised.

$$Leq >= 10\,log(\frac{10^{\frac{Lmax}{10}}}{X}) \quad where\ X\ is\ the\ number\ of\ uniform\ observation\ points \qquad \textbf{E20}$$

$$X >= 10^{(Lmax-Leq)/10} \quad where\ X\ is\ the\ number\ of\ sample\ points \qquad \textbf{E21}$$

The typical relationship for the mean L_{Amax} – L_{Aeq} observed in the acoustical environment of many land areas is of the order of 20dB, to which the value of at least one standard deviation should be added. That is, a sampling resolution for environmental acoustical data analysis should make provision for a range of L_{max} to L_{eq}, value of approximately 30dB, requiring a sampling resolution across the input sound pressure percentiles of 1000 points, or a bin width resolution of 0.1 percent. This resolution is used in the following discussion of interpolation issues.

8.4 Interpolation Issues

The data obtained from a statistical noise level survey is usually an array of known data points, each of which represents a sample from a continuous numerical function. The use of the algorithm of Figure 57 requires interpolation between such known data points to produce a level probability distribution function. Unlike many fields of data analysis where measures of departure from central tendency are a statistical parameter of interest, acoustical investigations commonly involve interest in the extreme values of the overall data. A common set of statistical sound pressure level sample points is [L_0, L_1, L_{10}, L_{50}, L_{90} and L_{100}] representing the L_{max} and L_{min} at the respective extremes. Increasingly non-linear level increment occurs with sources associated with acoustical environments and, in fact, in any parameters approaching the extremes of a normal distribution, affecting interpolated data mining values where a numerical simulation is involved.

One simple method of expanding raw data into a full data set is to use a linear interpolation between raw-data measurement points similar to Figure 58. The effect of any interpolation on the logarithmic addition of Equation E15 is to bias the sampling outcome, albeit slightly, toward the value of the higher sample value, or toward the less statistically likely sample value.

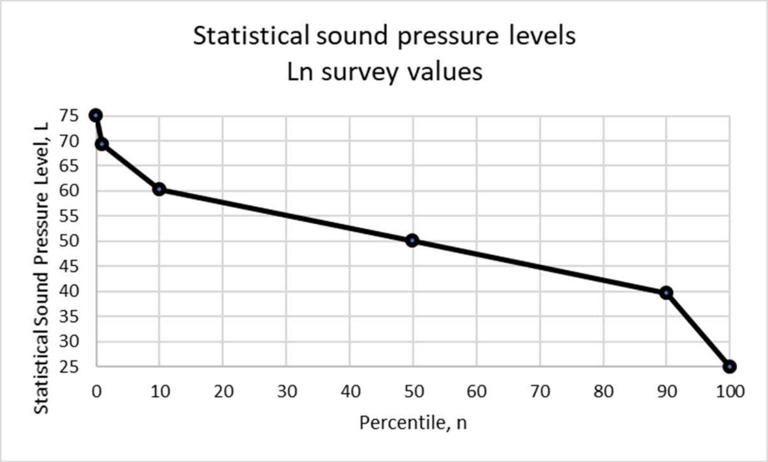


Figure 58: Statistical noise level survey example

A relatively simple but useful improvement to interpolation is the addition of a triangular median interpolation point between each pair of statistical metrics, shown for the same data in Figure 59. Two interpolation test statistics were used to validate this data interpolation techniques, based on raw data statistics of L_{max}, L_1, L_{10}, L_{50}, L_{90} and L_{min}:

1. The predicted equivalent energy level calculated from interpolated datasets were compared with the measured equivalent energy levels, and
2. Statistical parameters for a one-hour measurement period, compiled by merging of interpolated arrays from sequential short statistical periods – 15 minute and 1 minute - were compared with directly measured metrics for the same one-hour periods.

Survey data (N=54) expanded by linear interpolation such as Figure 58 to a dataset produced a mean outcome calculated L_{Aeq} vs measured L_{Aeq} error of +1.4dB with a standard deviation of 1.62dB. Adding triangular interpolation (Figure 59) for the same data reduced mean L_{Aeq} error to +0.4dB, with a standard deviation of 1.52dB. Considering shorter periods and larger data sets using median triangular interpolation, N=226 and N=670, for 15 minute measurement period data, produced mean L_{Aeq} error of -0.12dB and -0.16dB respectively, with standard deviations of 0.77 and 0.29dB respectively. That is, using a median triangular interpolation is likely to result in a systematic calculated L_{Aeq} error of the order of +/-0.2dB.

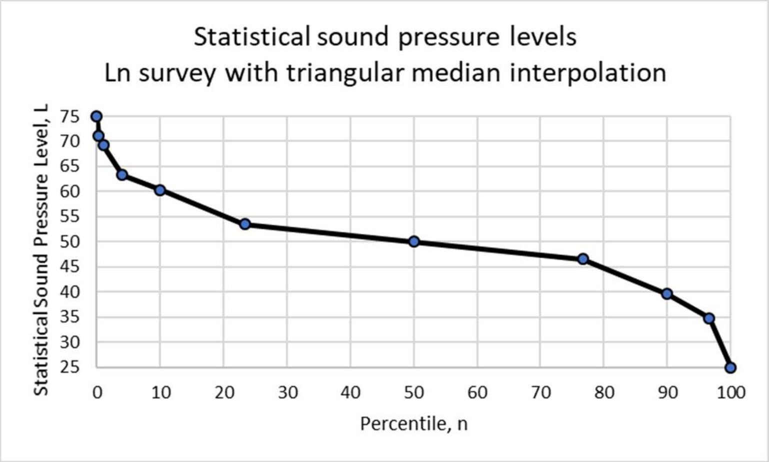


Figure 59: Interpolated raw survey data

The largest error due to interpolation effects was found to occur for the metrics between L_{10} and L_{max}. While this suggests further smoothing using multiple triangular median interpolation points may lead to improvement, the mean error due to interpolation is less than 1dB and almost certainly sufficient for practical applications.

8.5 The Statistical Effect of Multiple Sources

The effect of the presence of multiple sources in an acoustical system is shown in Figure 60. This shows the outcome statistical sound pressure levels for increasing numbers of a highly variable source, each one of which produces sound levels from 20 to 80 dB(A). The outcome is shown to compress the values of the threshold statistical levels relative to the higher statistics, which is not necessarily intuitive. The effect on the stochastically varying sound levels of multiple-source systems, summarised into Figure 61, is that multiple component systems trend toward a steady-state sound generating system.

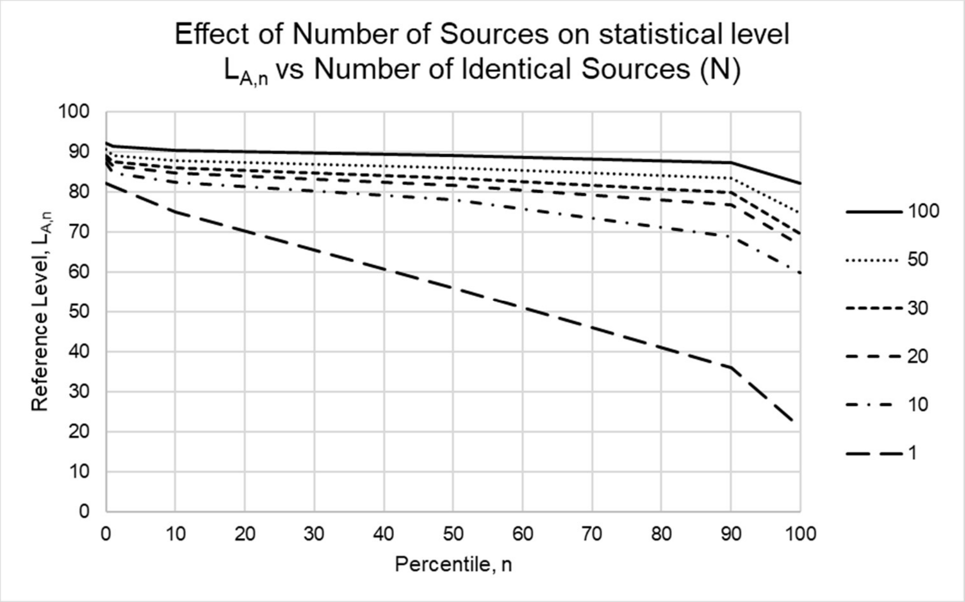


Figure 60: Statistical metric compression due to number of sources

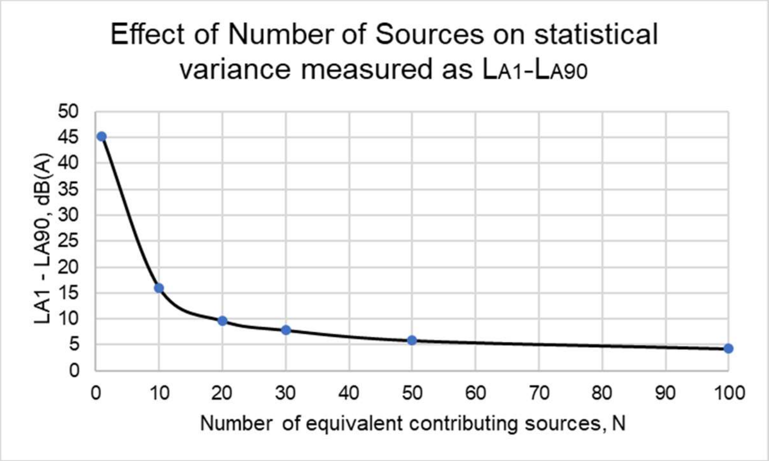


Figure 61: Effect on statistical level variance vs number of sources

This is an important factor when considering potential impact on an acoustical environment as many assessment metrics have developed due to their perceived relevance in situations already involving many component parts. This statistical compression effect, particularly on threshold levels and lower percentile values, is somewhat counter-intuitive in the context of current environmental noise assessment methodology, which focusses on the higher value percentiles.

It is not necessarily obvious that the presence of increasing large numbers of sources in an environment leads to that environment becoming an increasingly stationary sound system. A possible outcome of this was that early impact assessment procedures were found to be satisfactory using a simple “average maxima” minus “average minima” metric because the legislative task was to achieve an overall lowering of noise from industry represented by large scale systems.

9 APPENDIX 3 – Modelling Combined Statistics

Impact assessment for paired conditions - imposed superimposed on existing ambient

The inputs consist of one array representing an existing ambient condition and one array representing an incoherent introduced noise source

Output is a variable NewAmbient representing the statistical levels of the consequential condition

```
******* Declared conditions *******

Resolution=1000;         i.e. Statistics resolved to 0.1%
Iterations=10000;        i.e. The number of accrued summations on which outcomes are based
Numstats=6;
stats=[0,1,10,50,90,100];
JustNoticeableDifference=3;    i.e.  Declared just noticeable difference in dB
```

The interpolation of statistical data used median triangular interpolation between each pair of statistical parameter values.

Six standard statistical parameters were used, being L00, L90, L50, L10, L01 and L100

The algorithms populate statistically based levels for each of the source and the existing ambient across two one-dimensional arrays representing n=Resolution data points between the 0th percentile and the 100th percentile.

Statadd produces an array of instantaneous data, of length equal to the declared number of iterations, each value of which represents a random summation of randomly sampled values for L1 (source) and L2 (existing ambient). The statistical distribution of the table of values provides the statistical levels of the combined level for source superimposed on the existing ambient.

```
for i=1:Iterations

   s1=rand*100;
   L1(p,i)=prctile(arrayx(p,:),s1);      %imposed sample
   s2=rand*100;
   L2(p,i)=prctile(arrayy(p,:),s2);      %ambient sample
   level(p,i)=10*log10(10^(L1(p,i)/10)+10^(L2(p,i)/10));

   if L1(p,i)>L2(p,i)+JustNoticeableDifference;
      sourceemergence(p,i)=L1(p,i)-L2(p,i);
   end

   if L2(p,i)>=L1(p,i)
      CountL2=CountL2+1;
      ambientemergence(p,i)=L2(p,i)-L1(p,i);
   end
end
```

Statadd provides the foundation for more complex analyses:

- Emergence of one source above the existing ambient.
- Emergence of one source above the concurrent aggregate of one or more other sources.
- Emergence of one source beyond a defined threshold above the concurrent sum of one or more other sources.
- Emergence including a defined (+ve or -ve) importance weighting for any of the above.

Emergence can be determined using A-weighted levels or for frequency band data.

10 APPENDIX 4 – Road Modelling Considerations

Roadway definition:

A multiple level co-ordinate array defining:
- Carriageways – for each road (Northbound, Southbound)
- Segments – for each carriageway, segment start/stop coordinates and posted speed limit
- Lanes – for each segment, the number of lanes

The aggregate carriageway length and mean vehicle flow speed jointly influence the mean expected instantaneous number of vehicles located on each carriageway.

Source to receiver propagation matrix - algorithm inputs

Air absorption vs distance, defined as a power series function derived from octave band spectral Analysis of vehicle noise observed at different distances

Shielding vs distance, due to intervening ground contours as a normalised logarithmic function derived from analysis of a range of field observations

Ground absorption vs distance, as a logarithmic function derived from analysis of Concawe data

Dispersion attenuation, for defined Q

Vehicular source presence

Table of AAHT and mean passing speed for 12 vehicle classes utilised to compute hourly time-of-day mean flow statistics for aggregate vehicle flow for each class.

Poisson computation of actual number of vehicles present for each simulation

Vehicle source location, for each vehicle class

Iterative N[0:1] key selection of vehicle location carriageway segment, then lane number

Expected source sound power generation

Independent source sound power level vs speed vs passing speed derived by field survey

Dual source emission levels were examined for propulsion and road-tyre interaction

Vehicle speed management:

Average expected passby speed (EPS) vs posted speed limit derived by field survey.

For multiple lanes, expected passby speed was scaled to 5% above average for vehicles occupying centre lanes to 5% below average for vehicles at kerbside lane.

For each vehicle:

N[0:1] key to add variance to EPS to obtain actual passing speed (APS)
APS used to compute expected sound power level
N[0:1] key to amend expected sound power plus variance to obtain LwThisVehicle

Notes:

Allocation of the number of vehicles on the carriageway at any given instant uses the Matlab function icdf('Poisson',y,lambda), where lambda may be any real number. (Gamma Distribution)

Computation principle:

```
Each simulated snapshot produces an aggregate Lp at a receiver:
  Each snapshot involves, for each land and each class
        the actual number of vehicles, and for each vehicle
        the location, speed and Lw emitted
  For the receiver location,
     the outcome VehicleLp to obtain IndividualEnergy
     aggregating IndividualEnergy to obtain SnapshotEnergy (lane,class)
     aggregating SnapshotEnergy across numlanes*numclasses to obtain SampleEnergy
```

Program structure:

```
for n=1:numreceivers
   for t=1:timeperiods
      for thisrun=1:NumSimulations
         for i=1:NumCarriageways
            for k=1:numclasses
               lambda=VehiclesOnCarriageway(t,k,i)*SampleScaling(i);
               key=rand;   % to select number of vehicles
               alpha=icdf('Poisson',key,lambda);
               if alpha==0
                  alphathisrun=1;
                  else
                  alphathisrun=alpha;
               end
               IndividualEnergy=0;
               for count=1:alphathisrun
                  vehicleposition=fix(rand*sourcepoints)+1;
                  laneselection=round(rand*100)+1;
                  lanekey=round(CarriagePositions(vehicleposition,i+2));
                  runninglane=LaneProbability(lanekey,laneselection,k);
                  EPS=CarriagePositions(vehicleposition,2);
                  APS=(num14(k,1)+VarianceMultiple*(icdf('normal',rand,0,num14(k,2))))*EPS;

LwThisVehicle=10*log10(10^((num13(k,1)*log10(APS)+num13(k,2))/10)+10^((num13(k,3)*log10(APS)+num13(
                  k,4))/10));

                  LwVARThisVehicle=VarianceMultiple*(icdf('normal',rand,0,num13(k,6)));
                  LwThisVehicle=LwThisVehicle+LwVARThisVehicle;
                  directpath=distance(vehicleposition,LanesNorth*(i-1)+runninglane,n);
                  if Nbarrier==1
                     if directpath>ShieldingDistance
                        shielding=10*log10(directpath^2)-20;
                     else shielding=0;
                     end
                     else shielding=0;
                  end
                     if Nground==0
                        GroundAbsorption=0;
                        else
                        if directpath>100
                        GroundAbsorption=6*log10(directpath)-12.283;
                        else GroundAbsorption=0;
                        end
                     end
                     if Nair==0
                        AirAbsorption=0;
                     else
                        AirAbsorption=0.2043*(directpath^0.4574);
                     end

LpThisVehicle=LwThisVehicle+10*log10(Q/(4*pi*(directpath^2)))-shielding-GroundAbsorption-AirAbsorption-
                  (Nextra)*directpath;

                  end
                  IndividualEnergy=10^(LpThisVehicle/10);
                  SnapshotEnergy(i,k)=SnapshotEnergy(i,k)+IndividualEnergy;
                  TotalEnergy(n,t)=TotalEnergy(n,t)+IndividualEnergy;
               end    %end this snapshot of alpha vehicles (count)
            end     %end vehicle class loop for this snapshot (k)
         end        %end carriageway loop (i)
```

```
            for i=1:NumCarriageways
                for k=1:numclasses
                ThisRunEnergy(n,t,thisrun)=ThisRunEnergy(n,t,thisrun)+SnapshotEnergy(i,k);
                end
            end
            SnapshotEnergy=zeros(NumCarriageways,numclasses);
            ThisRunLp(n,t,thisrun)=10*log10(ThisRunEnergy(n,t,thisrun));
        end            %end this simulation run (thisrun)
        TotalEnergy=real(TotalEnergy);
        ThisRunLeq(n,t)=10*log10((TotalEnergy(n,t)/NumSimulations));
   end         %end timeperiod loop
end    %end receiver loop
```

Computation output:

Standard metrics - L_{Aeq}, L_{Amax}, L_{A01}, L_{A10}, L_{A50}, L_{A90}, L_{Amin} for each hourly time period

Recommended modelling expansion:

More work is required on motor bike noise in particular, including motor bike rider convoys.

Consider if 'loud' should be an optional function applied to cars and motor bikes as a further source variance function associated with driver behaviour.

The concurrent assessment of impact from more than one road will require either iterative application of the above algorithms for each of the z=1:NumRoads, or the declaration of more carriageways to represent the alternative roadway, depending on the outcome of interest.

11 APPENDIX 5 – Publications in the Course of This Work

1. Fitzell R.J. (2019) “Prediction of Statistical Noise Metrics for Road Traffic”. InterNoise 2019
2. Fitzell R.J. (2019) “Environmental Noise Analyses – A Rethink”. interNoise 2019
3. Fitzell R.J. (2019) "Impact and its Magnitude". Acoustics 2019
4. Fitzell, R.J. (2019) "Expected ambient noise levels in different land-use areas". ACOUSTICS 2019

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