Investigating Sound Decrement per Doubling of Distance as a Universal Room Acoustics Parameter

by

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B.A.Sc. The University of British Columbia, 2014

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Mechanical Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

February 2020

The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, a thesis entitled:

Investigating Sound Decrement per Doubling of Distance as a Universal Room Acoustics Parameter

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Abstract

The suitability of Sound Decay per Doubling of Distance (DL_2), as a universal room acoustics rating parameter was investigated.

DL_2 was combined with the Speech Transmission Index (STI) to rate acoustical room quality. This follows the methodology of ISO 3382-3, allowing evaluation of room quality using speech intelligibility as a foundation quantity.

To prescribe rating criteria, all rooms where unamplified speech is present were postulated to be categorizable into one of three room types: Case 1 (intelligibility) rooms where intelligibility is required at all distances, Case 2 (distraction) rooms where distraction is permissible until a defined distance, or Case 3 (privacy) rooms where privacy is expected beyond a defined distance. For rating metrics, Case 1 used listening effort, Case 2 used loss of productivity, and Case 3 used percentage of speech intelligible.

An idealized initial tool was developed which calculates STI at all points along a DL_2 curve. The tool calculated STI based only on reverberant speech and was therefore applicable only to rooms where direct speech is impeded by obstacles.

Assumptions used in the initial tool were checked using experimental data collected in 62 rooms of varying case classifications from 22 buildings. The data were used to evaluate the accuracy of regressions using sound pressure level measurements over a limited range of 1 – 16 m ($DL_{2,s,A,1-16m,}$), the octave band variation in DL_2, and the sound pressure level at 1 m from a sound source. The maximum regression error for $DL_{2,s,A,1-16m,}$ was 5.6 dB, and 2.5 dB on average.

DL_2 trends observed in the experimental data were then implemented in the DL_2 tool and the STI calculation model was updated to include direct speech contributions.

The updated tool was used to evaluate theoretical rooms for each case using the developed rating schemes. Room reverberation time (RT, T) and background noise levels (BNL, L_n) were modeled using values recommended in standards.

Due to the variability of RT and BNL within rooms of similar types, standardized rating schemes based on DL_2 were deemed unfeasible. However, DL_2 and the tool developed provide valuable insight on how to optimize rooms acoustically.

Lay Summary

The rate that sound decreases with increasing distance from a sound source is proposed as a quantity for evaluating the acoustical quality of rooms.

A model relating the rate of sound decay to the intelligibility of speech was implemented as a tool.

Three room categories were hypothesized and a rating scheme for each category was developed. A literature review was conducted to find rating metrics that would be intuitive to lay users.

The tool originally assumed perfect conditions and was verified using experimental data. Modifications were made according trends observed in the data to better approximate the real behavior of sound.

The updated tool accepts reverberation time, background noise level, sound propagation and speech effort as inputs to produce charts relating intelligibility and distance. Due to variable room conditions, standardized ratings were not feasible and the tool is best suited for aiding design and remedial decisions.

Preface

This dissertation includes a DL_2 vs Distance model which uses a DL_2 implementation scheme based on ISO 3382-3 “Acoustics – Measurement of room acoustic parameters – Part 3: Open plan offices”, which in turn is based on the publication “Determination of Acoustical Conditions in Open-Plan Offices: Proposala for New Measurement Method and Target Values” by Petra Virjonen, Jukka Keranen, and Valtteri Hongisto.

Proposition of an alternative rating scheme as opposed to using the Speech Transmission Index (STI) is my original work. The ratings are based on existing research.

The intelligibility case (Case 1, Chapter 2.2.1.1) and the privacy case (Case 3, Chapter 2.2.1.3) use data from J. Rennies and H. Schepker’s publication “Listening Effort and Speech Intelligibility in Listening Situations Affected by Noise and Reverberation”. Figure 2.5 of this thesis was taken directly from the aforementioned publication (Page 2647 of J. Acoust. Soc. Am., Vol. 136, No. 5, November 2014).

The distraction case, (Case 2, Chapter 252.2.1.2) uses data from V. Hongisto’s publication “A model for Predicting the Effect of Speech of Varying Intelligibility on Work Performance”. Figure 2.6 of this thesis was taken directly from the aforementioned publication (Page 465 of Indoor Air, Vol. 15, 2006).

The Speech Transmission Calculation schemes (reverberant speech calculation scheme and direct speech calculation scheme) were obtained from T. Houtgast and M. Steeneken’s publication “Predicting Speech Intelligibility in Rooms from the Modulation Transfer Function”, published in Acustica, Vol. 16, pp. 60-72, 1980. Modifications to the direct speech calculation scheme proposed in Chapter 4.1.1 are my original work.

Speech vocal effort spectra in for the calculation of STI were obtained from ANSI S3.5-1997 “Methods for Calculation of the Speech Intelligibility Index”, published by the American National Standards Institute in New York. The data is presented in this thesis in Table 2.1.

The Balanced Noise Criterion background noise spectra used in the calculation of STI were obtained from L. Beranek's publication "Balanced noise-criterion (NCB) curves", published in the Journal of the Acoustical Society of America, vol. 86, no. 2, in 1989.

Human directivity factors used in the calculation of STI were obtained from R. Watson and O. Downey's publication "The Little Red Book of Acoustics: A Practical Guide", published by Blue Tree Acoustics in Sheffield, in 2008. The data is presented in this thesis in Table 2.3.

The free-field distances shown in Table 2.5 were obtained from M. Hodgson's and N. Heerema's publication "Sound-Propagation Curves in Industrial Workrooms: Statistical Trends and Empirical Prediction Models", published in Volume 3 of Building Acoustics in 1996.

Modifications to the DL_2 vs Distance model are my original work and are based on experimental data which was collected from a Healthcare Building Indoor Environment Quality (IEQ) study conducted by Dr. K. Bartlett, Dr. M. Hodgson, Dr. L. Scannell, Jinying Sun, Juliette Rauscher, and Denny Ng. Access to office buildings operated by Fraser Health (FH), Providence Health Care (PHC), Provincial Health Services Authority (PHSA) and Vancouver Coastal Health (VCH) was coordinated by Maureen Haddock and Rob Kolen. The data is presented in Chapter 3. I assisted in data collection and analysis as an intern student.

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Glossary

α – Absorption coefficient of a surface, defined from 0 – 1

α_{ST} – Average surface absorption of a room

α_c – Ceiling absorption, defined from 0 – 1

α_f – Apparent furnishing absorption, defined from 0 – 1

CIS – Common Intelligibility Scale

dBA – A-weighted sound pressure level

$\delta(t)$ – The dirac-pulse function

DL_2 – Decrement of sound pressure level per doubling of distance, in dB/DD

$DL_{2,f}$ - DL_2 of frequency band f, in dB/DD

$DL_{2,s,A}$ – DL_2 of A-weighted speech pressure level, in dB/DD

$DL_{2,s,4m}$ – DL_2 of speech pressure level starting at a distance of 4 m, in dB/DD

$DL_{2,s,A,1-16m}$ – DL_2 of speech pressure levels between distances of 1 – 16 m, in dB/DD

DP – Loss in productivity, in %

EDT – Early decay time, in seconds

f – Frequency, in Hertz

$H_{divider}$ – Height of office divider, in metres

Hz – Frequency, in Hertz

L – Sound pressure or power level, in dB

$L_{A,s,1m}$ – A-weighted speech pressure level evaluated at a distance of 1 m, in dB

L_n – background noise level, in dB

L_p – Sound pressure level, in dB – relative to $2x10^{-5}$ pascals

$L_{p,1m}$ – The sound pressure level at a distance of 1 m from a source, in dB

$L_{p,1m,FF}$ – The sound pressure level at a distance of 1 m from a source in a free field, in dB

$L_{p,direct}$ – Direct sound pressure level of a sound source

$L_{p,indirect}$ – Indirect sound pressure level in a room resulting from a sound source

$L_{p,total}$ – Total sound, comprising both direct and indirect sound

$L_{p,s,4m}$ – A-weighted speech pressure level evaluated at a distance of 4 m, in dB

$L_{p,s,1m,0^\circ}$ – Speech pressure level measured at a distance of 1 m, and at direct incidence, in dB

$L_{p,s,1m,avg}$ – Average speech pressure level at a distance of 1 m, in dB

$L_{p,avg}$ – Sound pressure level averaged over 360° around a source, in dB

$L_{p,0^\circ}$ - Sound pressure level at direct incidence (0°) from a source, in dB

$L_{p,S,A,exp}$ – Measured speech pressure level along a DL_2 curve

$L_{p,S,A,reg}$ – Predicted speech pressure level according to a DL_2curve

L_w – Sound power level, in dB – relative to 10^{-12} watts

$m(f)$ – The modulation transfer function evaluated at frequency f

N – Total number of measurements in a series of measurements for calculating DL_2

NCB – Balanced Noise Criterion contours, spectra for describing HVAC noise in occupied rooms

NC – Noise Criterion contours, spectra for describing HVAC noise in unoccupied rooms

ρ – Reflection coefficient of a surface, defined from 0 – 1

P_{ref} – Reference sound pressure level – $2\text{x}10^{-5}$ pascals

P_{rms} – Room mean squared pressure, used in calculation of sound pressure level

Q_θ – Source directivity factor

Q_t – Directivity index of a talker

Q_l – Directivity index of a listener

r – Distance, in metres

$r(t)$ – The total squared impulse response for a room

r_0 – Distance of first L_p measurement in a series of L_p measurements for calculating DL_2

r_c – Critical radius, defined as the distance where indirect direct sound are equal, in metres

$r_d(t)$ – The direct sound contribution to the room impulse response

r_d – Distraction distance, in metres

$r_i(t)$ – The indirect sound contribution to the room impulse response

r_n – Distance of L_p measurement in a series of L_p measurements for calculating DL_2

r_p – Privacy distance, in metres

r_{tr} – The transition distance, where the intelligibility rating classification changes, in metres

RIR – Room impulse response

RIR_{real} – Real room impulse response

RIR_{sim} – Simulated room impulse response

RIR_{wn} – Room impulse response generated using white noise

RT, T – Reverberation time, typically refers to T_{20}

s – Seconds

s – Scattering coefficient

S – Surface area of a room

SII – Speech Intelligibility Index

SLA – A-weighted speech pressure level, in dB

S/N – The signal to noise ratio

S/N_{app} – The apparent signal to noise ratio, truncated at -15 dB, and 15 dB

SP – Sound propagation, in dB/DD, see also: DL_2

STI – Speech Transmission Index, defined from 0 – 1

STI_f – The speech transmission index at frequency f

t – Time, in seconds

τ – Transmission coefficient of a wall or divider, defined from 0 – 1

T_{20} – Reverberation time calculated from first 20 dB of sound decay starting at -5 dB

T_{30} – Reverberation time calculated from first 30 dB of sound decay starting at -5 dB

T_{60} – Reverberation time calculated from 60 dB of sound decay starting at -5 dB

Acknowledgements

I would like to express my sincerest gratitude to the late Dr. Murray Hodgson for inviting me to study as a graduate student and providing me with his unconditional support and guidance throughout my studies.

I would also like to thank Shira Daltrop for agreeing to be the technical expert on my defense committee and taking time out of her personal life to help review this thesis. I would not have been able to finish my degree if it weren't for her support during the final phases of my studies.

Finally, I would like to thank Dr. Steven Rogak for acting as my supervisor. In the absence of an entity overseeing the progress of my thesis, I had halted all work. It is thanks to his support that I was able to figure out the logistics of finishing my degree.

1 Introduction

1.1 Motivation

Current methods for acoustical characterization of rooms are based on the following set of parameters: background noise level, signal level, and reverberation time. These parameters make up the temporal and steady-state characterization at specific locations in a room. However, the spatial characteristics of the sound field are unaddressed without the use of numerical modeling.

In the case of listening situations such as classrooms, a minimalist assessment will focus only on a limited number of talker-listener position pairs such as a talker at the front of the classroom and the closest seat, then the farthest seat. The assessment may find that the front row has excellent speech intelligibility and that the back row has poor speech intelligibility – the speech intelligibility at intermediate positions remains unaccounted for. In cases where funds for remedial work is limited, knowing the spatial characteristics of sound in a room could facilitate better use without the need for extraneous expenditures.

The decay of sound pressure per doubling of distance (DL_2, in dB/DD) characterizes the behaviour of sound as a function of distance. Since DL_2 is a property of the room (resulting from room geometry, sound absorption characteristics, and surface sound scattering characteristics) it can be assumed that the rate of sound decrement from any source is identical regardless of where it is located or the direction of propagation. The sound pressure level (L_p) at any location can be predicted if the number of sound sources, their sound power levels (L_w), and distances (r) from a receiver are known. In cases with normal human talkers, an average human talker sound power spectrum may be assumed.

DL_2 can be thought of as how sources and receivers are connected or disconnected, regardless of whether the sound is useful or detrimental. For a given speaker-listener distance, DL_2 will indicate whether the speaker will be connected (intelligible, audible) or disconnected (unintelligible, inaudible). Understanding the factors which affect DL_2 will facilitate better acoustical design in rooms.

Therefore, adoption of DL_2 is proposed as a universal room acoustics parameter. As opposed to spot measurements, where intuition is required to select suitable measurement locations, DL_2 is a spatial property by definition and a single series of measurements spanning the length of a room is expect to suffice in approximating a room's acoustical environment.

It is therefore of interest to investigate a method for applying DL_2 to rooms. In addition, developing rating schemes based on DL_2 will provide users with an intuitive evaluation method.

1.2 Acoustical Background Information

The following subsections will explain the basic quantities and principles used in acoustics. Advanced quantities and principles specific to this thesis will be explained as they are introduced.

1.2.1 Sources and Receivers

Fluctuations in pressure in fluids are perceived as sound. In acoustics, sources of pressure fluctuations (such as loudspeakers, human talkers, etc.) are referred to as sources and receptors of sound (human listeners, microphones, etc.) are referred to as receivers.

1.2.2 Sound Pressure Level (L_p)

Sound pressure level (L_p) is the main quantity of interest in acoustics. It is related to the physical amplitude of sound waves and the loudness of sound. The amplitude refers to the absolute maximum pressure and is therefore quantified in Pascals (Pa). Since the range of pressure fluctuations detectable by the human ear spans several orders of magnitude, L_p is quantified in a logarithmic term referred to as decibels (dB). As all logarithmic terms are relative, L_p is calculated from the root mean square of a pressure fluctuation (P_{rms}^2) in relation to the P_{rms}^2 of the lowest sound pressure audible to human beings (P_{ref}^2) using Eq. (1.1). L_p is a term used to quantify all sounds whether beneficial (e.g. speech) or harmful (e.g. noise).

$$L_p = 10\, log\left(\frac{P_{rms}^2}{P_{ref}^2}\right) \quad \textbf{(1.1)}$$

Where:

P_{rms} is the room mean square pressure

P_{ref} is the reference pressure, which is equal to 2x10^{-5} Pa. This is cited to be the lowest audible level for a human of normal hearing at 1,000 Hz.

1.2.3 Addition and Subtraction of Sound Pressure Levels

As sound pressure levels are logarithmic terms, they cannot be added or subtracted arithmetically. Addition and subtraction operations are done logarithmically as shown in Eq. (1.2) and Eq. (1.3).

$$L_{1+2} = 10\,log\left(10^{\left(\frac{L_1}{10}\right)} + 10^{\left(\frac{L_2}{10}\right)}\right) \tag{1.2}$$

$$L_{1-2} = 10\,log\left(10^{\left(\frac{L_1}{10}\right)} - 10^{\left(\frac{L_2}{10}\right)}\right) \tag{1.3}$$

Where:

L_1 and L_2 are sound pressure levels in decibels.

Note that the summation of two sound pressure levels which differ by 10 dB results in a value that is 0.5 dB greater than the higher sound pressure level. For example, the logarithmic sum of 50 dB and 60 dB is 60.5 dB. In acoustics, a signal can be considered negligible if it is 10 dB lower than another.

1.2.4 Frequency and Octave Bands

Frequency, in Hertz (Hz), is related to the human perception of pitch. The audible frequency range in humans is 20 to 20,000 Hz. Predetermined ranges of frequencies are combined into bins called bands.

In acoustics, the bands are referred to as octave bands and third octave bands. The term octave is derived from the Latin term *octavus*, or eighth, and is defined as the interval between two pitches where the second pitch is double that of the first. In acoustics, each band's centre frequency is double that of the previous band, and the bandwidth increases with increasing frequency. Acoustics also makes use of third-octave bands, where the bins are reduced in size. The sound pressure level of an octave band is the sum all the pressure levels of its constituent frequencies. Table 1.1 shows the standard octave band numbers and centre-frequency of full octave bands used in acoustics.

Table 1.1 - Full-octave octave band numbers and their associated frequencies in acoustics

Band number	1	2	3	4	5	6	7	8
Frequency [HZ]	63	125	250	500	1,000	2,000	4,000	8,000

1.2.5 A-weighting

Despite being of the same sound pressure level, sounds of different frequencies are perceived as being different in loudness. The perceived loudness as a function of frequency is due to the physical makeup of the human auditory system.

The A-weighting network is a series of frequency-dependent correction factors that are used to adjust measured sound pressure levels to represent what humans will perceive. The A-weighting network correction factors and their corresponding centre frequencies and are shown in Table 1.2. The adjustments are simply added or subtracted to the octave-band sound pressure level. The resulting values are referred to as the A-weighted sound pressure level, notated as dBA.

Table 1.2 - A-Weighting value for each Octave Band

Octave band	125	250	500	1,000	2,000	4,000	8,000	16,000
WEIGHTING [DB]	-16.1	-8.6	-3.2	0	1.2	1.0	-1.1	-6.6

The A-weighted sound pressure level (dBA) of a signal is then the A-weighted octave-band sound pressure levels summed in accordance to Eq. (1.2).

1.2.6 Characterization of surfaces

All surfaces can be defined acoustically using the following quantities: absorptivity (α) the percentage of incident sound on a surface that is absorbed and then converted either to heat or vibration; transmissivity (τ) the percentage of incident sound on a surface that is transmitted to the other side as sound; reflectivity (ρ) the percentage of incident sound that is reflected. Each of these quantities range from 0 to 1, and their sum is 1.

Reflectivity is then further defined by its scattering coefficient (s). The scattering coefficient ranges from 0 to 1. With a scattering coefficient of 0, the incident sound is reflected specularly and is likened to light reflected by a mirror. With a scattering coefficient of 1, the incident sound is scattered randomly, and the amount of sound being reflected is equal in all directions.

1.2.7 Definition of a Room

A room is defined as a space enclosed by a floor, walls and a ceiling, typically for human occupation. For the acoustics inside an individual room, the relevant parameters are the absorptivity and scattering coefficients.

1.2.8 Direct and Indirect Sound

Sound is typically categorized as being direct or indirect. In rooms, sound that is reflected off of a surface is considered to be indirect sound ($L_{p,indirect}$). Conversely, sound that reaches a receiver without being reflected is called direct sound ($L_{p,direct}$). Except for engineered environments such as anechoic chambers, or at a large distance from any surface, direct sound is rarely found isolated from indirect sound. The combination of direct and indirect sound is referred to as the total sound ($L_{p,total}$).

According to diffuse field theory, the total sound pressure level due to a point source in a room can be predicted using Eq. (1.4):

$$L_{p,total} = L_w + 10log\left[\frac{Q_\theta}{4\pi r^2} + \frac{4(1-\alpha_{ST})}{S\alpha_{ST}}\right] \quad \textbf{(1.4)}$$

Where:

L_w is the source power level in decibels relative to the reference sound power level of 10^{-12} watts

Q_θ is the source directivity factor, which equals 1 for omnidirectional point sources

r is the source-receiver distance in m

S is the total surface area of the room

α_{ST} is the room averaged absorption coefficient

Within the logarithmic argument are the direct-field and reverberant (indirect) field contributions, respectively.

When considering only direct sound (i.e. in a free-field), only the first term of the logarithmic argument remains. Then for omnidirectional point sources, Q_θ is 1, resulting in Eq. (1.5).This form is also useful for sound source calibrations, which are undertaken in approximated free-field environments known as Anechoic chambers. For calibration measurements at 1 m, the logarithmic term becomes zero, and the sound power level is simply the average sound pressure level plus 11 dB. For every doubling of distance, $L_{p,direct}$ decreases by 6 dB. This behavior is also known as the inverse square law. The 6 dB decay per doubling of distance is constant regardless of environment for the direct sound component of an omnidirectional point source in three dimensional space.

$$L_{p,direct} = L_w - 11 - 10log(r^2) \tag{1.5}$$

Conversely, the reverberant field contribution does not include any distance terms, suggesting that the reverberant sound pressure level is constant at all distances from a source. However, this generally only occurs in an engineered environment known as a reverberation chamber. Reverberation chambers are designed such that the room is nearly cubic in geometry, is large in volume, has hard reflective surfaces only, and have sound scattering surfaces distributed throughout the volume of the chamber.

The conditions required to achieve a uniform reverberant field are rarely satisfied by real rooms. Real rooms are rarely cubic in geometry and acoustically absorptive surfaces are typically unevenly distributed. As such, the indirect sound is typically calculated by logarithmic subtraction of the calculated direct sound (using L_w) from the measured total sound in accordance with Eq. (1.3), resulting in Eq. (1.6).

$$L_{p,indirect} = 10log\left(10^{(L_{p,total}/10)} - 10^{(L_{p,direct}/10)}\right) \tag{1.6}$$

1.2.9 Reverberation Time (RT)

Reverberation time (RT) quantifies the temporal decay of sound. It is defined as the time required for sound pressure level to decrease by 60 dB. Measuring 60 dB of decay requires that the signal exceed the background noise level by 60 dB in every band, which is difficult to achieve in practice. Instead, the reverberation time is approximated by measuring the decay time between two thresholds and extrapolating to 60 dB. Common reverberation time calculation schemes are shown in Table 1.3.

Table 1.3 - Reverberation Time Quantities and Calculation Thresholds

RT Scheme	Start Threshold [dB]	End Threshold [dB]
Early Decay Time (EDT)	0	-10
$\mathbf{T_{20}}$	-5	-25
$\mathbf{T_{30}}$	-5	- 35

As Early Decay Time (EDT) is based on the first 10 dB of decay, it is highly affected by local surfaces. EDT is expected to vary immensely with location in a room. T_{20} and T_{30} exclude the first 5 dB, and extrapolate over a larger range, making them more representative of the average reverberation time. T_{20} is widely used in acoustical engineering.

1.2.10 Decrease in Sound Pressure Level per Doubling of Distance (DL_2)

DL_2 is the rate of spatial decay of sound and is defined as the decrease in sound pressure level per doubling of distance (dB/DD) from a source. DL_2 is calculated using Eq. (1.7). For reference, free-field decay for an omnidirectional point source in 3-dimensional space (as introduced in Section 1.2.8) has a DL_2 value of 6 dB/DD.

Typical presentation of data for DL_2 involves plotting sound pressure level on a base-2 logarithmic scale for easy comparison to the free-field case. Moreover, logarithmic regressions are favorable over linear regressions as experimental data suggests that sound typically decays exponentially with distance.

$$DL_2 = -log_{10}(2) \frac{N \sum_{n=1}^{N} \left[L_{p,n}\, log_{10}\left(\frac{r_n}{r_0}\right)\right] - \sum_{n=1}^{N} L_{p,n} \sum_{n=1}^{N} log_{10}\left(\frac{r_n}{r_0}\right)}{N \sum_{n=1}^{N}\left[log_{10}\left(\frac{r_n}{r_0}\right)\right]^2 - \left[\sum_{n=1}^{N} log_{10}\left(\frac{r_n}{r_0}\right)\right]^2} \qquad \textbf{(1.7)}$$

Where:

N is the total number of sound pressure level data points
$L_{p,n}$ is the sound pressure level at data point n

r_n is the distance at which $L_{p,n}$ was measured
r_0 is the initial (or smallest) measurement distance

1.2.11 Speech Transmission Index (STI)

Speech Transmission Index (STI) is a measure developed by Houtgast and Steeneken to quantify the quality of speech at a listener position [1]. It is based on a technique used in optics called the Modulation Transfer Function (MTF) and assesses the degradation of speech signal integrity due to noise and reverberation time. Increasing noise and reverberation time reduces intelligibility. STI is rated on a scale of 0 to 1, with 0 being totally unintelligible, and 1 being perfectly intelligible with no signal degradation.

Table 1.4 - Quality Ratings and STI Value Ranges for Speech Intelligibility (From IEC 60268-16)

STI Rating	Bad	Poor	Fair	Good	Excellent
STI Range	0.00 – 0.30	0.30 – 0.45	0.45 – 0.60	0.60 – 0.75	0.75 – 1.00

1.3 Literature Review

Prior to its current name of DL_2, sound decrement per doubling of distance was introduced by Sharland as an estimate for sound propagation in open-plan offices [2]. Free-field decrement of 6 dB per doubling of distance was used as a comparison for the sound decrement in open-plan offices. Sharland's theoretical analysis of a sound source in an open-plan office resulted in an expected decrement of 3 dB per doubling of distance.

In addition to its application in open-plan offices, DL_2 was used to predict noise exposure due to equipment in industrial rooms. DL_2 has been described using different terms throughout its use, and all descriptions of existing work will use the original terminology and conventions. When referring to DL_2, increasing DL_2 magnitude means an increasing rate of decrease in sound pressure level. Sound propagation is the converse of DL_2: when DL_2 is high, sound propagation is low, and vice versa.

1.3.1 DL_2 for Predicting Noise Exposure

In 1981, Lindqvist presented experimental sound pressure level data versus distance on a logarithmic scale [3]. A logarithmic distance scale was used for direct comparison to point-source free-field decay of 6 dB per doubling of distance. While logarithmic regressions were not applied to the data, Lindqvist made extensive reference to the rate of spatial sound decay, and factors that influenced it. Lindqvist observed that values of sound decay approached 6 dB/DD as absorption increased, but never exceeded it.

Hodgson used the term sound propagation (SP) to describe the decay of sound pressure level per doubling of distance in four industrial rooms under unfitted, partially fitted, and fully fitted conditions in 1983 [4]. Sound propagation was found to be insensitive to direction of propagation when the roof is not pitched. When the roof is pitched, sound propagation varied with direction in the room. This was theorized to be caused by either the pitched roof reflecting sound back towards the source, or away from it depending on the pitch direction.

In the smallest factory, sound propagation decreased with increasing fitting density. At maximum fitting density, a secondary slope appeared in the sound propagation – that is, the value of sound propagation changed a some distance from the source. In other cases, the sound propagation was single-sloped and decreased when fittings were introduced. However, the sound propagation for partial and fully fitted rooms was similar.

Hodgson *et. al.* then created an empirical model for predicting sound propagation curves in industrial rooms using experimental data in 1996 [5]. The model accounted for a change in slope in sound propagation by dividing the total sound propagation curve into an initial and final slope. Experimental data showed that the initial slope had values ranging from 2-5 dB/DD, and the final slope had values ranging from 4-9 dB/DD.

Ondet *et. al.* modeled sound propagation in industrial rooms using RAYSCAT, a ray tracing model in 1989 [6]. RAYSCAT was used to study the effect of fitting distribution and absorption. As expected, Pdd (equivalent to SP and the inverse of DL_2) decreased when fittings were introduced, and sound propagation was lowest in rooms of high fitting density. Ondet *et. al.* then developed assessment criterion by parametric analysis of industrial rooms using RAYSCAT in 1995 [7]. The results were verified using experimental data from 200 rooms, whose Pdd values ranged from 1.5-4.5 dB/DD for both treated and untreated rooms.

1.3.2 DL_2 for Speech Applications

In 1999, Hodgson measured propagation of speech using sound propagation in university classrooms as part of a speech quality assessment using speech intelligibility index, signal to noise ratio, and reverberation time [8]. Octave-band sound pressure levels were measured, A-weighted, and summed to yield the A-weighted Speech pressure level (SLA). Sound propagation was then calculated, yielding values of 1.1 dB/DD, 1.0 dB/DD, 1.6 dB/DD, and 2.4 dB/DD in four classrooms. Hodgson also produced an empirical model for predicting sound propagation for A-weighted speech levels in classrooms [9]. The model used the length, height, and presence of basic acoustical treatment to predict sound propagation. The prediction was applied to small and large classrooms of low and high absorption, resulting in measured/predicted sound propagation values of -0.6/-0.6 dB/DD for small rooms of low absorption, -1.4/-1.8 dB/DD large rooms of low absorption, -1.8/-1.7 dB/DD small rooms of high absorption, and -2.6/-3.0 dB/DD for large rooms of high absorption.

Current applications of DL_2 focus on speech distraction in open-plan offices. Keranen measured DL_2 in 16 open-plan offices to propose a standardized measurement method and quality metrics [10]. Like Hodgson's work in classrooms, Keranen calculated DL_2 for the A-weighted speech pressure level ($DL_{2,s,A}$). It was observed that DL_2 in open-plan offices is like DL_2 in furnished industrial rooms as both feature a change in DL_2 at some distance from a source. To avoid the change in DL_2, Keranen proposed that DL_2 be measured from 4 m and beyond ($DL_{2,s,4m}$), and to measure the speech pressure levels at 4 m ($L_{p,s,4m}$). Using these two values, Keranen used STI to introduce two new quantities called the distraction distance (r_d) and the privacy distance (r_p). r_d and r_p are the distances from a talker until which speech is distracting (STI > 0.50), and until which speech is confidential (STI < 0.20). $DL_{2,s,4m}$ values ranged from 4 dB/DD to 12.4 dB/DD, r_d ranged from 5.4 m to 18.5m, and r_p ranged from 11.9 m to 32.6 m. It should be noted that r_p exceeded the maximum room length in 6 cases. This work is the foundation for ISO 3382-3.

Using the same set of experimental data, Keranen produced an empirical model for predicting $L_{p,s,4m}$, $DL_{2,s,4m}$, and r_d [11]. The model uses the room length (L), room width (W), room height (H), average screen height (h), ceiling absorption (α_c), apparent furnishing absorption (α_f) and speech effort ($L_{A,S,1m}$). Prediction accuracy was cited to be 3.0 dB, 1.5 dB/DD and 2.5 m for $L_{p,s,4m}$, $DL_{2,s,4m}$, and r_d respectively.

1.4 Scope

Much work has been done on DL_2 in specific areas such as noise prediction in industrial rooms, or speech distraction in open-plan offices. DL_2 has also been measured in very short distances in classrooms, suggesting that it may also be useful in quantifying listening quality of rooms in the same way it can quantify speech privacy. This thesis aims to generalize the use of DL_2 as a quality metric for unamplified speech in all rooms.

The proposed work was separated into three components: a theoretical section, an experimental section, and an applications section. The theoretical section aimed to develop a base model for DL_2 and develop a set of rating criteria, the second component aimed to validate the DL_2 model, and the third component refined the model and applied it to sample rooms.

An idealized model for DL_2 was implemented as a tool in Microsoft Excel. The model calculates STI at all points along the sound propagation curve in a room. The model was based on an intial set of assumptions and idealizations. The intent was to use experimental data to either correct the model or better understand its limitations.

The initial model was then used to test initial quality rating schemes. Like the work conducted by Virjonen and Hongisto, the rating schemes aimed to use speech-related metrics such as STI. However, as STI quality ratings span large ranges of values, metrics that are intuitive to lay readers were also investigated. This was intended to give commissioners more insight into how their spaces perform acoustically.

DL_2 data collected in real rooms was then used to examine the behavior of sound in a wide variety of acoustical environments and furnishing arrangements. Observed trends in the data were used to improve the idealized DL_2 model to better reflect conditions found in real rooms. The data was also used to propose a suitable DL_2 measurement range in rooms.

Finally, as a proof of concept, the refined DL_2 model was used to evaluate a sample of hypothetical rooms. The recommendations were compared with observed DL_2 values to assess the reasonability of the recommendations.

2 Theoretical DL_2

2.1 Idealized DL_2 Model for STI

An initial, idealized model was developed and implemented in Microsoft Excel to assess how DL_2 affects STI as a function of distance from a speech source. In this iteration, STI is calculated using only the reverberant speech at various distances from a source and was therefore only applicable to large source-receiver distances or in rooms where the source is physically obstructed.

The speech sound pressure levels used to calculate STI at each distance increment were calculated assuming a standard human talker power spectrum decaying at a constant DL_2.

The main objective of this model was to examine how DL_2 and STI are related – that is: (1) how STI varies with distance for a given value of DL_2, and (2) how STI varies at a single position for different values of DL_2. The model was based on assumptions and idealizations, and was used to explore possible applications of DL_2 as a parameter. These idealizations were assessed and refined in later chapters using experimental data.

2.1.1 Fixed Model Components

The components of the model listed in this sub-section were expected to remain unchanged in the final iteration of the STI vs. DL_2 model.

2.1.1.1 Speech Effort Spectrum

The speech effort spectra used for calculating the speech sound pressure level at all distances were obtained from ANSI S3.5-1997 “Methods for Calculation of the Speech Intelligibility Index”.

Speech spectra for Normal, Raised, and Loud vocal effort are shown in Table 2.1. These spectra are averages of male and female talkers, at 1 m directly in front of a talker’s mouth.

Table 2.1 - Speech Pressure Level ($L_{p,s,1m,0°}$) Spectrum for Male and Female Talkers at 1 m Directly in Front of a Human Talker's Mouth (From ANSI S3.5-1997 "Methods for Calculation of the Speech Intelligibilty Index" [12])

Band [Hz]	125	250	500	1,000	2,000	4,000	8,000
Normal [dB]	54	57	60	54	49	44	39
Raised [dB]	62	61	66	62	57	51	43
Loud [dB]	70	64	70	71	66	60	49
Shout [dB]	78	65	75	80	76	69	58

2.1.2 Tentative Model Components

The following components of the model were assumed and were intended to be adjusted based on experimental observations.

2.1.2.1 Speech Transmission Index (STI)

The reverberant-speech Modulation Transfer Function-based (MTF) STI approximation method formulated by Houtgast *et. al*. was applied in the initial model. The MTF method calculates STI based solely on degradation of signal quality due to background noise and reverberation time.

As full calculation details are described in publication [1], a summary of the method will be provided instead. Two forms of the STI approximation method were presented in the publication: (1) an reverberant speech STI model, and (2) a direct and indirect speech (complete) STI model. The reverberant speech STI model requires the background noise level and reverberation time whereas the complete STI model requires the room volume as well. As the room volume was not yet included in the model, the reverberant speech STI model (Eq. (2.1)) was used.

For the reverberant speech model to be accurate, the total sound at the receiver needs to be comprised mainly of indirect sound. This requires that either (1) the distance be sufficiently large enough such that the direct sound field is negligible, or (2) there are obstructions between the talker and the listener. This is mostly applicable to open plan offices, where (1) workspace dividers are expected to obstruct the direct sound from reaching nearby listeners, or (2) the listener is located far away.

$$m(f) = \left[1 + \left(2\pi f \frac{T}{13.8}\right)\right]^{-1/2} \left[1 + 10^{((-S/N)/10)}\right]^{-1} \tag{2.1}$$

Where:

$m(f)$ is the modulation transfer function for a given modulation frequency
f is the modulation frequency (from 0.4 – 30 Hz at third octave intervals)
T is the reverberation time (assumed to be T_{20})
S/N is the signal to noise ratio

Eq. (2.1) is evaluated at 18 modulation frequencies between 0.4 and 20 Hz at third octave intervals. The apparent signal to noise ratio (S/N_{app}) for each modulation frequency is then evaluated using Eq. (2.2). The S/N_{app} is then truncated at -15 dB if it is below -15 dB or truncated at +15 dB if it exceeds 15 dB. The 18 values for S/N_{app} are then averaged and normalized according to Eq. (2.3) to yield the STI contribution for each frequency band. Each frequency band's STI contribution is then multiplied with their band weighting function for their contribution to intelligibility and summed to yield STI. The band weightings are shown in Table 2.2.

$$S/N_{app,F} = 10\,log\left(\frac{m(F)}{1 - m(F)}\right) \tag{2.2}$$

$$STI_f = \frac{\frac{1}{18}\Sigma\left(S/N_{app}\right) - 15}{30} \tag{2.3}$$

Table 2.2 - Octave Band STI Contributions [1]

Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Weighting	0.13	0.14	0.11	0.12	0.19	0.17	0.14

2.1.2.2 Directionally Averaged Speech Power Spectrum Input for MTF

In the complete STI model, the sound power level of the source is multiplied by human directivity factors for the direct field STI contribution. In the reverberant speech model, average sound power level was postulated to be required. This assumption was based on the idea that sound from a directive source would reflect off local surfaces, and the indirect sound reaching a listener would be averaged by this mechanism.

The average speech pressure levels ($L_{p,s,1m,avg}$) were calculated using the spectral human speech data from Table 2.1 and human-directivity data in Table 2.3 [13].

Source directivity (evaluated at angle θ) is the ratio between the pressure-squared value for a sound source at angle θ and the average pressure-squared value for the source over 360° (Eq. (2.4)). Taking the logarithm and multiplying both sides of Eq. (2.4) by 10 yields the conversion between $L_{p,s,1m,0°}$ and $L_{p,s,1m,avg}$ (Eq. (2.5)). Calculated values for $L_{p,s,1m,avg}$ are shown in Table 2.4.

Table 2.3 - Octave Band Human Directivity Data (From R. Watson, O. Downey "The Little Red Book of Acoustics: A Practical Guide", 2008 [13])

Band [Hz]	125	250	500	1,000	2,000	4,000	8,000
Directivity	1.4	1.7	1.5	1.5	2.1	2.5	3.3

Table 2.4 - Speech Sound Pressure Level ($L_{p,s,1m,avg}$) Spectrum for Male and Female Talkers at 1 m, Averaged over 360°

Band [Hz]	125	250	500	1,000	2,000	4,000	8,000
Normal [dB]	64	66	69	63	57	51	44
Raised [dB]	72	70	75	72	65	58	48
Loud [dB]	80	73	80	80	74	67	55
Shout [dB]	87	74	84	89	84	76	64

$$Q_\theta = \frac{P_\theta^2}{P_{avg}^2} \tag{2.4}$$

$$L_{p,avg} = L_{p,0^\circ} - 10\,log(Q_\theta) \tag{2.5}$$

2.1.2.3 Background Noise Spectrum (L_n)

In rooms where music is not played over a speaker system, the main source of background noise was expected to be from mechanical services such as HVAC systems. As such, the spectrum of the background noise was assumed to be identical to the Balanced Noise Criterion (NCB) contours proposed by Beranek [14]. The NCB contours are updated versions of the Noise Criterion (NC) contours, which were used to evaluate HVAC systems. The NC contours were based on equal loudness contours, but were not described to describe occupied rooms, a shortcoming addressed by the NCB contours. For the idealized iteration of the model, NCB contours whose A-weighted sum equals the lowest or highest recommended background noise level in a given type of room were used.

2.1.2.4 Reverberation Time (RT)

DL_2 was assumed to be independent of reverberation time, and the reverberation time was assumed to be the same at all frequencies. While Keranen's empirical model stated that DL_2 is dependent on absorption [11], which directly affects reverberation time, DL_2 also depends on other factors such as furnishing and room geometry. This assumption was based on the expectation that DL_2 can be modified independent of reverberation time.

While reverberation time is known to be frequency-dependent, the above assumption greatly simplifies the construction of the model.

2.1.2.5 Sound Pressure Level at 1m ($L_{p,1m}$)

Sound pressure level at 1 m in rooms is often assumed to be equal to free-field levels; the sound pressure level at 1m in a room is the same as it would be in a free field. The free-field distance is defined as the distance at which sound pressure level is equal to that of the same source in a free-field environment. Hodgson's findings for free-field distances in industrial rooms are shown in

Table 2.5. While general rooms may have higher furnishing density and more nearby surface than industrial rooms, $L_{p,1m}$ was tentatively assumed to be equal to free-field values for point sources.

Table 2.5 - Average and Standard Deviation (in Parentheses) for Free-Field Distances in Octave Bands for Empty, Fitted, and Fitted and Absorbent Industrial Rooms (From M. Hodgson, N. Heerema "Sound-Propagation Curves in Industrial Workrooms: Statistical Trends and Empirical Prediction Models" Building Acoustics, Vol. 3, 1996 [5])

Band [Hz]	Empty Room [m]	Fitted Room [m]	Fitted + Absorbent [m]
125	1.07 (0.17)	0.92 (0.06)	0.90 (0.03)
250	1.04 (0.12)	0.88 (0.06)	0.89 (0.03)
500	1.05 (0.14)	0.86 (0.04)	0.88 (0.01)
1000	1.01 (0.09)	0.79 (0.04)	0.80 (0.02)
2000	1.04 (0.13)	0.87 (0.05)	0.90 (0.08)
4000	1.03 (0.15)	0.91 (0.03)	0.93 (0.08)

2.1.2.6 Uniform, Broadband Decay

DL_2 was tentatively assumed to be frequency independent. That is, the value of DL_2 for all octave bands was assumed to be the same. As the DL_2 value of each octave band was assumed to be identical, the DL_2 value for the A-weighted speech sound pressure level would be the same as well. This assumption facilitates presentation of DL_2 as a single value.

2.1.2.7 Linear Decay

Ondet and Hodgson observed that the DL_2 in smaller industrial rooms may be modeled with reasonable accuracy with a straight line up until 30 m [5] [7]. As unamplified speech is not expected to reach beyond 30 m, a linear decay is assumed to be applicable.

2.1.3 Construction of DL_2 Model

The DL_2 model was constructed in Microsoft Excel. The spreadsheet is divided into 4 main sections: a data entry/user interface sheet, a chart output sheet, MTF calculation sheets (one sheet for each data point), and a common data sheet.

The vocal speech effort levels and their corresponding spectra were added to a common data tab of the spreadsheet. The spectra are called upon using a drop-down menu on the data entry/user interface sheet. The user selects a speech vocal effort level, and inputs the background noise spectrum, reverberation time spectrum, and DL_2 value (See Figure 2.1).

The spreadsheet then uses the vocal speech effort levels to calculate the sound pressure level at the 1 m location. The spreadsheet then, calculates the sound pressure level at each doubling of distance.

	A	B	C	D	E	F	G	H	I	J	K	L	M
3													
4	Reverberation Time	125	250	500	1000	2000	4000	8000					
5	RT(s)=	0.3	0.3	0.3	0.3	0.3	0.3	0.3					
6													
7	Background Noise	125	250	500	1000	2000	4000	8000					
8	Ln=	38	30	25	22	18	15	12	28.7				
9													
10													
11	Speech Level	Normal											
12													
13		125	250	500	1000	2000	4000	8000	A-tot				
14		64	66	69	63	57	51	44	68.5				
15													
16		6	6	6	6	6	6	6					
17		Measured Levels											
18	Position Distance	125	250	500	1000	2000	4000	8000	A-tot	SII	STI(AI)	STI(HS)	
19	1	53	55	58	52	46	40	33	57.5	0.73	0.80	0.80	
20	2	47	49	52	46	40	34	27	51.5	0.73	0.80	0.78	
21	4	41	43	46	40	34	28	21	45.5	0.70	0.77	0.72	
22	8	35	37	40	34	28	22	15	39.5	0.63	0.69	0.61	
23	16	29	31	34	28	22	16	9	33.5	0.50	0.55	0.47	
24	32	23	25	28	22	16	10	3	27.5	0.35	0.38	0.29	
25	64	17	19	22	16	10	4	-3	21.5	0.18	0.20	0.13	
26	128	11	13	16	10	4	-2	-9	15.5	0.04	0.04	0.03	
27	256	5	7	10	4	-2	-8	-15	9.5	0.00	0.00	0.00	
28	512	-1	1	4	-2	-8	-14	-21	3.5	0.00	0.00	0.00	
29	DL2	6.000	6.000	6.000	6.000	6.000	6.000	6.000	6.000				
37													
38													
39													

Yellow fields indicate user input required

MTF Calculation sheets

Revision Notes | Data Entry | Chart1 | Common Data | P1 | P2 | P3 | P4 | P5 | P6...

Figure 2.1 - Screenshot of Data Entry sheet of DL_2 calculation tool

The speech pressure level data in each row is then referenced in their respective MTF calculation sheets (i.e. Position 1 is referenced in sheet P1, Position 2 is referenced in sheet P2). Each calculation sheet then evaluates the modulation transfer function according to Eq. (2.1) through (2.3).

The MTF is evaluated for each octave band at each modulation frequency. The spreadsheet then calculates the apparent signal to noise ratio, applies the band contribution weighting for each average apparent signal to noise ratio, then calculates the STI using three different speech weighting functions. The main weighting function of interest is the one specified by Houtgast and Steeneken. A screenshot of a typical calculation sheet is shown in Figure 2.2.

The model was implemented in two forms: (1) a Fixed DL_2 model where DL_2 is fixed and the STI is calculated at incremental distances (STI vs Distance), and (2) a Fixed Distance model where the evaluation distance is fixed and the STI is calculated at incrementing DL_2 values (STI vs DL_2). In both models, speech effort level, background noise level, and reverberation time are chosen to approximate the application under investigation.

The Fixed DL_2 model (1) calculates the octave-band sound pressure level at incrementing distances based on a chosen DL_2 value. The Fixed Distance (2) model calculates the sound pressure level at a fixed distance at incrementing DL_2 values.

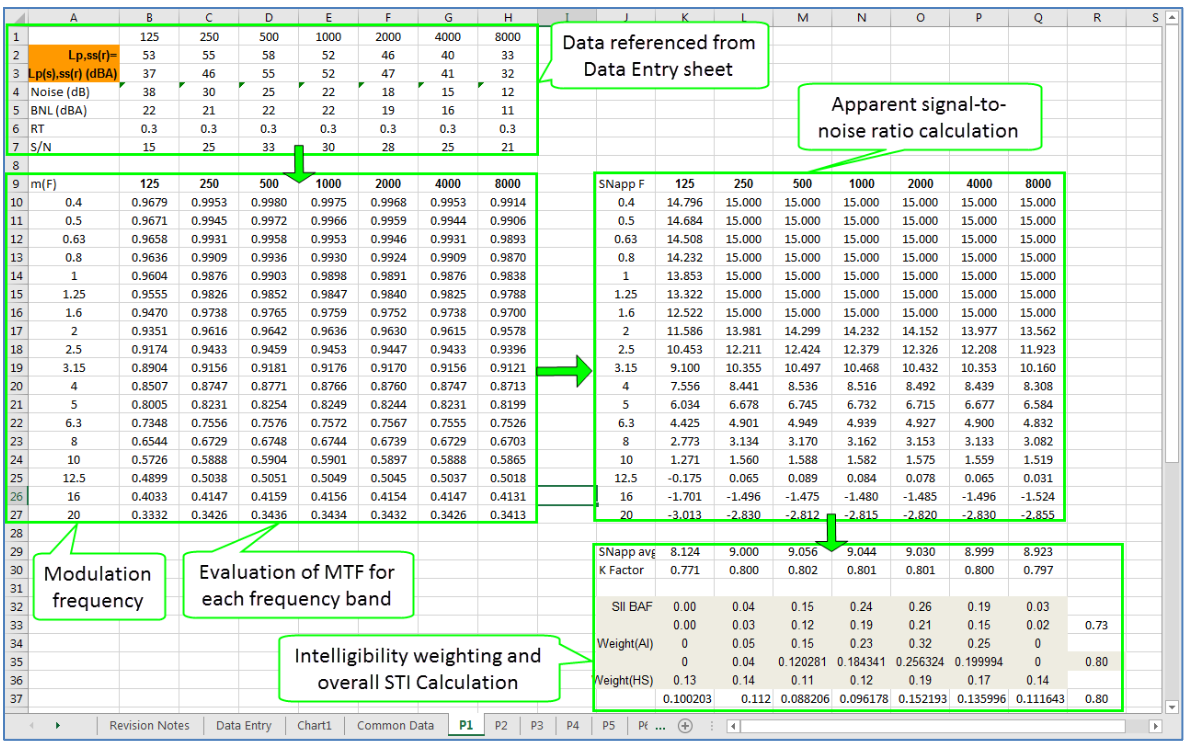

Figure 2.2 - Screenshot of MTF Calculation sheet of DL_2 calculation tool

2.1.4 Sample Model Plots

As the model is based on the indirect speech STI calculation scheme, the following sample plots represent environments where the direct sound is absent. Figures 2.3 and 2.4 were generated for a speaker at normal vocal effort in a room of broadband reverberation time = 0.3 s and background noise spectrum equal to NCB contour 20 (approximately equal to 29 dBA). These room conditions approximate an open-plan office.

Figure 2.3 is the STI vs Distance curve for DL_2 = 6 dB/DD. STI vs Distance curves are useful for post-occupancy evaluation of how STI varies between a talker and listeners at varying distances. The DL_2 measured is to be entered into this model along with an expected speech effort level to examine how STI decays as a function of distance.

Alternatively, for rooms where speech intelligibility is desired throughout a room, this plot would help determine the maximum seating distance from a talker. This information is valuable for optimizing the seating arrangement such that listening effort is not an issue.

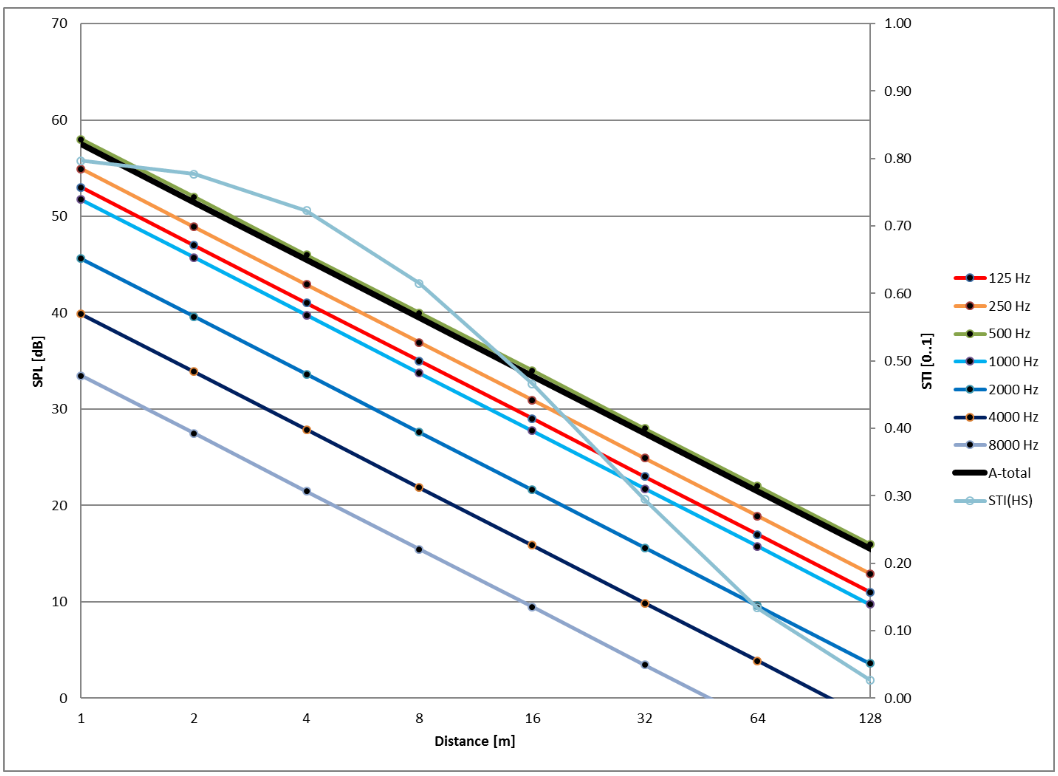

Figure 2.3 - Sample STI vs Distance Curve Evaluated at DL_2 = 6 dB/DD

Figure 2.4 is the STI vs DL_2 curve for a listener located 4 m from a talker. STI vs DL_2 curves are useful for design-phase decisions. By choosing the listener position of interest, designers can determine the DL_2 required to meet speech intelligibility or speech privacy targets.

According to IEC 60268-16, 'Bad' speech intelligibility is rated at STI 0.3 or less. This translates to good speech privacy and is therefore desirable in settings where speech distraction is to be minimized. According to Figure 2.4, an STI rating of 0.3 can be achieved at a distance of 4 m if the DL_2 is greater than 14.5 dB/DD. In Virjonen's work, the maximum observed DL_2 value was 11.9 dB/DD – indicating that privacy at 4 m from a talker is not a reasonable expectation. This would either suggest that designers should expect lower speech privacy at 4 m, or reconsider the intended purpose of the space.

Alternatively, according to the ASHRAE HVAC Handbook, the recommended maximum background noise level in open plan offices is 45 dBA [15]. Raising the background noise level to a broadband level of 45 dBA will reduce the DL_2 requirement to 7 dB/DD if good speech privacy is desired at a distance of 4 m from a speaker.

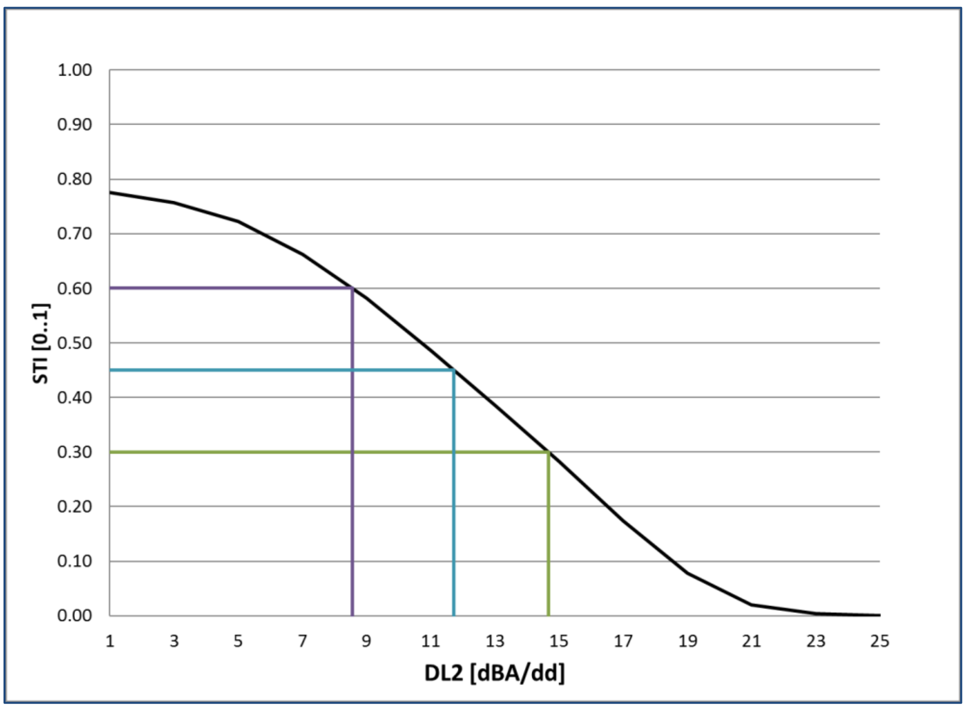

Figure 2.4 - Sample STI vs DL$_2$ Curve Evaluated at Distance = 4 m

2.2 DL_2 Rating Scheme Alternatives

Like the work by Virjonen *et. al.*, the development of requirements and rating criteria for DL_2 was based on speech-related metrics. STI was chosen as the metric of choice as it is widely used and is well-studied. Additionally, many speech-related studies refer to STI. Using other metrics such as the Speech Intelligibility Index (SII) are also viable options. Translation between metrics is made possible via tools such as the Common Intelligibility Scale (CIS).

However, one problem persists when STI is the primary rating metric: it is unintuitive to lay users. STI quality ratings span large ranges of values, using nebulous terms such as Excellent Intelligibility, Good Intelligibility, and Poor Intelligibility. The ranges of DL_2 values spanned by each STI quality rating in Figure 2.4 were compiled in Table 2.6. Noticeable differences are expected even within a single STI quality rating. Thus, more detailed and intuitive rating schemes were researched.

Table 2.6 - Sample STI Ranges and their Corresponding DL_2 Values According to IEC 60268-16

STI Range	Intelligibility Rating	DL_2 Range [dB/DD]
1.00 – 0.75	Excellent	0 – 3
0.75 – 0.60	Good	3 – 9
0.60 – 0.45	Fair	9 – 12
0.45 – 0.30	Poor	12 – 15
0.30 – 0.00	Bad	>15

2.2.1 Room Purpose

All rooms were categorized into one of three cases: (1) intelligibility, (2) distraction, and (3) privacy. The measurement and rating methodology are identical in all cases, differing only in the STI rating scheme. In all cases, the transition distance (r_{tr}) was introduced. The transition distance is a user-defined distance where the designer intends for the STI rating designation to change, and is the proposed distance where intelligibility is to be evaluated. This metric will be explained on a case-by-case basis.

2.2.1.1 Case 1: Intelligibility

The intelligibility case was defined as rooms where high speech intelligibility is desired throughout the space. Example applications are classrooms and auditoria. In this setting, a speech intelligibility percentage of 100% is required; all speech must be audible. The rating brackets for the intelligibility case are then based on listening effort. Then, r_{tr} is the farthest listener position from a talker as it represents the location where maximum listening effort is required.

The rating criterion for this case is based on Rennies *et. al.*'s listening tests evaluating listening effort as a function of STI [16]. 16 normal-hearing German speakers were given 120 sample sentences at STI = 0.17, 0.30, 0.43, 0.50, 0.57, and 0.70. Each STI value was tested using different combinations of reverberation time and signal to noise ratio as it was postulated that the listening effort would be identical since intelligibility is theoretically linked to listening effort. Listeners were asked to report an effort between 1 to 11: 1 – very little effort, 3 – little effort, 5 – moderate effort, 7 – considerable effort, 9 – much effort, 11 – extreme effort.

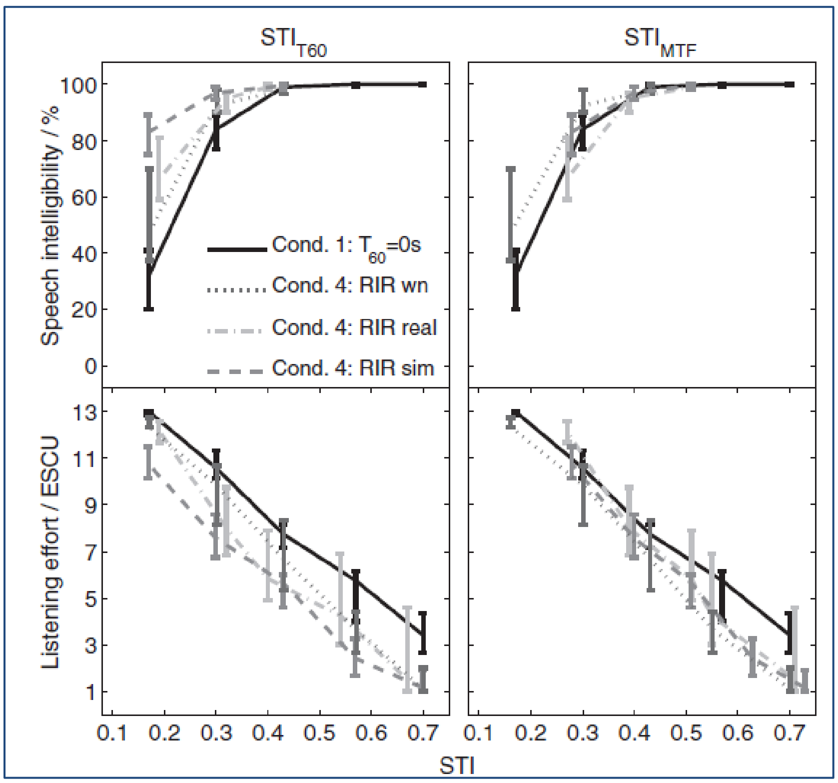

Figure 2.5 - Listening Effort vs. STI for 16 Normal-Hearing German Subjects for 120 German Sentences (Copied from J. Rennies and H. Schepker, "Listening Effort and Speech Intelligibility in Listening Situations Affected by Noise and Reverberation," *Journal of the Acoustical Society of America,* vol. 136, no. 5, pp. 2642-2653, 2014.)

Figure 2.5 shows the listening effort and percentage of speech intelligibility as a function of STI. This figure was copied from J. Rennies and H. Schepker's publication "Listening Effort and Speech

Intelligibility in Listening Situations Affected by Noise and Reverberation," published in volume 136 of the *Journal of the Acoustical Society of America* in 2014. Condition 1 (T_{60} = 0) results were omitted as all rooms are expected to have non-zero reverberation times. In Condition 4, the test speech signal was generated by convolving a clean speech signal with different Room Impulse Response (RIR). RIR_{wn} was a room impulse response generated using white noise, RIR_{real} used RIR taken from real rooms, and RIR_{sim} used simulated RIR.

STI thresholds in Table 2.7 were chosen based on the maximum effort between the three RIR condition results.

Table 2.7 - Quality Ratings for STI Based on Listening Effort [16]

Effort Rating	Listening Effort	STI Range	Intelligibility [%]	Acceptable	Rating
1	Very little effort	0.73 – 1.00	100	Yes	Excellent
3	Little effort	0.62 – 0.73	100	Yes	Good
5	Moderate effort	0.53 – 0.62	100	Yes	Poor
7	Considerable effort	0.43 – 0.53	100	Yes	Bad
9	Much effort	0.35 – 0.43	88	No	N/A
11	Extreme effort	0.30 – 0.35	80	No	N/A

2.2.1.2 Case 2: Distraction

The distraction case encompasses rooms where concentration on tasks is the main purpose, such as study spaces or open-plan offices. The rating criterion for this case is based on the notion that semantic speech is detrimental to serial memory and concentration. In the distraction case, r_{tr} is the distance to the nearest seat in rooms such as libraries or study halls, or to the nearest workspace in rooms such as open plan offices.

Hongisto conducted a literature review on performance versus STI tests under the postulation that loss of productivity is a function of STI [17]. The results between silence and when STI was greater than 0 were compiled and are shown in Figure 2.6, this figure was copied from Hongisto's publication "A Model for Predicting the Effect of Speech of Varying Intelligibility on Work Performance," published in volume 15 of *Indoor Air* in 2005 [17]. The prediction model used a Boltzmann's sigmoidal function, and is an approximation of a wide variety of speech signals, including normal speech in the participant's native language, normal speech in a foreign language, incoherent words and reversed speech.

Ebissou *et. al.* evaluated Hongisto's model with a serial memory task at STI values of 0.25, 0.35, 0.45, and 0.65 [18]. Subjects were either unaffected, as they found the task easy, or were severely affected. A sharp decrease in productivity was also observed between STI = 0.35 – 0.45, but the maximum distraction occurred much sooner at 0.45. This thesis assumes that the tasks conducted in typical work or study environments are difficult and that most people will be affected adversely.

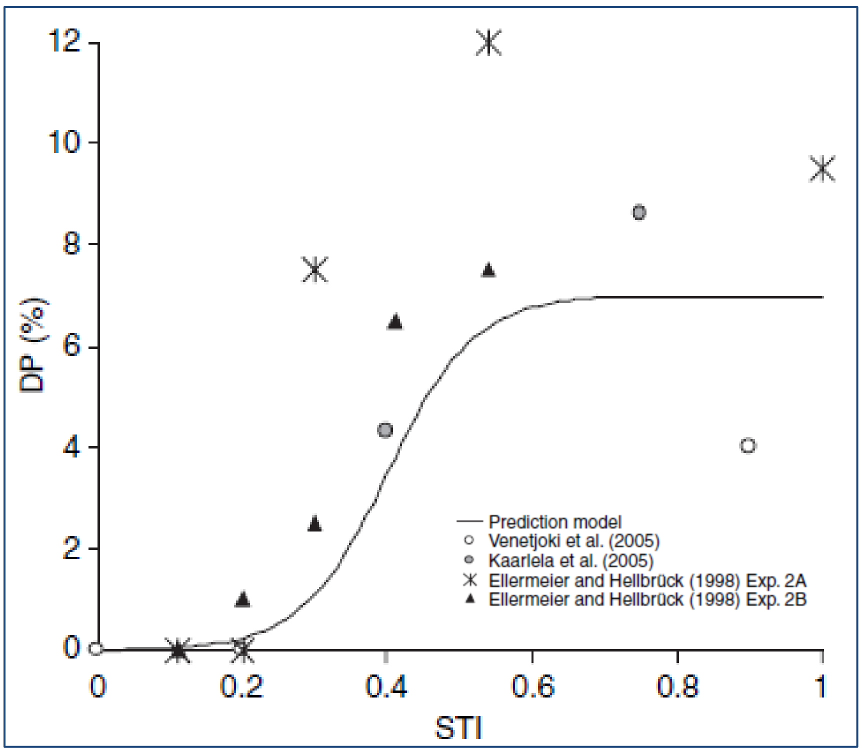

Figure 2.6 - Compiled Data and Prediction Model for Loss of Productivity (DP) vs STI (Copied from V. Hongisto, "A Model for Predicting the Effect of Speech of Varying Intelligibility on Work Performance," *Indoor Air,* vol. 15, pp. 458-468, 2005 [17])

Quality rating brackets were assigned by subdividing the range between 0 – 7% loss in productivity (DP). This corresponds to an STI range of between 0.2 – 0.6. DP exceeding 7% (STI > 0.6) was deemed unacceptable, while DP at 0% (STI < 0.2) was deemed excellent. Table 2.8 shows the proposed quality ratings and their associated STI ranges if Hongisto's prediction model were subdivided into equal percentages of distraction. Note that the steep increase in the loss of productivity between STI = 0.35 – 0.50 leads to narrower STI ranges for Fair and Poor ratings.

It should be noted that, since the prediction curve was based on a variety of speech types across different experiments, the curve presented in Figure 2.6 shows the minimum expected loss of productivity for any speech distraction. Intelligible conversations are therefore expected to result in even greater degrees of productivity loss.

However, the form of the loss of productivity curve is expected to be an accurate representation regardless of the type of speech. The region between STI = 0.2 – 0.6 is still expected to be where loss of productivity transitions from 0% to its steady maximum.

Table 2.8 - Proposed Quality Ratings for Speech-Related Productivity Loss

Rating	Loss of Productivity [%]	STI
Excellent	0	0.00 – 0.20
Good	0 – 2	0.20 – 0.35
Fair	2 – 4	0.35 – 0.43
Poor	4 – 6	0.43 – 0.50
Bad	6 – 7	0.50 – 0.60
Unacceptable	> 7	> 0.60

2.2.1.3 Case 3: Privacy

The privacy case refers to situations where reasonable intelligibility is expected at an intended recipient and privacy is expected at the next nearest listener. In rooms such as eating establishments and reception areas, the intended recipient should be able to understand the talker with little to no effort (STI greater than 0.62 according to Table 2.7), and should have less than 100% speech intelligibility at the next nearest listener.

In this case, the r_{tr} is the distance to the nearest listener where privacy is desired. However, the STI at the intended listener must also be checked to ensure that the intelligibility is sufficiently high (STI > 0.62). Table 2.9 shows the quality ratings and their corresponding STI values derived from Figure 2.5.

Table 2.9 - Proposed Quality Ratings for Speech Privacy

Rating	Percentage of Intelligible Speech [%]	STI
Excellent	< 50	< 0.15
Good	50 – 60	0.15 – 0.20
Fair	60 – 80	0.20 – 0.27
Poor	80 – 90	0.27 – 0.35
Bad	90 – 100	0.36 – 0.43
Unacceptable	> 100	> 0.43

2.3 Conclusion

An ideal, preliminary DL_2 model was developed using Houtgast and Steeneken's reverberant speech STI calculation method (Eq. (2.1)) to establish a base for improving with experimental data. The model uses standardized speech spectra provided by ANSI S3.5 1997. The speech pressure level at 1 m was assumed to be equal to levels expected according to free-field sound decay for a point source. DL_2 was then assumed to be frequency-independent and constant as a function of distance. Reverberation time was assumed to be frequency independent while the background noise level in rooms was assumed to be accurately approximated using the Balanced Noise Criterion curves. The model calculates the speech sound pressure level at distance intervals that increase by a factor of 2 and calculates the STI at each position.

The model was used to produce two different visual presentations of DL_2. The first presents STI as a function of distance for a given DL_2 value. The second presents STI as a function of DL_2 for a given distance. These two visual presentations are expected to give full insight to the acoustical performance of a room.

Acoustical quality rating schemes were formulated by assuming all rooms are classifiable under one of three categories: good speech intelligibility desired throughout the room (Case 1, intelligibility); good speech intelligibility desired until a certain point, beyond which, low speech intelligibility is desired to reduce speech distraction (Case 2, distraction); and good speech intelligibility desired until a certain point, beyond which, high speech privacy is desired for confidentiality reasons (Case 3, privacy).

3 Experimental Verification

In the chapter 2, an idealized model for DL_2 was introduced. This chapter uses data collected in existing rooms to assess the assumptions employed in the idealized DL_2 model such that it can be improved to better reflect the behavior of sound in real rooms.

3.1 DL_2 in Real Rooms

This chapter investigates three assumptions made in Chapter 2 and is therefore divided into three subsections. Since the three subsections are different analyses of the same data set, they share a common methodology section. Each subsection is then divided into its own Measurement Results, Discussion and Conclusions sections.

3.1.1 Motivation

The main objective of using DL_2 measurements was to re-evaluate three assumptions made in Chapter 2. The first assumption, *uniform, broadband decay* (Chapter 2.1.2.6) assumed that DL_2 is frequency independent, and that all octave bands and the A-weighted speech pressure level decay at the same rate. The second assumption, *linear decay* (Chapter 2.1.2.7) assumed that a DL_2 is constant and does not change with distance from the source. The third assumption, *sound pressure levels at 1 m, $L_{p,1m}$* (Chapter 2.1.2.6), assumed that the sound pressure at 1 m from a source in a room is identical to that of a free-field environment.

As surface absorption and reverberation time are frequency dependent, DL_2 is also expected to vary with frequency (i.e. the assumption of uniform, broadband decay may not hold true). As such, experimental data was necessary to either confirm the applicability of assuming that DL_2 is acceptably uniform from 125 – 8,000 Hz or refine the model with any observable trends. The data was also used to assess the suitability of DL_2 applied to the A-weighted speech pressure level ($DL_{2,s,A}$) as a representative quantity.

The assumption of linear decay was reassessed since a single room has been observed to have two different values for DL_2 (i.e. a change in slope): a lower rate of sound decay at small distances, and a higher rate of sound decay at larger distances. However, this behavior is mostly documented in open-plan offices and industrial rooms, which span large measurement distances in highly furnished environments. Measurements in other types of rooms and at shorter distances are lacking, other than Hodgson's measurements in classrooms [8], whose data suggests that a single DL_2 value may be sufficient in describing a room.

As DL_2 was proposed as a universal room acoustics parameter, its measurement methodology should be consistent regardless of room type or rating scheme. The three rating schemes proposed in chapter 2.2 assumed the presence of an intended listener at short distance (e.g. in the same workstation of an open-plan office, or across an eating establishment table). As such, DL_2 measurements should start at a distance of 1 m from the source. The maximum recommended distance for measuring DL_2 should yield a regression that approximates actual spatial decay behavior with reasonable accuracy regardless of room type. It was therefore of interest to examine the behavior of DL_2 in a wide variety of rooms to confirm the maximum distance until which a single value of DL_2 is sufficiently accurate.

The assumption that the sound pressure level in rooms at 1 m is equal to that of point-source decay in a free-field environment was based on Hodgson's observation for the free field distance in industrial rooms [5]. However, this assumption may only hold true for rooms where acoustically reflective surfaces or objects are located far from a source. When fittings were introduced in empty industrial rooms, the free-field distance decreased from 1.01 – 1.07 m to 0.79 – 0.92 m. Calculating STI normally requires the sound power level of the source be known, but loudspeaker calibrations may change over time. Thus, measurements within the free-field distance are commonly used as field calibration checks since anechoic loudspeaker calibrations are time and labour intensive. However, the free-field distance being from 0.72 – 0.92 m for fitted industrial rooms suggests that using $L_{p,1m}$ data for field calibrations is insufficient. As such, comparing $L_{p,1m}$ to its expected free-field decay for point sources was of interest.

3.1.2 Methodology

Analysis was performed on existing DL_2 data collected from a post-occupancy evaluation in 21 healthcare office buildings, and data collected from a separate acoustical study of the Macmillan building on UBC's Vancouver campus. In total, 62 DL_2 measurements from 22 buildings were used. For each DL_2 dataset, background noise level, reverberation time, and sound pressure level versus distance was measured.

An Acer Aspire 5100 laptop equipped with WinMLS 2004 room acoustics software was used to measure the room's impulse response, which was then used to calculate reverberation time.

To measure the reverberation time, WinMLS was used to generate a Maximum Length Sequence (MLS) signal. The signal was amplified through a QSC USA 370 power amplifier and played through a dodecahedral loudspeaker array. The skewed MLS was then detected using a Rion NA-28 sound level meter functioning as an audio capture microphone, where the signal was routed to the laptop's line-in input for data acquisition. The signal chain is illustrated in Figure 3.1.

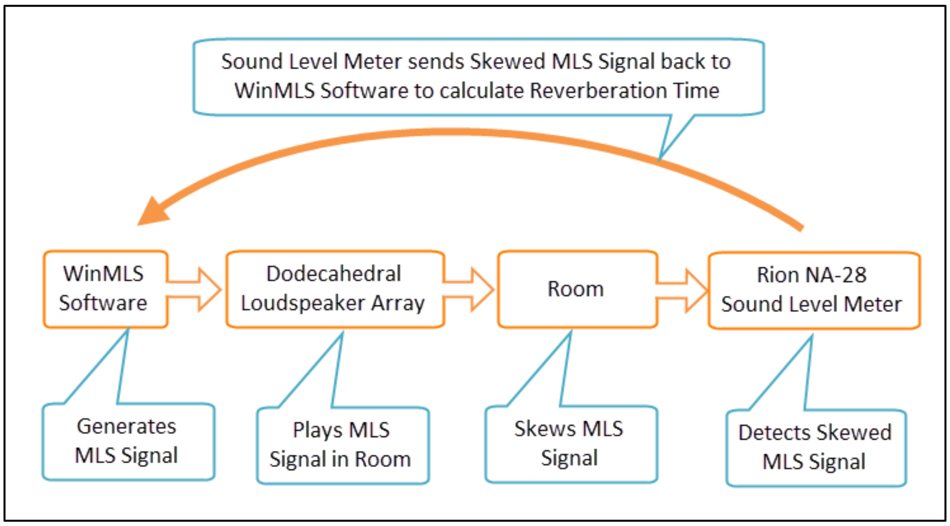

Figure 3.1 - Diagram showing signal chain for measuring reverberation time

Reverberation time was measured 3 – 5 times at different loudspeaker-microphone pair locations in each room depending on the room size. More reverberation time measurements were taken in larger rooms such as open-plan offices, and less in smaller rooms such as meeting rooms. T_{20} reverberation times were used, and the measurements were averaged in each octave band from 125 – 8,000 Hz.

The same equipment was used to measure the steady-state sound pressure level (L_p). Here, the Rion NA-28 was used as a sound level meter instead of an audio capture microphone. For ease of setup repeatability, the laptop and power amplifiers were set to their maximum output levels. WinMLS was used to generate a constant MLS signal as it is spectrally similar to white noise, which has the same energy at all frequencies.

The signal chain was calibrated for output sound power level in an anechoic chamber. The sound level meter was used to measure the dodecahedral array 40 times at 1 m. Each sound pressure level measurement was converted to its pressure-squared quantity using Eq. (1.1), then averaged. The resulting average pressure-squared quantity was converted back to sound pressure level to calculate the sound power level using Eq. (1.5).

For each DL_2 measurement, the dodecahedral array was positioned at a height of 1.2 m to simulate a seated talker and was placed at least 1 m away from any nearby surfaces to avoid the Waterhouse Effect. The Waterhouse Effect accounts for sound reflection (and then direct wave superimposition), stating that each surface within 1/4 wavelengths of a source doubles the source's directivity factor, resulting in an additional 3 dB per nearby orthogonal surface. The lowest frequency band measured was 125 Hz, which corresponds to a quarter-wavelength of 0.69 m. The sound level meter was then used to measure the sound pressure level at a height of 1.2 m, at intervals of doubling distance, starting at 1 m (1, 2, 4, 8, 16, … m). In cases where measurements were not possible at the exact distance, the nearest possible measurement location was used, and the measurement distance was documented. A typical measurement setup is illustrated in Figure 3.2.

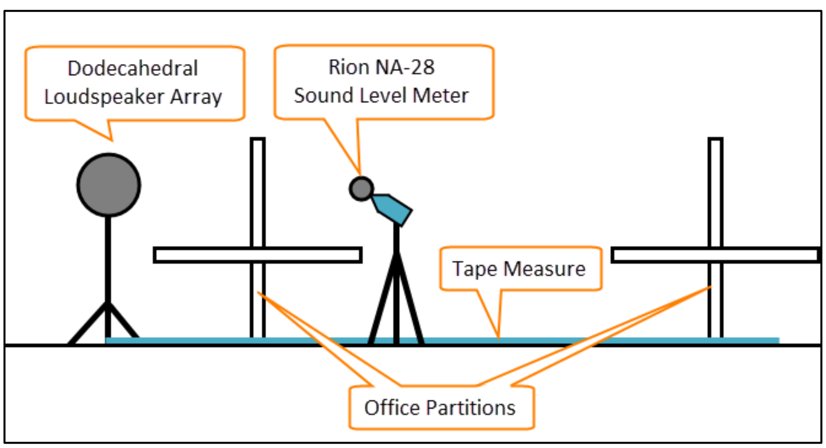

Figure 3.2 - Diagram showing the typical measurement setup

All raw sound pressure level data are provided in Appendix . The data provided are the distance, the sound pressure level as measured from the dodecahedral loudspeaker array, and the A-weighted speech pressure level for normal vocal effort. The following naming convention was used: building number – room number – measurement number. For example: B-22-3 and B-22-4 would be rooms 3 and 4 in building 22, then B-22-4-1 and B-22-4-2 would be measurements 1 and 2 in room 4. Multiple measurements in one room were mostly taken in building 22.

3.1.3 Uniform, Broadband Decay

DL_2 measurements were divided into ones made in standard rooms and ones made in open-plan offices. Rooms where the airspace was continuous were referred to as standard rooms. Open-plan offices were defined by the presence of workspace dividers.

3.1.3.1 Measurement Results

For each measurement, DL_2 was calculated over the full range of data in each octave band ($DL_{2,f}$) and the A-weighted speech pressure level ($DL_{2,s,A}$). The average DL_2 values are shown in Table 3.1. The difference between $DL_{2,f}$ and $DL_{2,s,A}$ was also calculated, and the averages are shown in Table 3.2. Overall averages using all measurement data were excluded as most of the data was taken in open-plan offices. This would skew the averages in favor of behavior in open-plan offices.

Table 3.1 - Average $DL_{2,f}$ and $DL_{2,s,A}$ for (1) Open-plan Offices and (2) Standard Rooms in dB/DD.

Open-plan Offices								
Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	$L_{p,s,A}$
Average [dB/DD]	4.7	6.5	7.4	8.1	7.9	7.6	7.9	7.2
St. Dev [dB/DD]	1.1	**1.4**	**1.6**	1.8	1.8	1.9	2.1	1.4
Standard Rooms								
Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	$L_{p,s,A}$
Average [dB/DD]	3.1	3.1	3.3	3.2	3.2	3.5	4.2	3.2
St. Dev [dB/DD]	1.3	1.4	1.3	1.2	1.3	1.1	1.1	1.3

Table 3.2 - Average Difference between $DL_{2,f}$ and $DL_{2,s,A}$ for (1) Open-plan Offices and (2) Standard Rooms in dB/DD.

Open-plan Offices							
Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Average [dB/DD]	-2.5	-0.7	0.1	0.9	0.7	0.4	0.7
St. dev. [dB/DD]	1.4	0.7	0.3	0.6	0.8	0.9	1.0
Standard Rooms							
Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Average [dB/DD]	-0.1	-0.1	0.1	0.0	-0.1	0.2	0.9
St. dev. [dB/DD]	0.9	0.5	0.2	0.2	0.3	0.5	0.8

3.1.3.2 Discussion

The standard deviation ranged from 0.3 – 1.4 dB/DD in open-plan offices and 0.2 – 0.9 dB/DD in standard rooms. By comparing the averages to the individual measurement data (which contained both positive and negative values in all bands), it was apparent that a simple arithmetic averaging produced misleadingly low differences between $DL_{2,f}$ and $DL_{2,s,A}$. The absolute difference between $DL_{2,f}$ and $DL_{2,s,A}$ was also computed, and is shown in Table 3.3. As expected, the average difference increased while standard deviation decreased. The absolute differences were then used to assess the sensitivities of $DL_{2,s,A}$ and STI to deviations in individual octave bands.

Table 3.3 - Average Absolute Difference for $DL_{2,f} - DL_{2,s,A}$ for (1) Open-plan Offices and (2) Standard Rooms.

Open-plan Offices							
Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Average [dB/DD]	2.5	0.8	0.2	0.9	0.8	0.7	1.0
St. dev. [dB/DD]	1.4	0.5	0.2	0.6	0.6	0.6	0.7
Standard Rooms							
Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Average [dB/DD]	0.7	0.4	0.1	0.2	0.3	0.4	1.0
St. dev. [dB/DD]	0.5	0.3	0.1	0.2	0.2	0.4	0.7

Open-plan Offices

For open plan offices, the greatest difference between $DL_{2,f}$ and $DL_{2,s,A}$ occurred in the 125 Hz band, with $DL_{2,125Hz}$ being typically 2.5 dB/DD lower than that of $DL_{2,s,A}$. This difference may be attributed to acoustical treatment in rooms being less effective at lower frequencies. Additionally, low frequencies exhibit more refraction than high frequencies. This is evident as the DL_2 values were lowest at 125 Hz and increased with increasing frequency up to 500 Hz.

As the A-weighting for the 125, 250, and 500 Hz bands are -16.1 dB, -8.6 dB, and -3.2 dB respectively, these bands were expected to influence the A-weighted speech pressure level less than the 1,000, 2,000, 4,000, and 8,000 Hz bands whose adjustments are 0 dB, +1.2 dB, +1.0 dB, and -1.1 dB.

DL_2 for the octave bands from 500 to 8,000 Hz was higher that $DL_{2,s,A}$, ranging from 0.2 – 1.0 dB/DD. $DL_{2,500Hz}$ was closest to $DL_{2,s,A}$ at an average value of 0.2 dB/DD and a standard deviation of 0.2 dB/DD, suggesting its usefulness as an approximation to $DL_{2,s,A}$.

Standard Rooms

The octave bands with the greatest deviation from $DL_{2,s,A}$ were the 125 Hz band at -0.7 dB/DD and the 8,000 Hz band at 1.0 dB/DD. The deviation in the 125 Hz band was due to standard room furnishing being not thick enough to absorb energy at lower frequencies. Conversely, standard acoustic treatment is expected to absorb sound energy at 8,000 Hz most effectively, resulting in a higher DL_2 value.

The 500, 1,000 and 2,000 and 4,000 Hz bands are close to $DL_{2,s,A}$ because they are largely unaffected by the A-weighting and thus contribute the most energy to the human speech spectrum. Deviations in 125 Hz affect $DL_{2,s,A}$ less due to the 16.1 dB penalty from the A-weighting.

$DL_{2,s,A}$ Sensitivity

A sensitivity analysis was conducted using the model developed in Chapter 2. The changes in $DL_{2,s,A}$ due to frequency-dependent deviations were observed by varying the DL_2 value of individual bands by +/- 1 dB/DD. The largest deviations shown in Table 3.3 were also assessed. The results are shown in Table 3.4.

Table 3.4 - $DL_{2,s,A}$ Sensitivity to Deviations in Individual Octave Bands.

FREQUENCY [Hz]	125	250	500	1000	2000	4000	8000
+1 dB/DD [dB/DD]	+0.001	+0.065	+0.449	+0.123	+0.048	+0.011	+0.002
-1 dB/DD [dB/DD]	-0.004	-0.181	-0.718	-0.306	-0.137	-0.036	-0.006
Table 3.3 [dB/DD]	-0.031	-0.130	+0.113	+0.116	+0.042	+0.009	+0.002

$DL_{2,s,A}$ was most sensitive to deviations in the 250 – 2,000 Hz octave bands, which lead to changes of between 0.2 – 0.8 dB/DD per dB/DD of deviation. $DL_{2,s,A}$ was significantly less sensitive to deviations in the 4,000 and 8,000 Hz bands, which lead to changes of between 0.01 – 0.07 dB/DD per dB/DD of deviation.

Using the model developed in Chapter 2, the effects on STI were evaluated for the maximum deviations observed in the 4,000 and 8,000 Hz bands. At deviations of 2.0 dB/DD at 4,000 Hz and 2.3 dB/DD at 8,000 Hz, the total change in $DL_{2,s,A}$ was -0.162 dB/DD, but changes in STI were up to 0.07 points.

Approximation of $DL_{2,f}$ Relative to $DL_{2,s,A}$

The average values of $DL_{2,f}$ suggest that uniform, broadband decay was an invalid assumption for open plan offices. While $DL_{2,s,A}$ is insensitive to deviations in the 125, 250, 4,000 and 8,000 Hz bands, STI is not. As such, using the average deviations from $DL_{2,s,A}$ shown in Table 3.2 to adjust $DL_{2,f}$ relative to $DL_{2,s,A}$ may be used to better predict how STI varies with distance.

In standard rooms, this assumption appeared to hold true as furnishing in standard rooms is rarely expected to obstruct the line of sight between a speaker and a receiver. For improved prediction accuracy, the adjustment values in Table 3.2 may be used.

3.1.3.3 Conclusion

For each room, DL_2 was computed for the A-weighted speech pressure level and each octave band. The results were grouped into open-plan offices and standard rooms. The difference between $DL_{2,s,A}$ and $DL_{2,f}$ were also computed to investigate how $DL_{2,f}$ differs from $DL_{2,s,A}$.

In open-plan offices, $DL_{2,500Hz}$ was most similar to $DL_{2,s,A}$. The maximum deviations from $DL_{2,s,A}$ were -2.5 dB/DD in the 125 Hz band, and +1.0 dB/DD in the 8,000 Hz band. On average, relative to $DL_{2,s,A}$, $DL_{2,f}$ was -2.5 dB/DD at 125 Hz, -0.8 dB/DD at 250 Hz, +0.2 dB/DD at 500 Hz, +0.9 dB/DD at 1,000 Hz, +0.8 dB/DD at 2,000 Hz, +0.7 dB/DD at 4,000 Hz, and +1.0 dB/DD at 8,000 Hz.

In standard rooms, the difference between $DL_{2,f}$ and $DL_{2,s,A}$ was small with the exception of 125 and 8,000 Hz band. On average, relative to $DL_{2,s,A}$, $DL_{2,f}$ was -0.7 dB/DD at 125 Hz, -0.4 dB/DD at 250 Hz, +0.1 dB/DD at 500 Hz, +0.2 dB/DD at 1,000 Hz, +0.3 dB/DD at 2,000 Hz, +0.4 dB/DD at 4,000 Hz and +1.0 dB/DD at 8,000 Hz.

Uniform, broadband decay was shown to be invalid for open plan offices. However, this assumption was reasonable for standard rooms without sub-dividers in the space. In the model, the octave-band DL_2 values were adjusted using the average deviations shown in Table 3.2 for open plan offices, and adjustment values can be considered optional for standard rooms.

3.1.4 Linear Decay

3.1.4.1 Measurement results

The A-weighted speech pressure level, $L_{p,s,A}$, was plotted versus distance for open plan offices and standard rooms in Figures 3.3 through 3.8. For open plan offices, the data was grouped based on workspace divider height ($H_{divider}$).

DL_2 values were then calculated over two ranges: (1) from 1 – 16 m, $DL_{2,s,A,1-16m}$ and (2) between distances of 4 m and the maximum room distance, in accordance with Keranen, $DL_{2,s,A,4m}$ [10]. The values are shown in Table 3.5 and Figures 3.3 and 3.8. Measurements were grouped into open-plan offices and standard rooms. The open-plan office measurements were further divided based on workspace divider height. The following room types were classified as standard rooms: meeting rooms (MR), activity rooms (AR), classrooms (CR), acoustically untreated computer labs (CL-U), acoustically treated computer labs (CL-T), empty lunch rooms (LR-E), and furnished lunch rooms (LR-T).

Two base-2 logarithmic regressions were calculated for each room. The first regression was for data between the distances of 1 m and 16 m. A maximum distance of 16m was chosen as rooms rarely exceeded this length ($DL_{2,s,A,1-16m}$). The second regression was for the measurement range proposed by Keranen ($DL_{2,s,A,4m}$), which starts at 4 m and ends at the maximum possible distance in the space.

The regressions were used to predict $L_{p,S,A}$ values at all measurement distances for each dataset. Prediction errors were then calculated for both regression models. The prediction error, E_{e-r}, was defined as the error between measured A-weighted speech pressure level ($L_{p,S,A,exp}$) and the A-weighted predicted speech pressure level ($L_{p,S,A,reg}$). The prediction errors were compiled and are shown in Figures 3.9 through 3.14 for DL_2 between 1 – 16 m ($DL_{2,s,A,1-16m}$), and Figures 3.15 through 3.20 for DL_2 between 4 m and the maximum distance in a room ($DL_{2,s,4m}$). The averaged absolute prediction error and maximum prediction errors for each room are compiled in Tables 3.6 and 3.7.

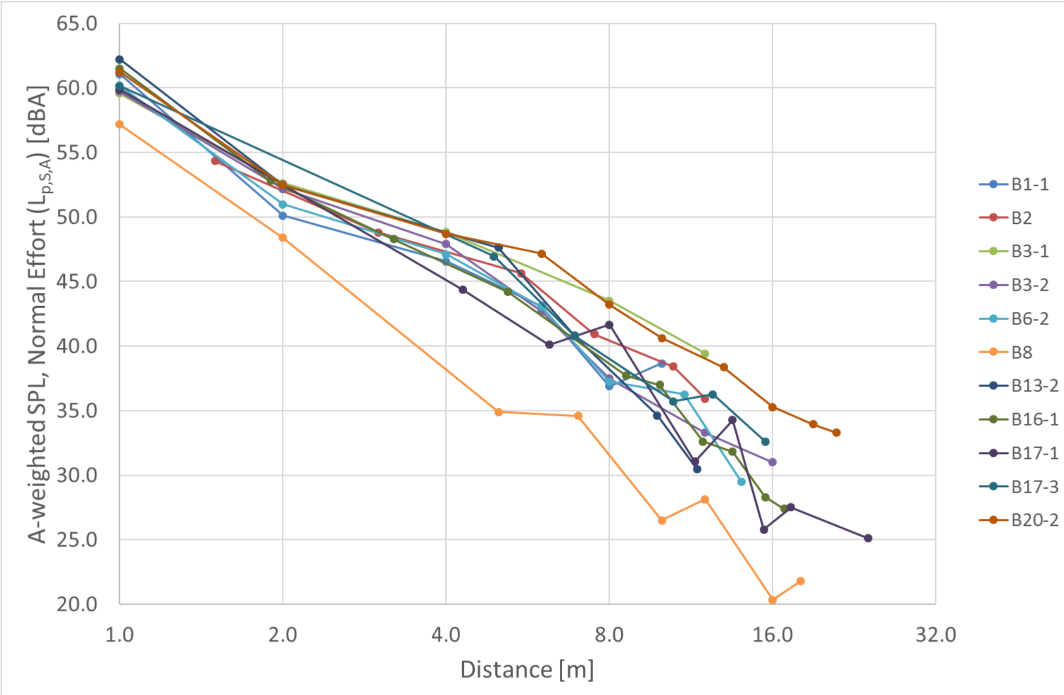

Figure 3.3 - $L_{p,s,A,exp}$ vs Distance for Open-plan Offices (1.2 m < $H_{divider}$ < 1.3 m).

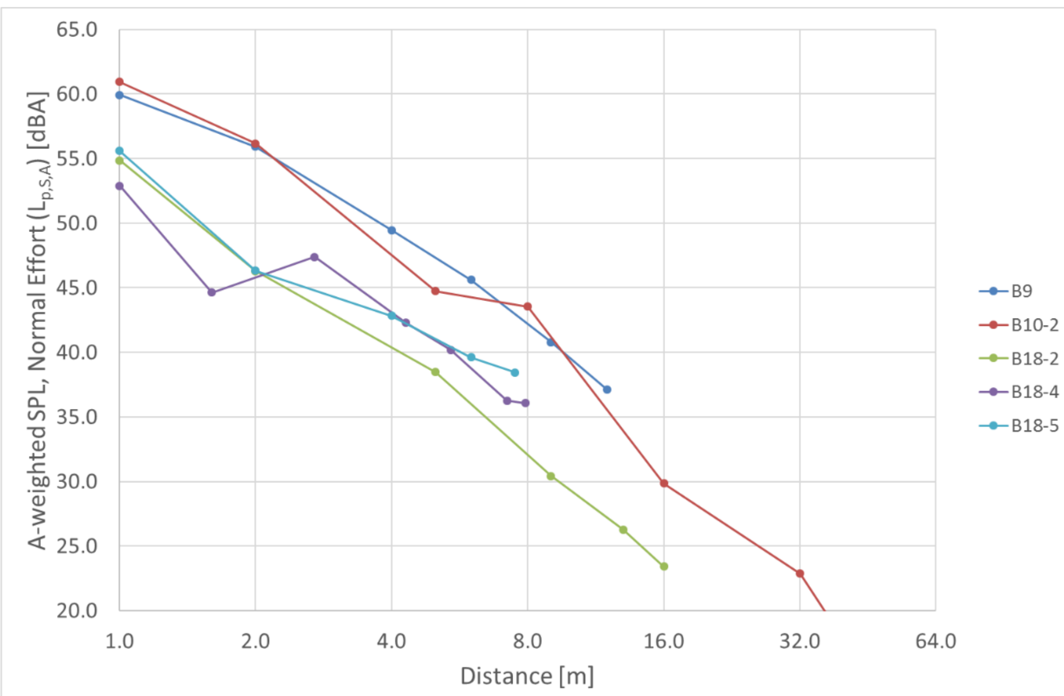

Figure 3.4 - $L_{p,s,A,exp}$ vs Distance for Open-plan Offices ($H_{divider}$ = 1.4 m).

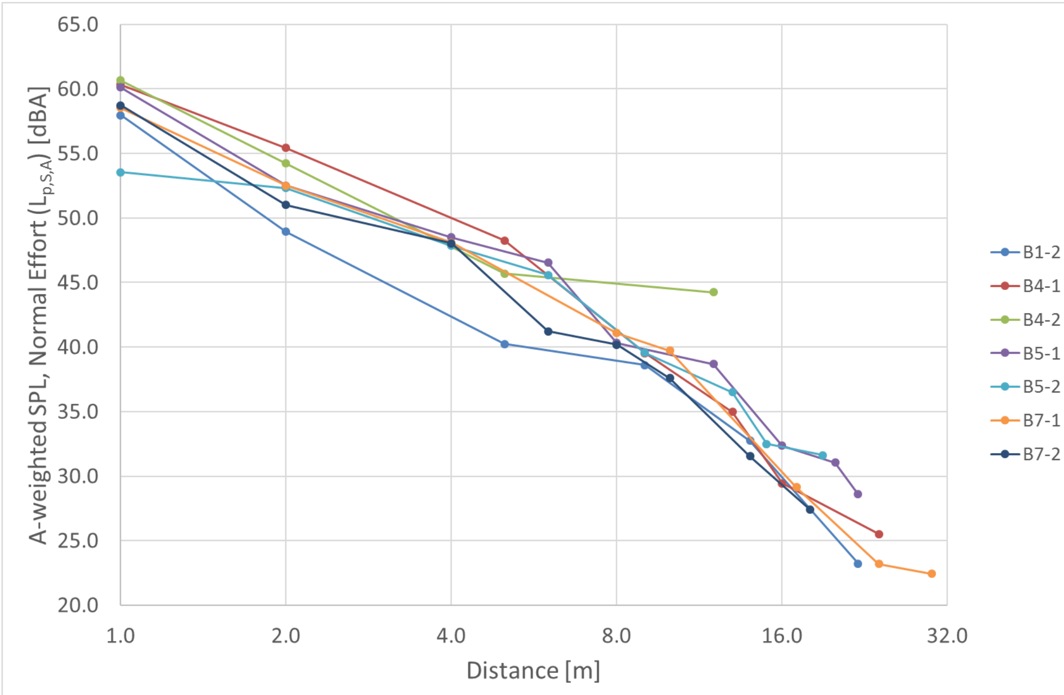

Figure 3.5 - $L_{p,s,A,exp}$ vs Distance for Open-plan Offices ($H_{divider}$ = 1.5 m).

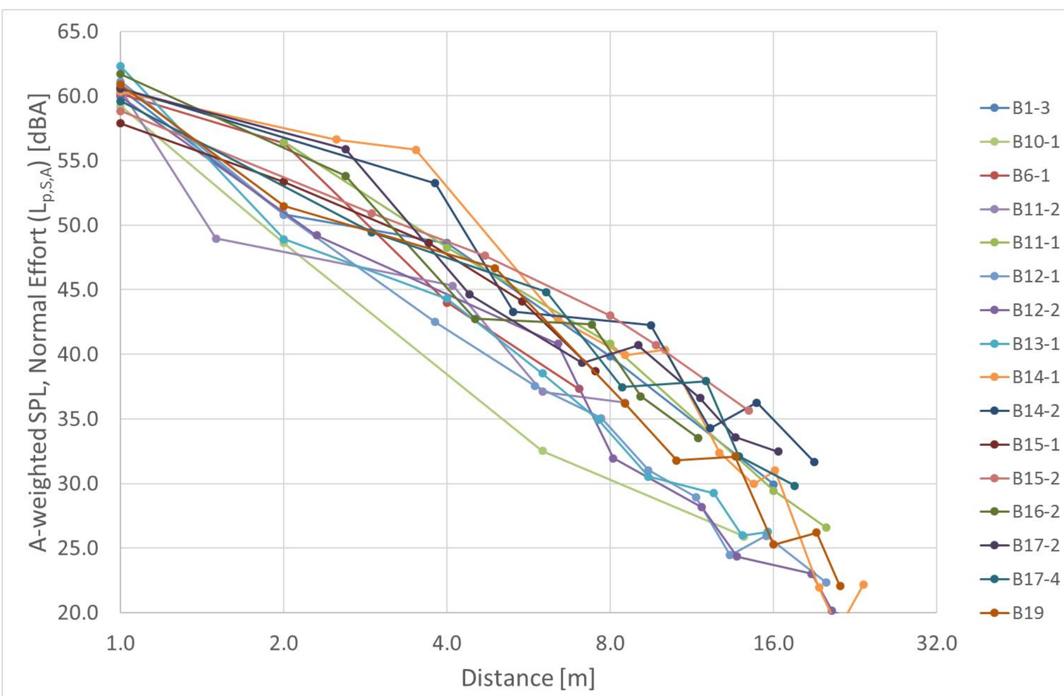

Figure 3.6 - $L_{p,s,A,exp}$ vs Distance for Open-plan Offices (1.6 m < $H_{divider}$ < 1.8 m).

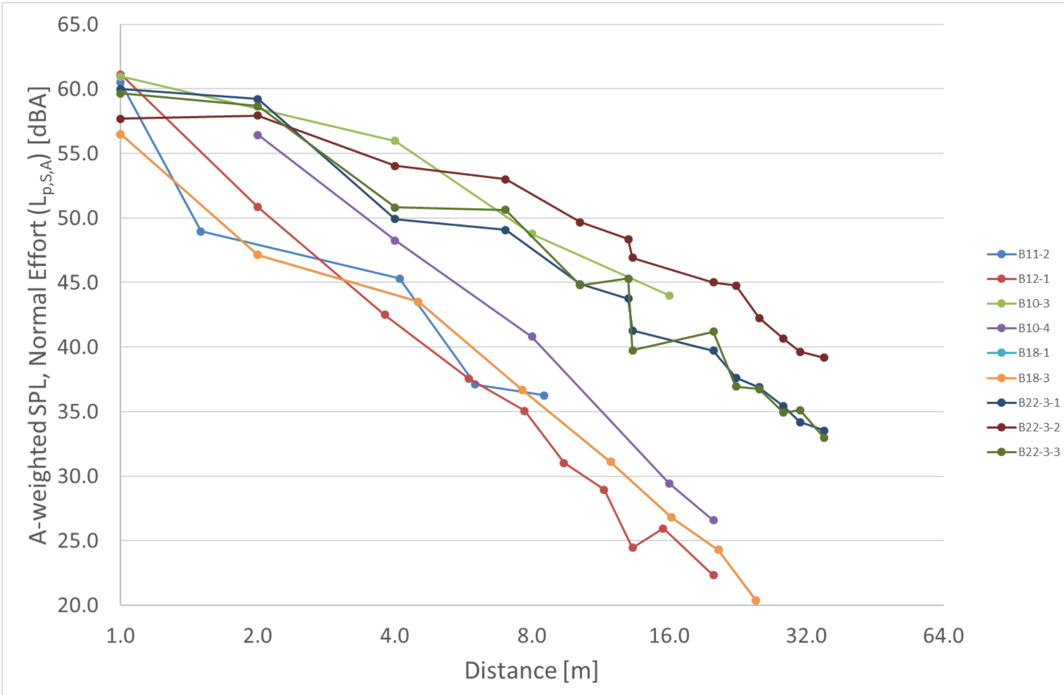

Figure 3.7 - $L_{p,s,A,exp}$ vs Distance for Open-plan Offices ($H_{divider}$ > 2 m).

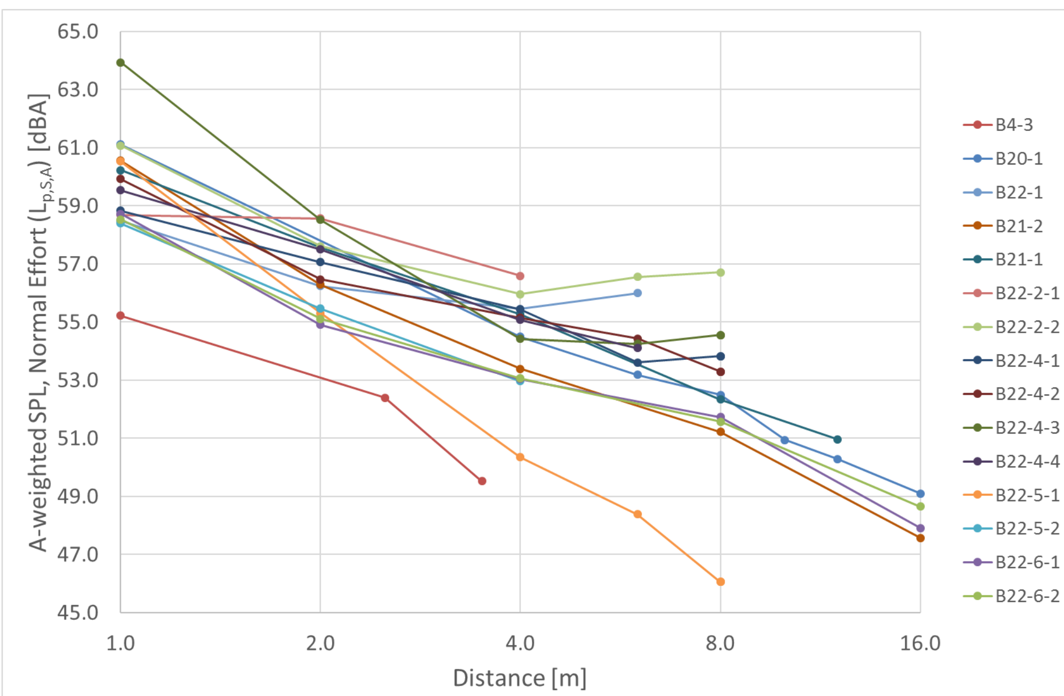

Figure 3.8 - $L_{p,s,A,exp}$ vs Distance for Standard Rooms.

Table 3.5 - Measured DL_2 Grouped by Room Type, then by Divider Height for Open-plan Offices.

Open-plan Offices											
1.2 - 1.3 m dividers (**Figure 3.3**)				1.4 m dividers (Figure 3.4)				1.5 m dividers (Figure 3.5)			
Room	$H_{divider}$	$DL_{2,1}$[1]	$DL_{2,2}$[1]	**Room**	$H_{divider}$	$DL_{2,1}$	$DL_{2,2}$	**Room**	$H_{divider}$	$DL_{2,1}$	$DL_{2,2}$
B1-1	1.2 m	6.8	7.0	**B9**	1.4 m	6.4	7.8	**B1-2**	1.5 m	6.2	7.9
B2	1.2 m	5.9	8.1	**B10-2**	1.4 m	7.5	9.5	**B4-1**	1.5 m	7.5	10.3
B3-1	1.2 m	5.4	5.9	**B18-2**	1.4 m	7.7	8.9	**B4-2**	1.5 m	4.8	1.1
B3-2	1.2 m	7.3	8.6	**B18-4**	1.4 m	5.1	7.5	**B5-1**	1.5 m	6.4	8.2
B6-2	1.3 m	7.4	9.2	**B18-5**	1.4 m	5.7	4.9	**B5-2**	1.5 m	5.3	7.8
B8	1.2 m	8.8	8.3					**B7-1**	1.5 m	5.7	9.6
B13-2	1.2 m	8.3	13.8					**B7-2**	1.5 m	6.7	9.1
B16-1	1.3 m	7.9	10.0								
B17-1	1.2 m	7.8	8.6								
B17-3	1.2 m	7.0	8.2								
B20-2	1.2 m	6.2	7.0								
Open-plan Offices								**Standard Rooms**			
1.6 - 1.8 m dividers (**Figure 3.6**)				**> 2 m dividers** (Figure 3.7)				**Standard rooms** (Figure 3.8)			
Room	$H_{divider}$	$DL_{2,1}$	$DL_{2,2}$	**Room**	$H_{divider}$	$DL_{2,1}$	$DL_{2,2}$	**Room**	**Desc.**	$DL_{2,1}$	$DL_{2,2}$
B1-3	1.7 m	7.2	9.3	**B10-3**	2.4 m	4.3	6.0	**B4-3**	MR[2]	2.9	2.9
B6-1	1.7 m	8.6	8.3	**B10-4**	2.4 m	8.8	9.6	**B20-1**	LR[2]	3.0	3.0
B10-1	1.8 m	8.9	5.4	**B18-1**	2 m	7.0	9.2	**B21-1**	LR[2]	2.6	2.7
B11-1	1.7 m	8.8	9.6	**B18-3**	2 m	7.0	9.2	**B21-2**	AR[2]	3.1	2.9
B11-2	1.7 m	7.2	8.7	**B22-3-1**	2 m	5.0	5.7	**B22-1**	CR[2]	1.0	0.9
B12-1	1.7 m	9.1	8.8	**B22-3-2**	2 m	2.9	5.1	**B22-2-1**	CR[2]	1.1	N/A
B12-2	1.7 m	9.1	9.2	**B22-3-3**	2 m	4.8	6.1	**B22-2-2**	CR[2]	1.4	0.8
B13-1	1.7 m	8.9	9.5					**B22-4-1**	CL-U[2]	1.8	1.7
B14-1	1.7 m	8.3	13.0					**B22-4-2**	CL-U[2]	2.1	1.8
B14-2	1.7 m	6.8	6.4					**B22-4-3**	CL-U[2]	3.2	0.1
B15-1	1.8 m	6.3	9.7					**B22-4-4**	CL-U[2]	2.1	1.7
B15-2	1.8 m	5.8	7.4					**B22-5-1**	CL-T[2]	4.8	4.2
B16-2	1.7 m	7.9	6.8					**B22-5-2**	CL-T[2]	2.7	N/A
B17-2	1.7 m	7.3	6.4					**B22-6-1**	LR-E[2]	2.5	2.6
B17-4	1.7 m	6.8	9.1					**B22-6-2**	LR-T[2]	2.3	2.2
B19	1.7 m	8.3	10.9								

1 - $DL_{2,1}$ is for DL_2 regression calculated between 1-16m ($DL_{2,S,A,1\text{-}16m}$), $DL_{2,2}$ is for DL_2 regressions calculated from 4m and onwards ($DL_{2,S,A,4m}$)

2 – MR = Meeting Room, LR = Lunch Room, AR = Activity Room, CR = Classroom, CL-U = Acoustically Untreated Computer Lab, CL-T = Acoustically Treated Computer Lab, LR-E = Empty Lunch Room, LR-T = Lunch Room with Tables

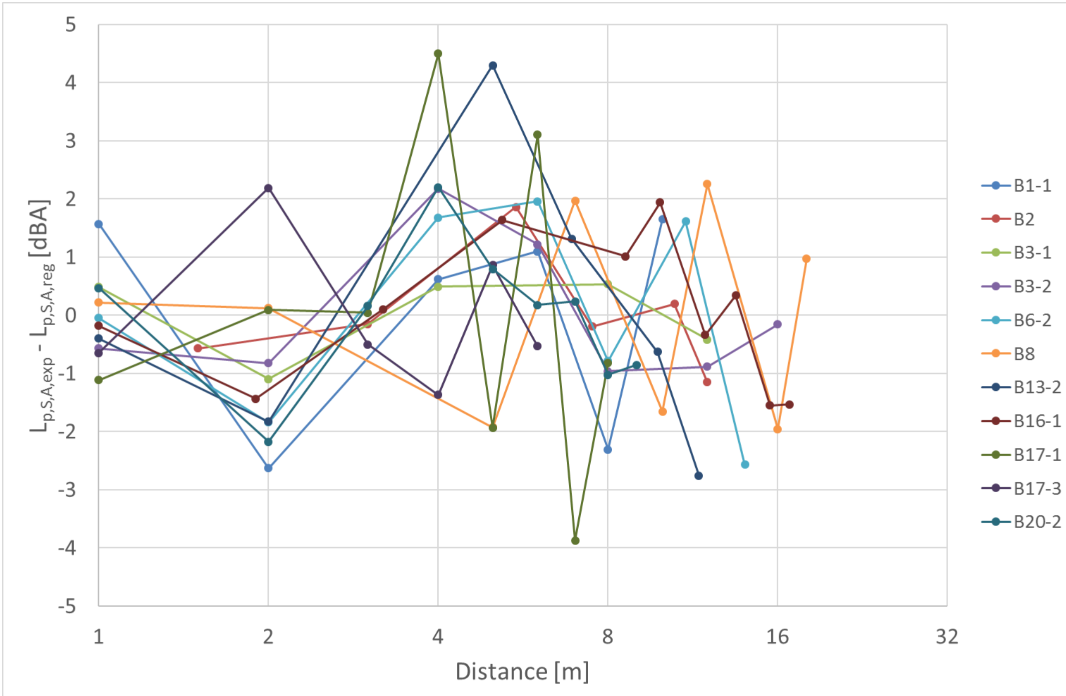

Figure 3.9 - DL_2 Regression Error for $DL_{2,S,A,1-16m}$ (Open-plan Offices, 1.2 m < $H_{divider}$ < 1.3 m).

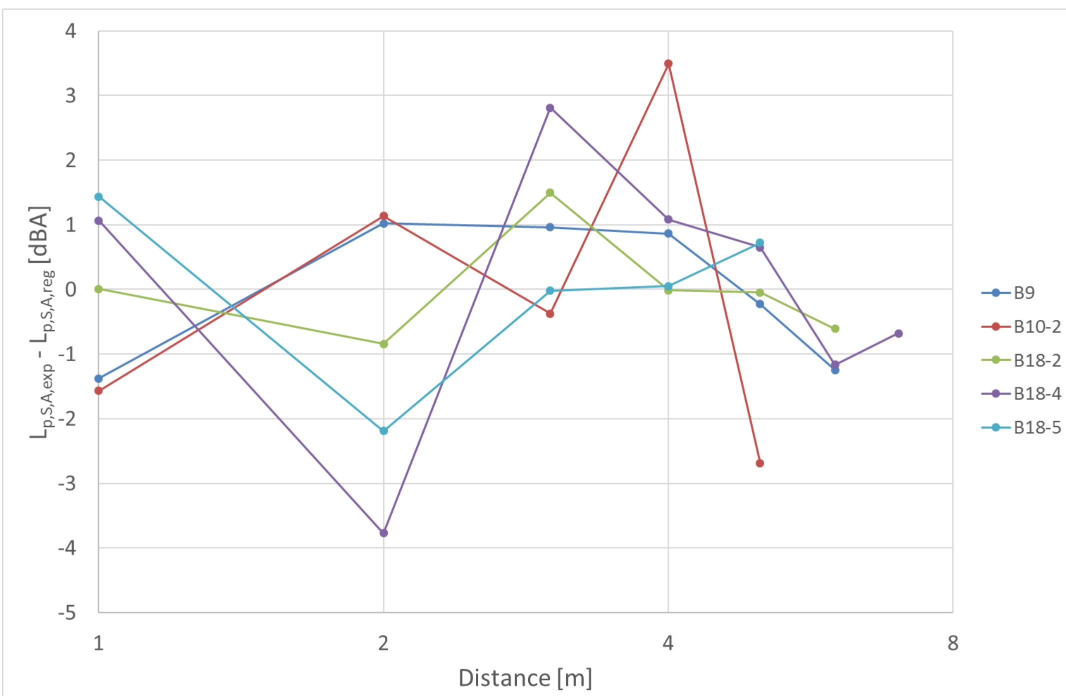

Figure 3.10 - DL_2 Regression Error for $DL_{2,S,A,1-16m}$ (Open-plan Offices, $H_{divider}$ = 1.4 m).

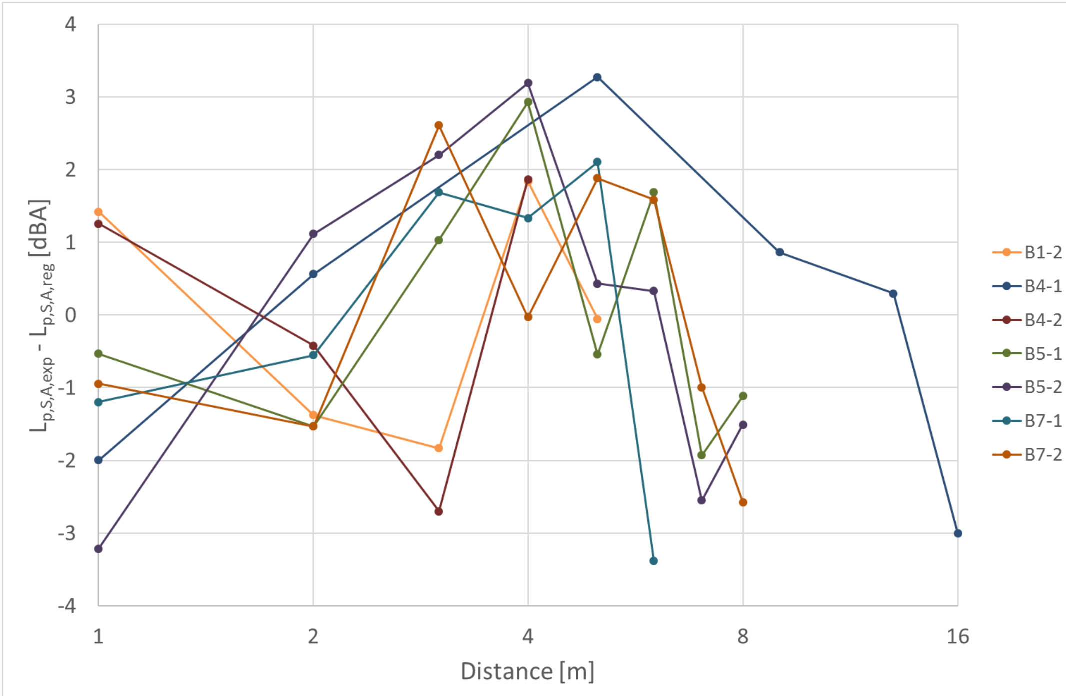

Figure 3.11 - DL_2 Regression Error for $DL_{2,S,A,1-16m}$ (Open-plan Offices, $H_{divider}$ = 1.5 m).

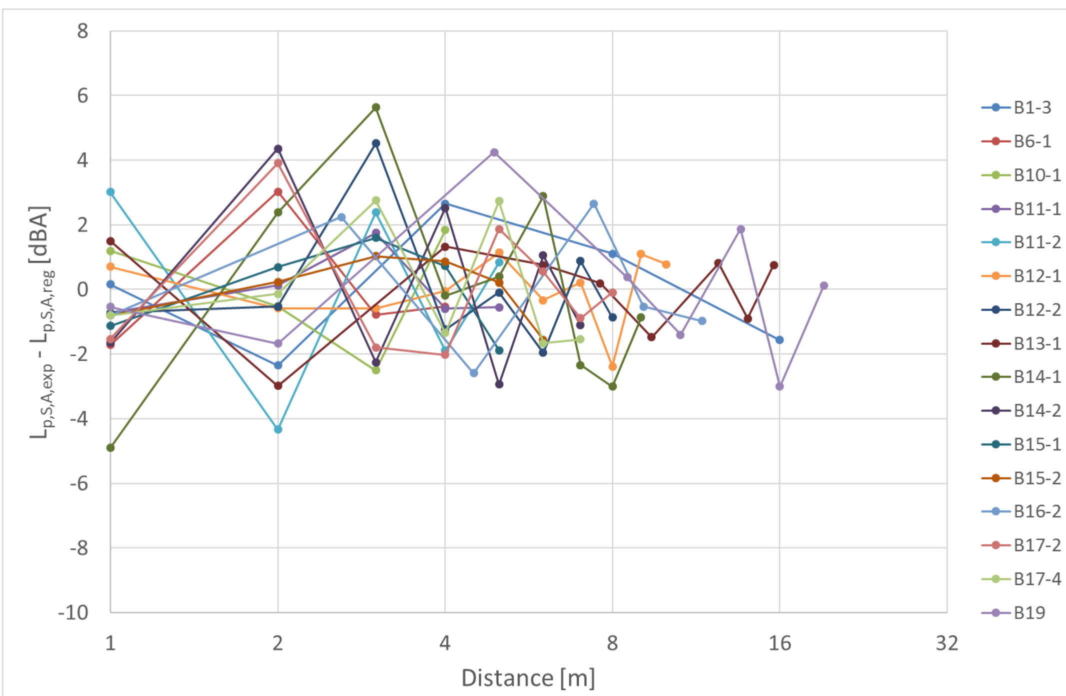

Figure 3.12 - DL_2 Regression Error for $DL_{2,S,A,1-16m}$ (Open-plan Offices, 1.6 m < $H_{divider}$ < 1.8 m).

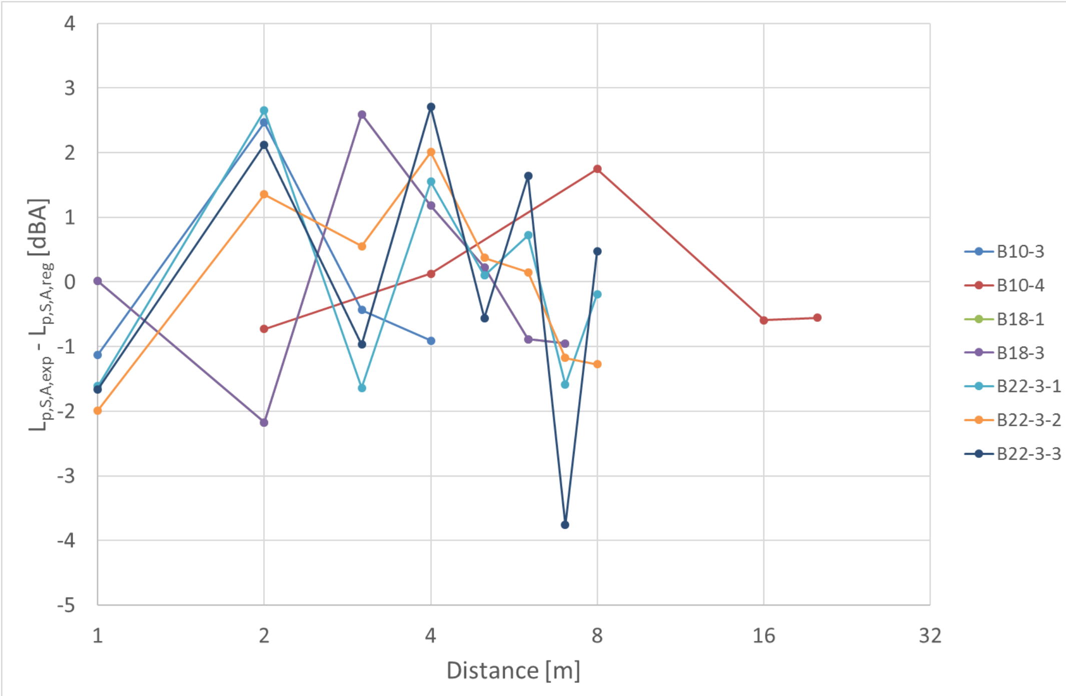

Figure 3.13 - DL_2 Regression Error for $DL_{2,S,A,1-16m}$ (Open-plan Offices, $H_{divider}$ > 2 m).

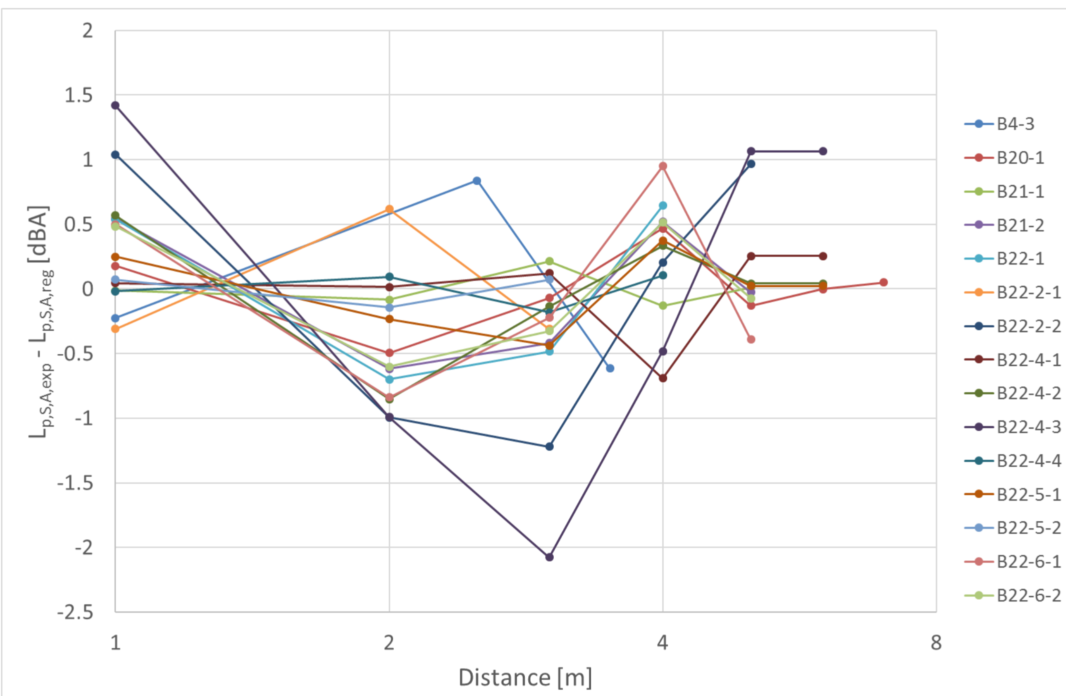

Figure 3.14 - DL_2 Regression Error for $DL_{2,S,A,1-16m}$ (Standard Rooms).

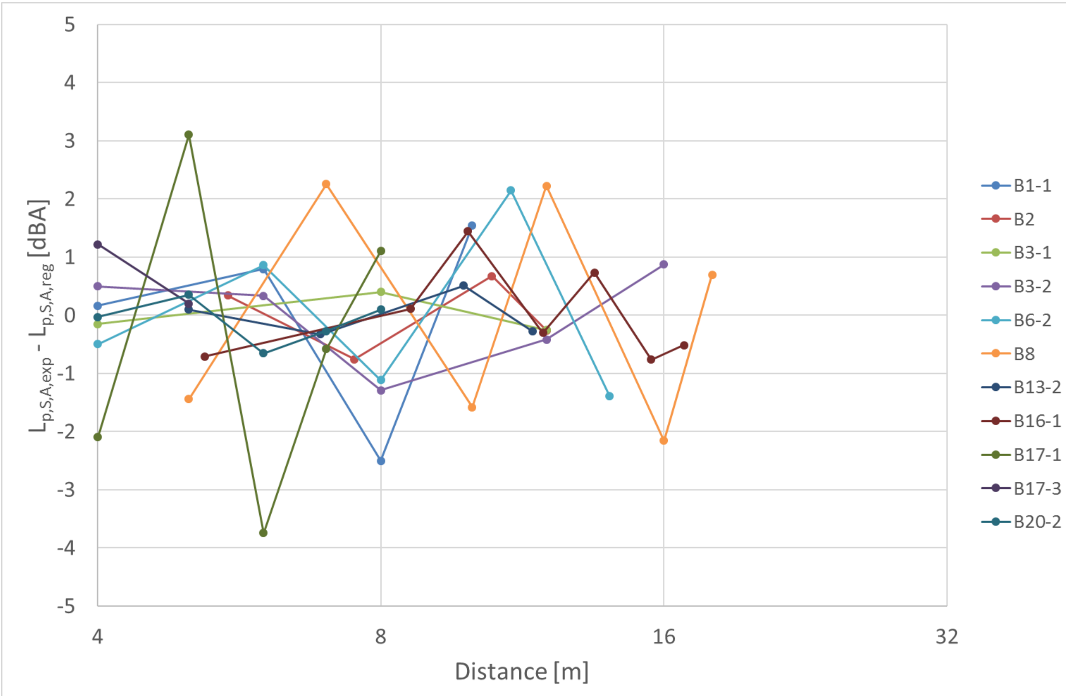

Figure 3.15 - DL_2 Regression Error for $DL_{2,s,4m}$ (Open-plan Offices, 1.2 m < $H_{divider}$ < 1.3 m).

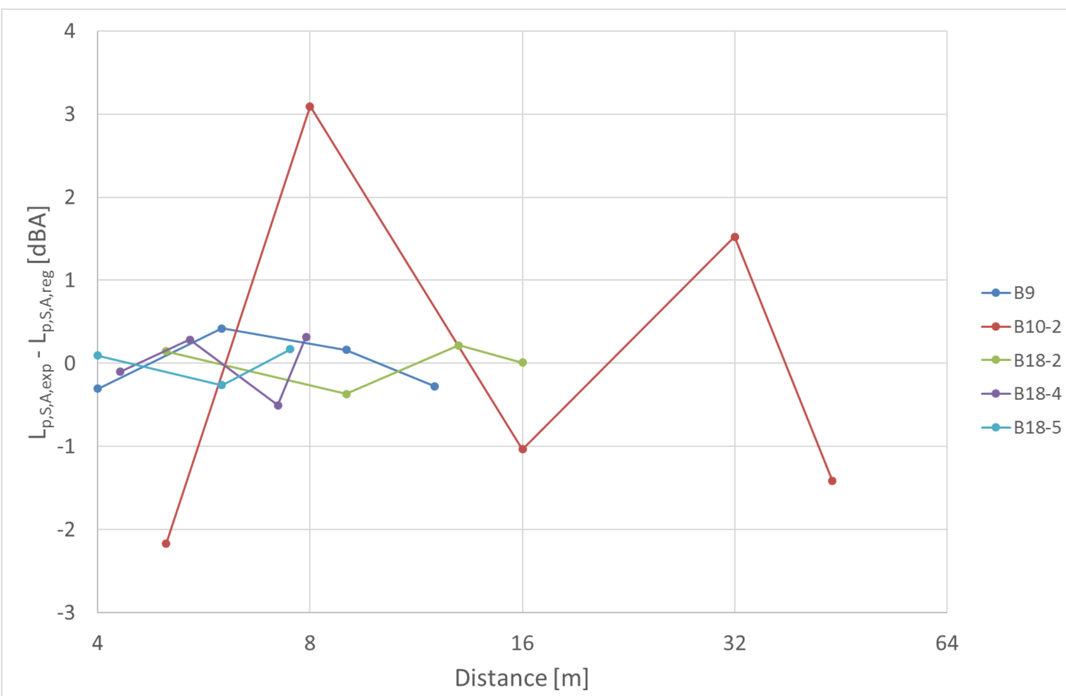

Figure 3.16 - DL_2 Regression Error for $DL_{2,s,4m}$ (Open-plan Offices, $H_{divider}$ = 1.4 m).

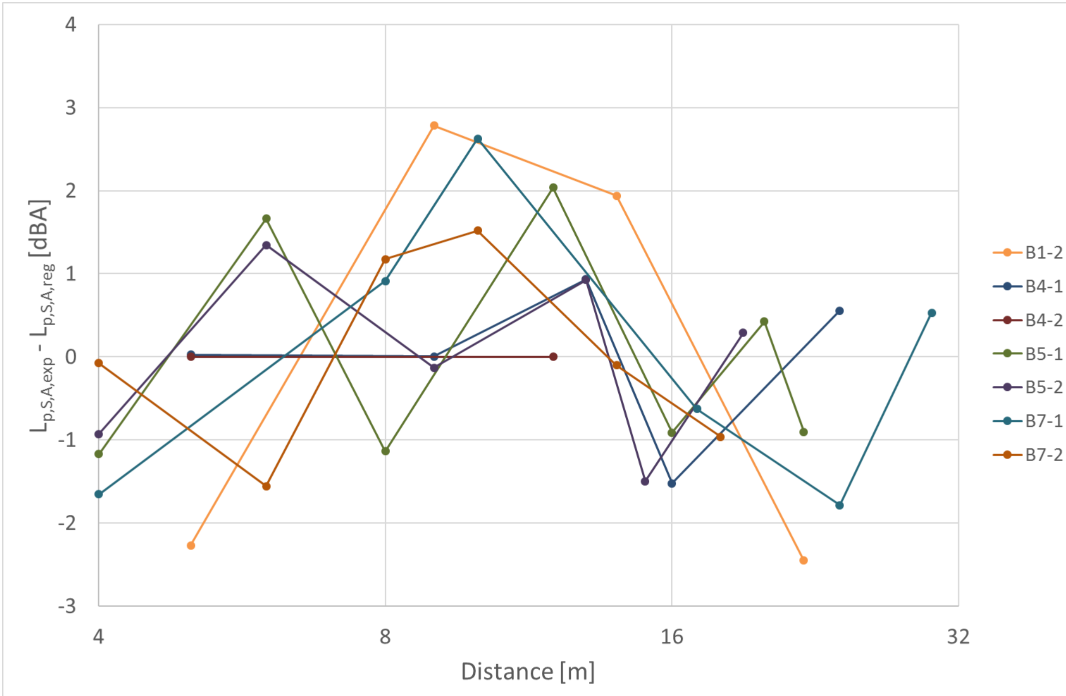

Figure 3.17 - DL_2 Regression Error for $DL_{2,s,4m}$ (Open-plan Offices, $H_{divider}$ = 1.5 m).

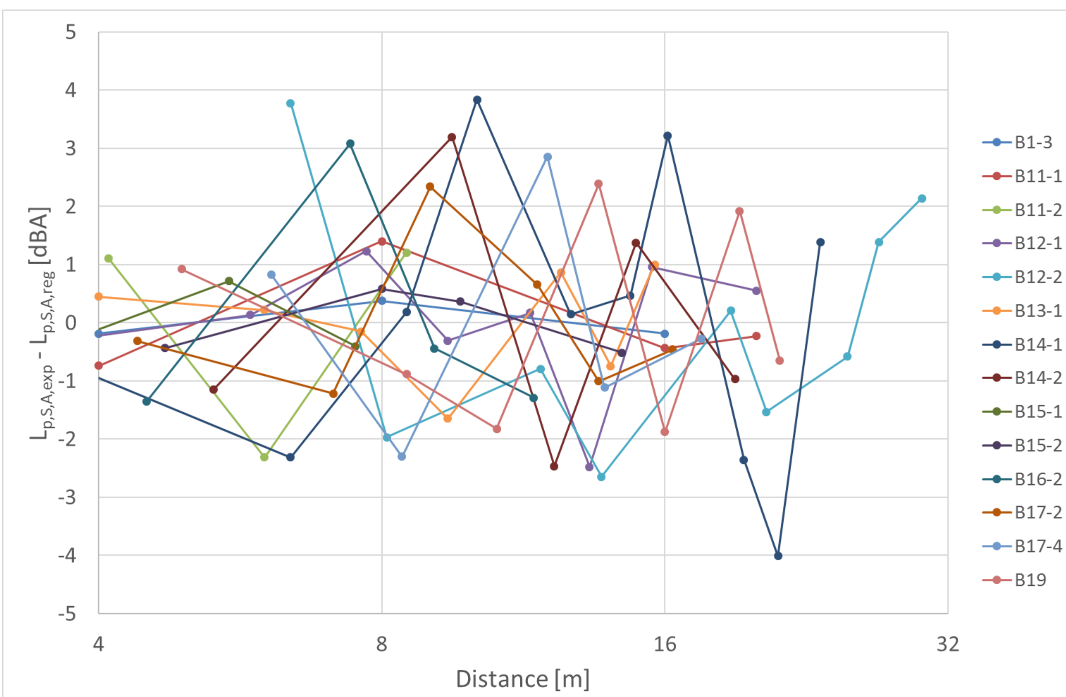

Figure 3.18 - DL_2 Regression Error for $DL_{2,s,4m}$ (Open-plan Offices, 1.6 m < $H_{divider}$ < 1.8 m).

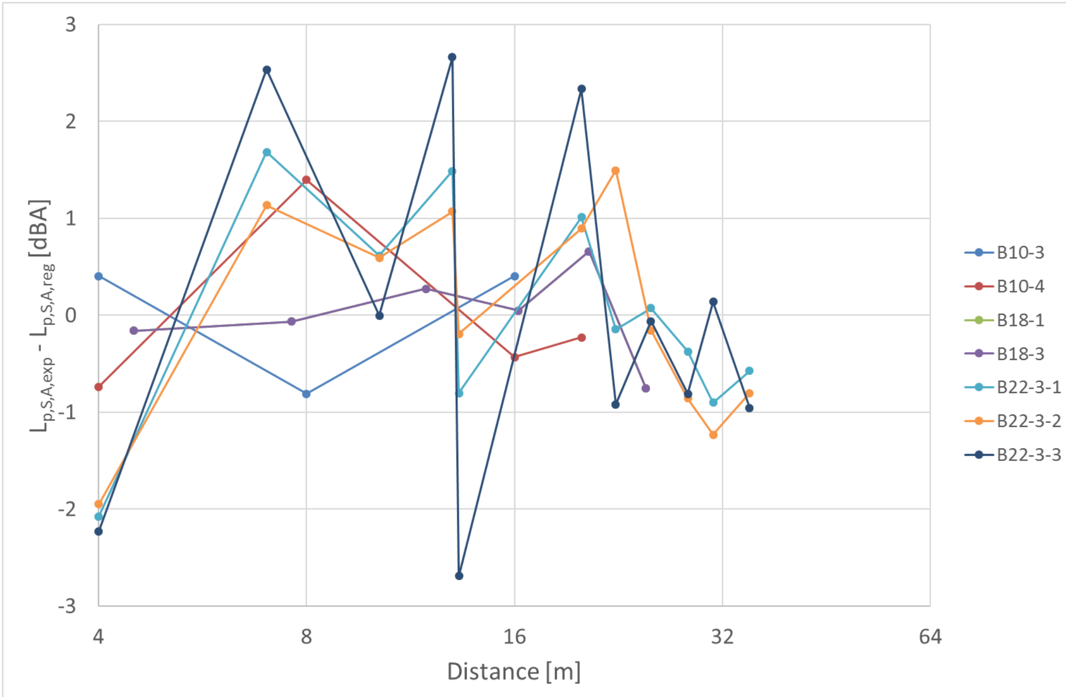

Figure 3.19 - DL_2 Regression Error for $DL_{2,s,4m}$ (Open-plan Offices, $H_{divider}$ > 2 m).

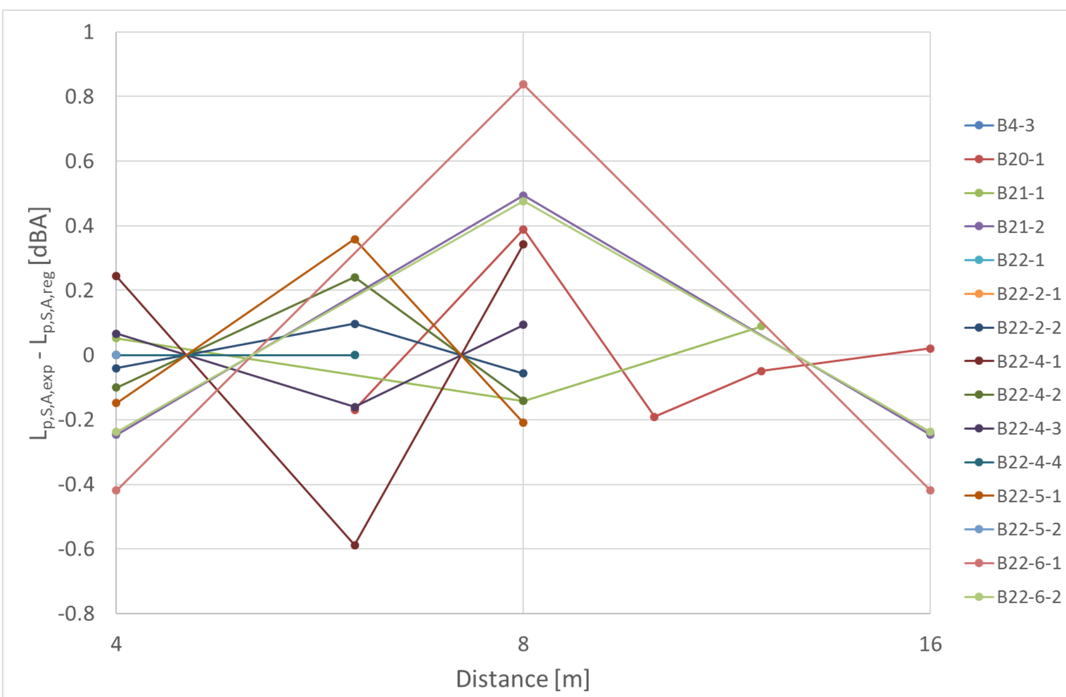

Figure 3.20 - DL_2 Regression Error for $DL_{2,s,4m}$ (Standard Rooms).

Table 3.6 - Average Absolute Regression Error Comparison Between $L_{p,S,A,1\text{-}16m}$ and $L_{p,S,A,4m}$ in dB.

Open-plan Office (Figures **3.9** and **3.15**)			**Open-plan Office** (Figures **3.10** and **3.16**)			**Open-plan Office** (Figures **3.11** and **3.17**)		
Room	**$E_{e-r,1-16m}$**	**$E_{e-r,4m}$**	**Room**	**$E_{e-r,1-16m}$**	**$E_{e-r,4m}$**	**Room**	**$E_{e-r,1-16m}$**	**$E_{e-r,4m}$**
B1-1	1.6	1.2	**B9**	0.9	0.3	**B1-2**	1.3	2.4
B2	0.7	0.5	**B10-2**	1.9	1.8	**B4-1**	1.7	0.6
B3-1	0.6	0.3	**B18-2**	0.5	0.2	**B4-2**	1.6	N/A
B3-2	1.0	0.7	**B18-4**	1.6	0.3	**B5-1**	1.4	1.2
B6-2	1.5	1.2	**B18-5**	0.9	0.2	**B5-2**	1.8	0.9
B8	1.4	1.7				**B7-1**	1.7	1.4
B13-2	1.9	0.3				**B7-2**	1.5	0.9
B16-1	1.0	0.7						
B17-1	1.9	2.0						
B17-3	1.0	1.0						
B20-2	0.9	0.5						
Open-plan Office (Figures **3.12** and **3.18**)			**Open-plan Office** (Figures 3.13 and 3.19)			**Standard Room** (Figures 3.14 and 3.20)		
Room	**$E_{e-r,1-16m}$**	**$E_{e-r,4m}$**	**Room**	**$E_{e-r,1-16m}$**	**$E_{e-r,4m}$**	**Room**	**$E_{e-r,1-16m}$**	**$E_{e-r,4m}$**
B1-3	1.6	0.2	**B10-3**	1.2	0.5	**B4-3**	0.6	0.6
B6-1	1.5	N/A	**B10-4**	0.7	0.7	**B20-1**	0.2	0.2
B10-1	1.5	N/A	**B18-1**	1.1	0.3	**B21-1**	0.1	0.1
B11-1	0.7	0.7	**B18-3**	1.1	0.3	**B21-2**	0.4	0.3
B11-2	2.5	1.5	**B22-3-1**	1.3	0.9	**B22-1**	0.6	N/A
B12-1	0.8	0.8	**B22-3-2**	1.1	0.9	**B22-2-1**	0.4	N/A
B12-2	1.4	1.7	**B22-3-3**	1.7	1.4	**B22-2-2**	0.9	0.1
B13-1	1.2	0.7				**B22-4-1**	0.2	0.4
B14-1	2.5	1.8				**B22-4-2**	0.3	0.2
B14-2	2.3	1.8				**B22-4-3**	1.2	0.1
B15-1	1.2	0.5				**B22-4-4**	0.1	N/A
B15-2	0.8	0.5				**B22-5-1**	0.2	0.2
B16-2	1.6	1.5				**B22-5-2**	0.1	N/A
B17-2	1.6	1.0				**B22-6-1**	0.6	0.6
B17-4	1.6	1.5				**B22-6-2**	0.4	0.3
B19	1.7	1.5						

Table 3.7 - Maximum Regression Error Comparison Between $L_{p,S,A,1\text{-}16m}$ and $L_{p,S,A,4m}$ in dB.

Open-plan Office (Figures **3.9** and **3.15**)			Open-plan Office (Figures **3.10** and **3.16**)			Open-plan Office (Figures **3.11** and **3.17**)		
Room	**$E_{e\text{-}r,1\text{-}16m}$**	**$E_{e\text{-}r,4m}$**	**Room**	**$E_{e\text{-}r,1\text{-}16m}$**	**$E_{e\text{-}r,4m}$**	**Room**	**$E_{e\text{-}r,1\text{-}16m}$**	**$E_{e\text{-}r,4m}$**
B1-1	2.6	2.5	**B9**	1.4	0.4	**B1-2**	1.8	2.8
B2	1.9	0.8	**B10-2**	3.5	3.1	**B4-1**	3.3	1.5
B3-1	1.1	0.4	**B18-2**	1.5	0.4	**B4-2**	2.7	N/A
B3-2	2.2	1.3	**B18-4**	3.8	0.5	**B5-1**	2.9	2.0
B6-2	2.6	2.1	**B18-5**	2.2	0.3	**B5-2**	3.2	1.5
B8	2.3	2.3				**B7-1**	3.4	2.6
B13-2	4.3	0.5				**B7-2**	2.6	1.6
B16-1	1.9	1.4						
B17-1	4.5	4.0						
B17-3	2.2	1.3						
B20-2	2.2	1.4						
Open-plan Office (Figures **3.12** and **3.18**)			**Open-plan Office** (Figures 3.13 and 3.19)			**Standard Room** (Figures 3.14 and 3.20)		
Room	**$E_{e\text{-}r,1\text{-}16m}$**	**$E_{e\text{-}r,4m}$**	**Room**	**$E_{e\text{-}r,1\text{-}16m}$**	**$E_{e\text{-}r,4m}$**	**Room**	**$E_{e\text{-}r,1\text{-}16m}$**	**$E_{e\text{-}r,4m}$**
B1-3	2.7	0.4	**B10-3**	2.5	0.8	**B4-3**	0.8	0.8
B6-1	3.0	N/A	**B10-4**	1.7	1.4	**B20-1**	0.5	0.4
B10-1	2.5	N/A	**B18-1**	2.6	0.8	**B21-1**	0.2	0.1
B11-1	1.7	1.4	**B18-3**	2.6	0.8	**B21-2**	0.6	0.5
B11-2	4.3	2.3	**B22-3-1**	2.7	2.1	**B22-1**	0.7	N/A
B12-1	2.4	2.5	**B22-3-2**	2.0	1.9	**B22-2-1**	0.6	N/A
B12-2	4.5	3.8	**B22-3-3**	3.8	2.7	**B22-2-2**	1.2	0.1
B13-1	3.0	1.6				**B22-4-1**	0.7	0.6
B14-1	5.6	4.0				**B22-4-2**	0.9	0.2
B14-2	4.4	3.2				**B22-4-3**	2.1	0.2
B15-1	1.9	0.7				**B22-4-4**	0.2	N/A
B15-2	1.5	0.6				**B22-5-1**	0.4	0.4
B16-2	2.7	3.1				**B22-5-2**	0.1	N/A
B17-2	3.9	2.3				**B22-6-1**	0.9	0.8
B17-4	2.8	2.9				**B22-6-2**	0.6	0.5
B19	4.2	2.4						

3.1.4.2 Discussion

In open-plan offices, $L_{p,s,A}$ tended to show a consistent pattern in variability. $L_{p,s,A}$ tended to decrease sharply upon crossing a divider, but increase again before the next divider. This trend develops at decreasing distances with increasing divider height.

This behavior is caused by a combination of ceiling reflections and dividers and is largely a function of geometry. While the direct sound is obstructed by the dividers, sound reflected from the ceiling enters pods of workspaces from above. Workspaces immediately behind dividers benefit from physical shielding. Workspaces located farther from the divider are no longer shielded from ceiling reflections, resulting in the potential for higher sound pressure levels despite being located farther from a noise source.

Additionally, sound may diffract over the top edge of the workspace dividers. In outdoor noise propagation applications, diffraction is a significant consideration as the nearest receivers may be far away, and even small angles of diffraction will render the barrier ineffective. Therefore, the performance of outdoor noise barriers is dictated mainly by the height of the barrier.

However, in indoor situations, the contribution of sound diffracting over the edges of workspace dividers may be insignificant compared to the sound reflected off the ceiling. In rooms where the ceiling is highly absorbent, diffraction may be a more significant contributor.

A change in slope was also observed in some open-plan offices (henceforth referred to as double slopes). In general, double slopes were more common in open-plan offices with higher dividers. This is also likely to be due to ceiling reflections and geometry. Contributions from ceiling reflections result in a lower value of DL_2 at closer distances. Ceiling reflection contributions then decrease with increasing distance. In combination with high divider heights that provide more shielding, DL_2 at farther distances is expected to be higher than at closer distances.

For open-plan offices, $DL_{2,s,A,1-16m}$ ranged from 3.9 – 9.7 dB/DD, while $DL_{2,S,A,4m}$ ranged from 3.9 – 13.8 dB/DD. Keranen observed similar values for $DL_{2,S,A,4m}$, ranging from 4.0 – 12.4 dB/DD. $DL_{2,S,A,4m}$ being typically higher in magnitude than $DL_{2,s,A,1-16m}$ indicates that a double-slope is present. Additionally, the change in DL_2 in open-plan offices is indicated by a visible increase in estimation error present between 4 and 8 m in Figures 3.9 through 3.13, which also suggests that the double-slope is a non-trivial contribution to regression error for $DL_{2,s,A,1-16m}$.

A visible trend is present in the regression error for $DL_{2,s,A,1-16m}$ (Figures 3.9 through 3.13). The regression error is typically positive at distances of between 4 – 8 m, and negative between distances of 1 – 4m and 8 m and beyond. For $DL_{2,S,A,4m}$ (Figures 3.15 through 3.19), this trend is absent. This is consistent with Keranen specifying for measurements to start from 4 m to avoid systemic bias due to double-slopes.

The range of estimation error for $DL_{2,s,A,1-16m}$ was approximately 4 – -4 dB, while $DL_{2,S,A,4m}$ was approximately -3 – 3 dB. The estimation error for $DL_{2,s,A,1-16m}$ is expected to be a sum of both slope-change error and the sharp increases and decreases in L_p before and after workspace dividers, whereas estimation error for $DL_{2,S,A,4m}$ is expected to be entirely due to workspace dividers.

Since workspace dividers were observed to cause overestimation of $L_{ps,A}$ behind diviers and underestimation before dividers, it should be possible to more accurately predict $L_{ps,A}$. $DL_{2,s,A,1-16m}$ data can be used to study the onset of this behavior and its dependence on divider height, while $DL_{2,s,A,4m}$ data may be used to further understand the magnitude of the overestimation and underestimation.

$DL_{2,s,A,1-16m}$ was 1.0 – 4.7 dB/DD for standard rooms. In the absence of obstructions, the direct sound transmission path DL_2 cannot exceed 6 dB/DD. The data measured in standard rooms matches this expectation. Prediction errors were also within 1.5 dB for all measured scenarios. Additionally, DL_2 was visually linear, suggesting that standard rooms may be sufficiently described using a single propagation curve.

The Macmillan building on UBC's Vancouver campus (building 22) was used for propagation direction and furnishing measurements. Room 4 was an acoustically untreated computer lab of approximately equal length and width where four DL_2 measurements were conducted. In this room, DL_2 ranged from 1.7 – 3.0 dB/DD. The same behavior was observed in room 5, an acoustically treated computer lab that was similar to room 4. DL_2 values ranged from 2.7 – 4.7

dB/DD, suggesting that DL_2 is dependent on propagation direction, even in standard rooms. This behavior was likely caused by the geometry and room surfaces, like Hodgson's observation that roof pitch in industrial rooms affected DL_2.

DL_2 in the lunchroom (room 6) decreased from 2.5 dB/DD – 2.3 dB/DD when tables were introduced. Furnishing typically increases DL_2 in rooms but furnishing the lunchroom with tables appeared to decrease DL_2. This is speculated to be due to the orientation of the table as the tables were all parallel to the ground. The tabletops are acoustically reflective and effectively become a large acoustic reflector as opposed to volume scattering.

Finally, it was noticed that measurement distances were not regularly spaced when placed on a logarithmic scale. In B22, it was noted that measurements were occurring at higher densities at larger distances. This may be a source or regression error as the DL_2 value is biased towards the distant data points. This could be resolved by collecting measurement data at locations which increase in distance by a constant factor (e.g. 2 times, $2^{1/2}$ times, $2^{1/3}$ times etc.). The regular intervals will give each measurement equal weighting in their contributions to the DL_2 value.

3.1.4.3 Conclusion

DL_2 was measured in 62 rooms in 22 buildings. DL_2 was calculated using data from distances between 1 – 16 m ($DL_{2,s,A,1-16m}$), and between 4 m and the maximum allowable distance in the rooms ($DL_{2,s,A,4m}$) with the objective of assessing the linear decay of $L_{p,s,A}$ on a logarithmic distance scale.

Double slopes were observed in open-plan offices at around 4 – 8 m from the source, revealing 1 – 2 dB of underestimation for ($DL_{2,s,A,1-16m}$ regressions. As $DL_{2,s,A,4m}$ was chosen to avoid changes in slope, no estimation errors were observed. The prediction accuracy of both $DL_{2,s,A,1-16m}$ and $DL_{2,s,A,4m}$ suffered due to the tendency for $L_{p,s,A}$ to increase before, and decrease significantly after dividers. The onset of this behavior is hypothesized to be a function of divider height.

Estimation error in $DL_{2,s,A,1-16m}$ is expected to be a combination of both slope-change and divider-related errors. By visual inspection, double-slope errors appeared to account for 1 – 2 dB of deviation. $DL_{2,s,A,4m}$ error data was used to determine that the overestimation and underestimation due to the presence of dividers accounted for approximately 3 dB of deviation. Further experimentation is recommended at finer measurement resolution to better study how workspace divider arrangements cause deviations from DL_2 regressions.

DL_2 in standard rooms was linear over the entire range; estimation errors were typically within 1 dB. Two computer labs were measured: one treated, and one untreated. DL_2 was 1.7 – 3.0 dB/DD in the untreated case and 2.7 – 4.7 dB/DD in the other. Measurements along different propagation directions in the same room resulted in different DL_2 values, suggesting that DL_2 is dependent on direction. This behavior is hypothesized to be caused by the distribution of acoustic absorption and the distribution of volume scattering.

In the model, standard rooms will not require any adjustments. Open plan offices will be adjusted by 1 – 2 dB in the range of 4 – 8 m from a sound source. Further investigation is required to understand the impact of workspace dividers.

From a measurement perspective, DL_2 may be more widely adopted if the measurement distances were applicable regardless of room type. While measurements from 1 – 16 m are associated with DL_2 regression errors in open plan offices, the errors are predictable. This is an acceptable trade-off for a universal DL_2 measurement method. The measurement distances are recommended to be taken at distances that are multiples of the previous distance (e.g. 1, 2, 4, 8, 16 m) as opposed to fixed measurement increments (e.g. 1, 2, 3, 4, 5, 6 m) to avoid regression bias in the DL_2 value.

3.1.5 $L_{p,1m}$

3.1.5.1 Measurement Results

Sound pressure level at 1 m from DL_2 measurements and speech intelligibility measurements (conducted at the same time as the DL_2 measurements) were compiled. The data was sorted by octave band then categorized under open-plan office or standard rooms.

To examine the deviation from expected free-field decay levels, the sound pressure level of a point source in a free-field environment at 1 m ($L_{p,1m,FF}$) as predicted by Eq. (1.5) was subtracted from each $L_{p,1m}$ measurement. The results are shown as a function of room volume in Figures 3.21

through 3.27. Three regressions were applied to each frequency band: (1) a logarithmic regression for standard rooms in regular font; (2) a linear regression for the open plan offices in italicized font; and (3), a logarithmic regression for the entire dataset in bold-faced font.

For standard rooms, the difference between $L_{p,1m}$ and $L_{p,1m,FF}$ decreased with increasing volume in all bands. The correlation coefficient was lowest in the 125 Hz band ($r^2 = 0.016$) and was significantly higher in other bands ($r^2 = 0.082 – 0.179$).

For open-plan offices, linear regressions yielded the highest r-squared value. In the 125 – 1,000 Hz bands, the regression predicted similar values for $L_{p,1m} - L_{p,1m,FF}$ over the range of 30 – 1,000 m^3; the slope of these four bands ranges from $-4x10^{-4}$ – $-1.2x10^{-3}$ dB/m^3. In the 2,000 – 8,000 bands, the regression slope ranged from $-2.9x10^{-3}$ – $-0.45x10^{-3}$ dB/m^3.

In all cases, the highest r-squared values, ranging from 0.10 – 0.27, were achieved by applying a logarithmic regression to the entire data set.

In the 125, 2,000, 4,000 and 8,000 Hz bands, many data points were negative, suggesting that $L_{p,1m}$ is lower in rooms than in a free-field environment. The 125 Hz band contained the most negative values. The 2,000 – 8,000 Hz bands had identical numbers of negative values. Additionally, the negative values all appear to be from the same measurements as they occur at the same volumes.

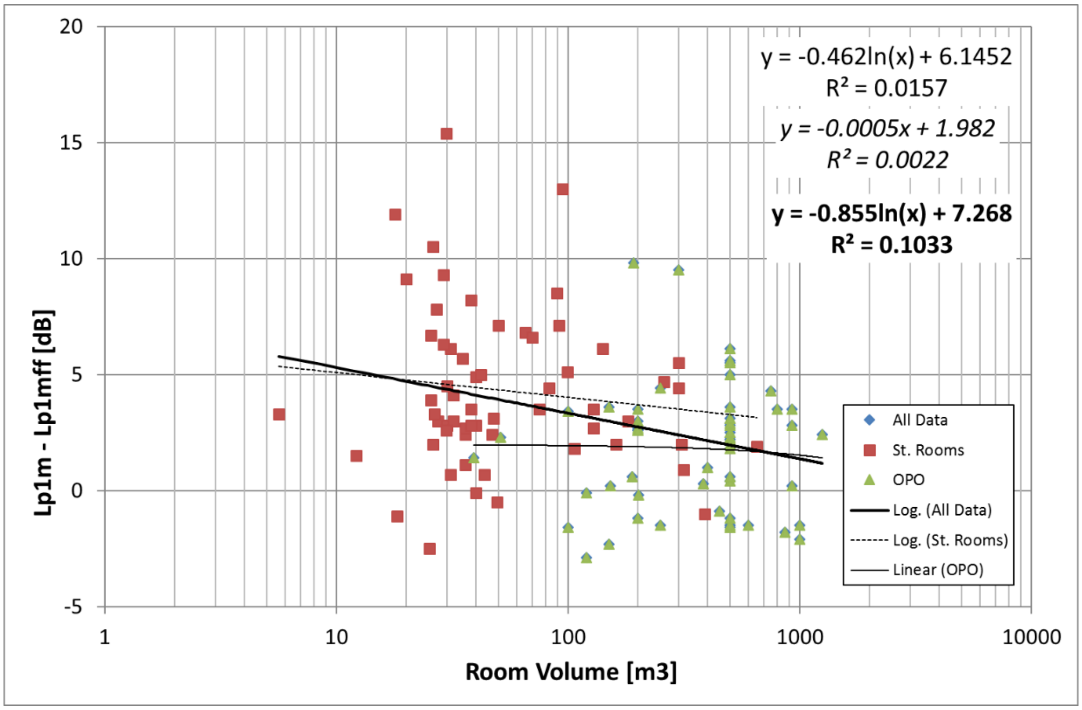

Figure 3.21 - $L_{p,1m}$ - $L_{p,1m,FF}$ for 125 Hz Band.

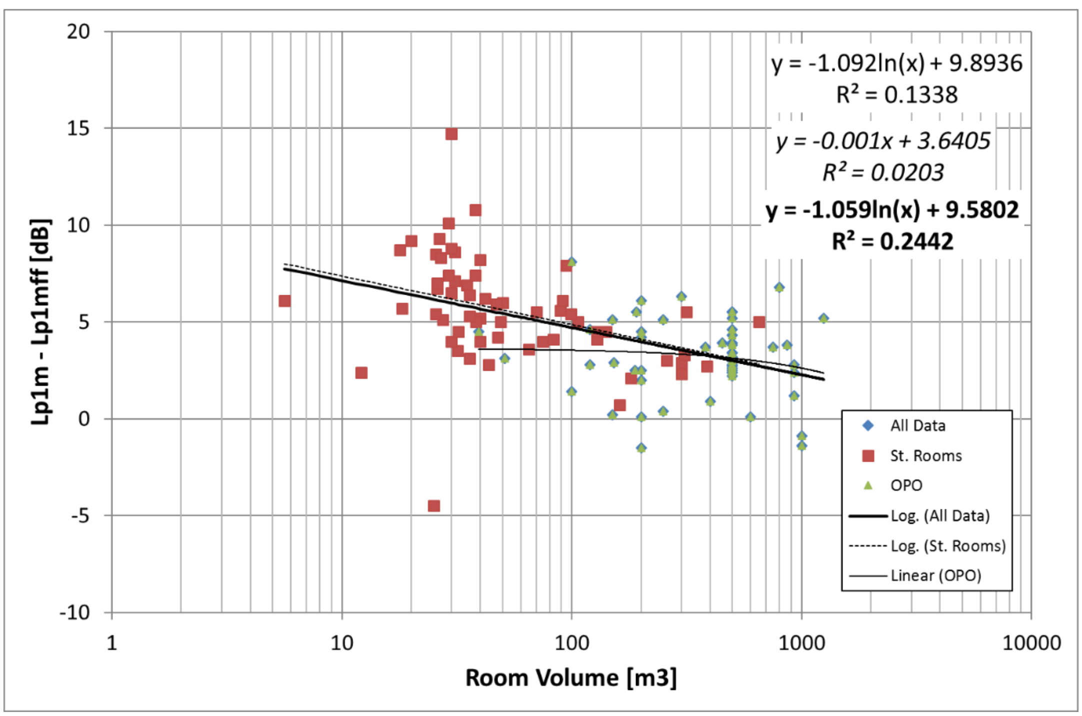

Figure 3.22 - $L_{p,1m}$ - $L_{p,1m,FF}$ for 250 Hz Band.

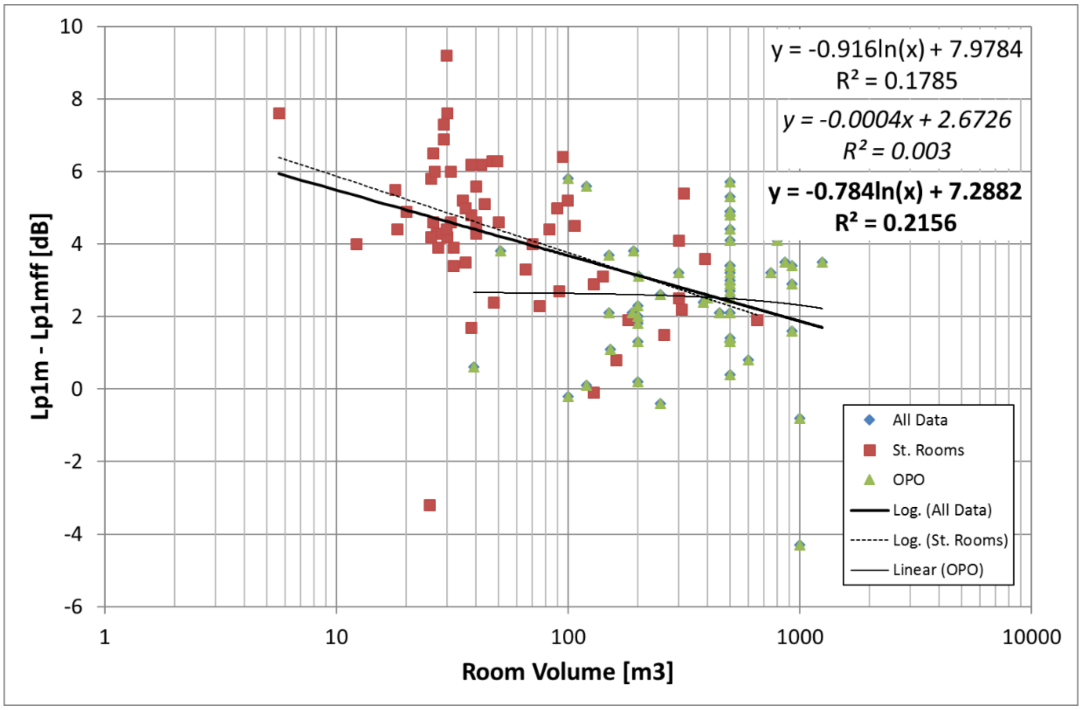

Figure 3.23 - $L_{p,1m}$ - $L_{p,1m,FF}$ for 500 Hz Band.

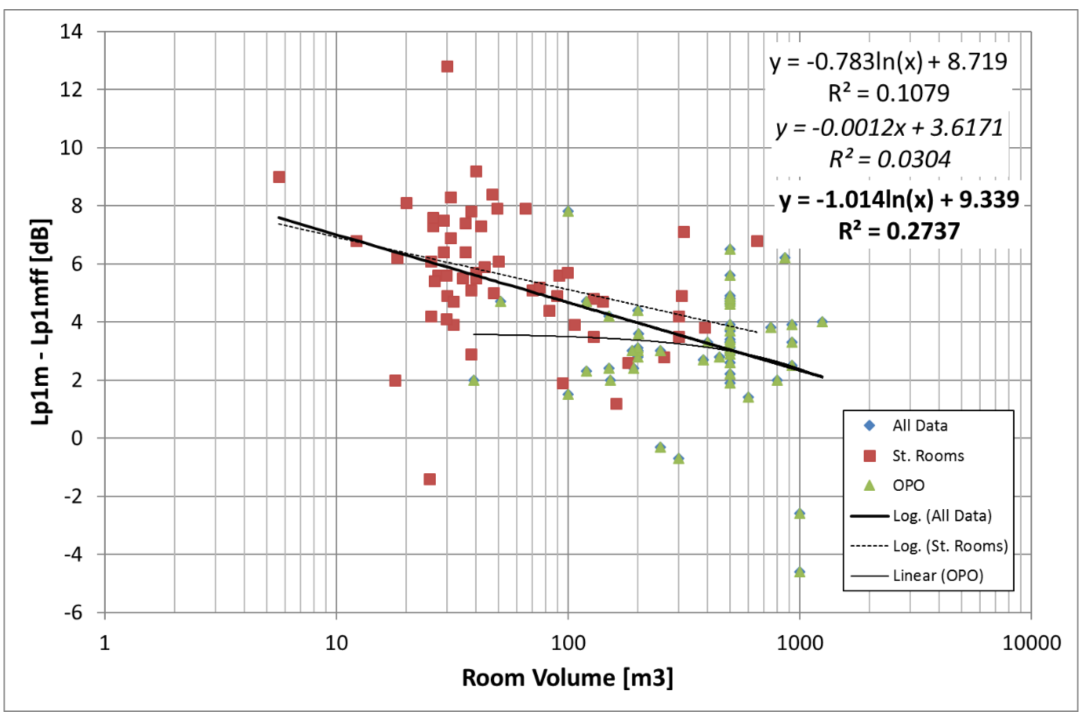

Figure 3.24 - $L_{p,1m}$ - $L_{p,1m,FF}$ for 1,000 Hz Band.

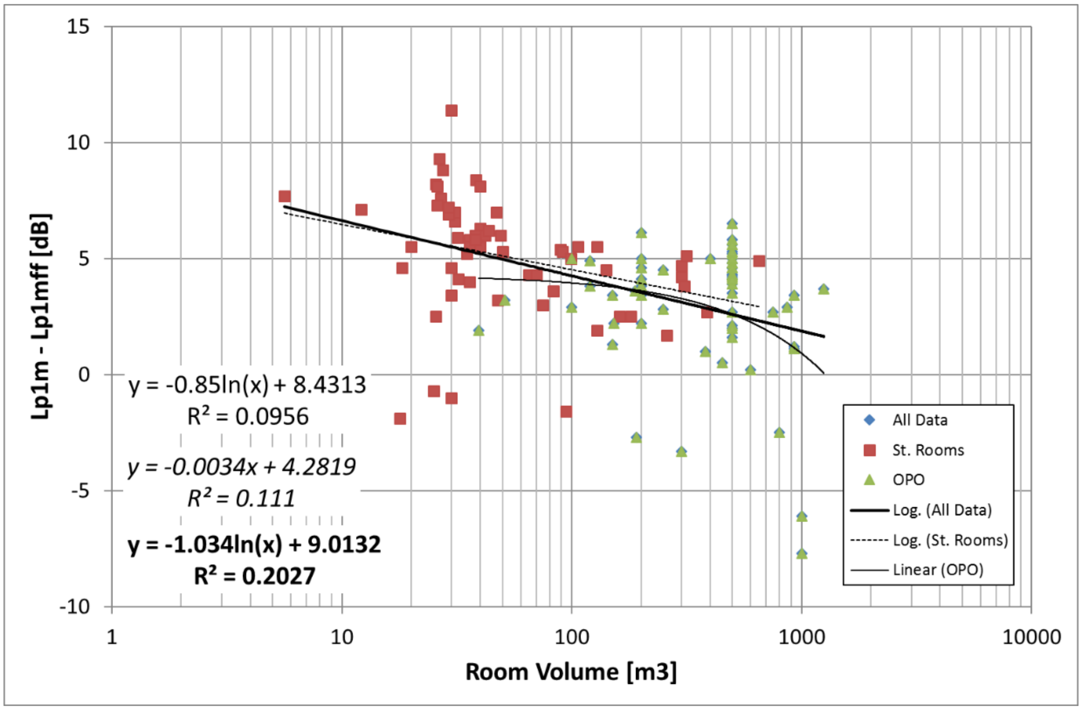

Figure 3.25 - $L_{p,1m}$ - $L_{p,1m,FF}$ for 2,000 Hz Band.

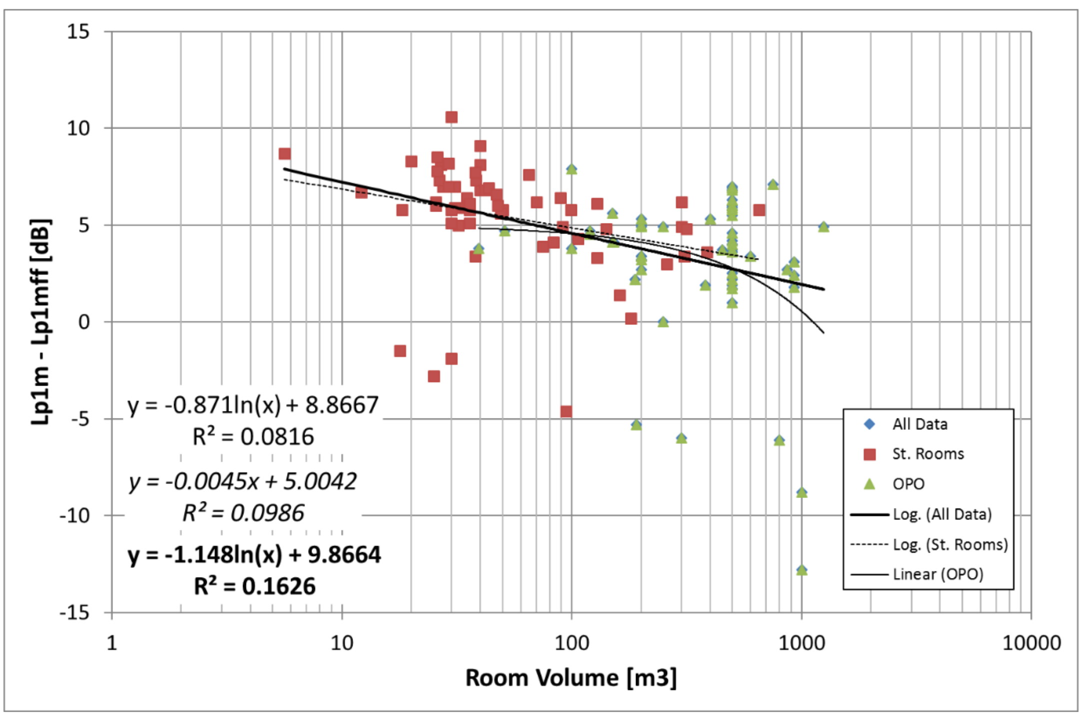

Figure 3.26 - $L_{p,1m}$ - $L_{p,1m,FF}$ for 4,000 Hz Band.

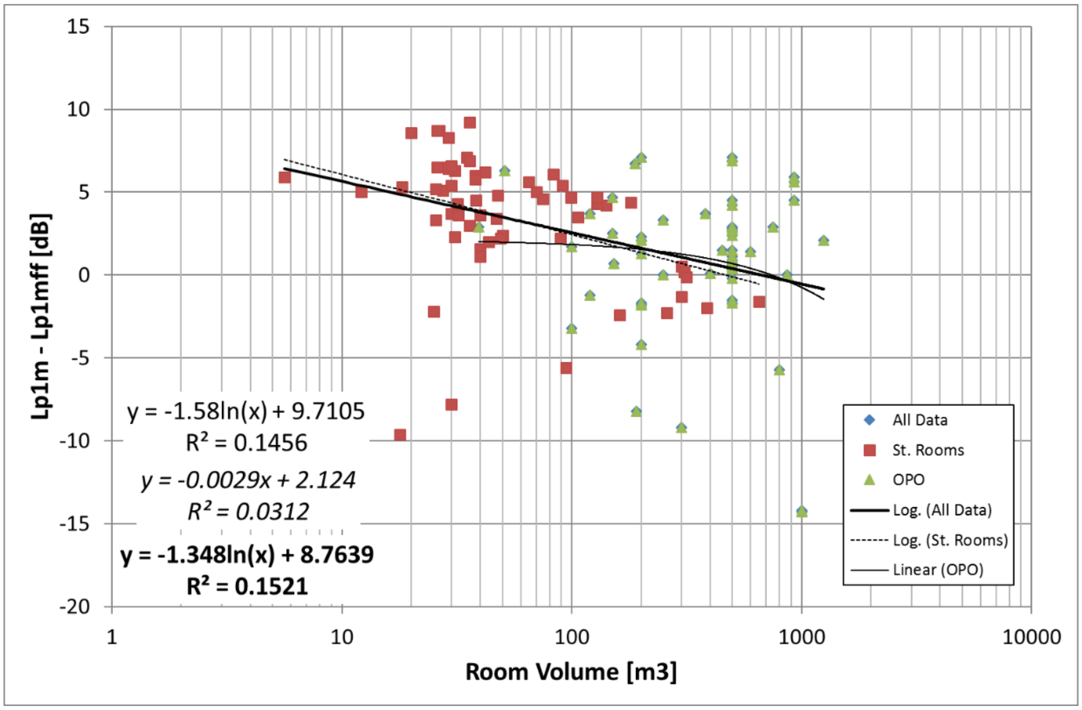

Figure 3.27 - $L_{p,1m}$ - $L_{p,1m,FF}$ for 8,000 Hz Band.

3.1.5.2 Discussion

Low r^2 values were expected for all frequency bands as the regression assumed that room volume was the only factor influencing $L_{p,1m}$. Additionally, all rooms were assumed to be 'normally furnished' (e.g. suspended acoustic ceilings, carpeting), where the surfaces in the room are neither highly absorptive nor reflective.

However, the r^2 value for the 125 Hz band was particularly low. This was likely due to some measurements being taken where the source and receiver were located across a table. This configuration was common as some of the $L_{p,1m}$ data was taken from speech intelligibility studies, which simulated scenarios such as meetings in private offices across a desk. As the source and receiver were both at heights of 1.2 m, tables or desks of 0.75 m height would then be within 0.45 m of the source-receiver pair. As the quarter-wavelength of the 125 Hz band is 0.69 m, this large data scatter could be due to a combination of the Waterhouse Effect (where the source is very close to the edge of the table) and interference effects (which depends on the length of the first-order reflection path caused by the height of the table). Additionally, at a wavelength of 2.7 m, in the 125 Hz band, there could have been standing wave effects, as many rooms were around 2.7 m in height.

In the 2,000 – 8,000 Hz bands, there were many negative values for $L_{p,1m} - L_{p,1m,FF}$, with the most in the 8,000 Hz band. The data points appeared to be from the same data measurements, as the room volumes were identical. Additionally, the trends in the negative values in these bands were similar. This is likely due to the directivity of the dodecahedral array, since this behavior is less apparent in the other frequency bands. As the calibration of the array was a randomized sample of 40 measurements, little was known about the directivity pattern at higher frequency bands. The directivity pattern of the array should be studied in greater detail to understand how closely dodecahedral loudspeaker arrays emulate omni-directional point sources.

Linear regressions yielded the highest r^2 values for open plan office datasets. As slopes ranged from $-4.0\text{x}10^{-4}$ – $-2.9\text{x}10^{-3}$ dB/m^3, $L_{p,1m} - L_{p,1m,FF}$ appeared to be independent of room volume. This is likely due to how open plan offices are typically furnished – all workspaces in open plan offices will have a desktop and dividers nearby regardless of the size of the office itself. Additionally, the typically large size of open plan offices resulted in the nearest surfaces being the desk and dividers. Therefore, $L_{p,1m} - L_{p,1m,FF}$ depends mostly on the local acoustical environment: subsections of the office space created by workspace dividers.

In all octave bands, logarithmic regressions yielded the highest r^2 values when applied to the entire dataset. In logarithmic regressions, the coefficient for the logarithmic term is the rate of change per magnitude. For base-10 regressions, the coefficient for the logarithmic term is the amount of change per multiplication of 10. In the context of room volumes, the greatest changes in $L_{p,1m}$ occurred at lower room volumes, and smallest changes occurred at higher room volumes. A logarithmic regression takes into consideration both the rapid decrease in $L_{p,1m} - L_{p,1m,FF}$ for standard rooms, and the nearly volume-independent behavior in open plan offices.

Finally, it should be acknowledged that dodecahedral loudspeaker arrays have a finite size. The measurements were taken 1 m from the centre of the loudspeaker array. This effectively means that the measurements were taken at a distance that is the radius of the array less than 1 m. This is expected to cause the measured level to be higher than what Eq. (1.5) predicts.

3.1.5.3 Conclusion

Experimental $L_{p,1m}$ values differ from what the expected free-field decay is for an omni-directional point source. The relationship between $L_{p,1m} - L_{p,1m,FF}$ appeared to be logarithmically dependent on room volume. For normally furnished rooms (i.e., with all surfaces neither highly absorptive nor highly reflective), a logarithmic $L_{p,1m} - L_{p,1m,FF}$ prediction model was introduced for each octave band, which was implemented in the finalized DL_2 model. $L_{p,1m} - L_{p,1m,FF}$ appeared to stabilize at larger volumes in all frequency bands. The behavior was attributed to the use of workspace screens in open plan offices.

Negative values for $L_{p,1m} - L_{p,1m,FF}$ were observed in all bands, and were most common in the 125, 4,000 and 8,000 Hz bands. The 125 Hz band discrepancy was likely to be destructive interference due to surfaces being located around 0.7 m from the source, while the 4,000 and 8,000 Hz bands were likely due to the directivity pattern of the dodecahedral loudspeaker array used as the source in the measurements.

4 Complete DL_2 vs STI Model

In this chapter, the model for predicting room acoustic quality as a function of DL_2 introduced in Chapter 2 will be modified to include the experimental observations in Chapter 3.1. Additionally, the STI calculation scheme (Eq.(2.1) through (2.3)) will be substituted with a form that accounts for the contributions of direct speech to intelligibility.

Finalized STI calculation tools, implemented as Microsoft Excel spreadsheets, are available for download from the cIRcle collection of Supplementary Thesis Materials and Errata.

4.1 Model Components

4.1.1 Modulation Transfer Function (Direct Speech)

As of Chapter 2, the DL_2 vs STI model used only the reveberant-speech modulation transfer function and was therefore limited to rooms where the direct speech is absent. This limited the model to rooms such as open plan offices, where there is usually no direct line of sight between a talker and listeners other than the intended recipient of speech. By including the contributions of direct speech in the modulation transfer function, all rooms may be assessed.

In addition to formulating the modulation transfer function for calculating the speech transmission index using only indirect sound, Houtgast and Steeneken derived a formulation which includes direct speech [1]. The modulation transfer function including direct speech is as follows:

$$m(f) = \frac{(A^2 + B^2)^{0.5}}{C} \quad \textbf{(4.1)}$$

With:

$$A = \frac{Q_t Q}{r^2} + \frac{1}{r_c^2}\left[1 + \left(\frac{2\pi T f}{13.8}\right)^2\right]^{-1} \quad \textbf{(4.2)}$$

$$B = \frac{1}{r_c^2}\frac{2\pi T f}{13.8}\left[1 + \left(\frac{2\pi T f}{13.8}\right)^2\right]^{-1} \quad \textbf{(4.3)}$$

$$C = \frac{Q_t Q_l}{r^2} + \frac{1}{r_c^2} + Q_t 10^{(L_n - L_{A,s,1m})/10} \tag{4.4}$$

Where:

$m(f)$ is the modulation transfer function at frequency f

f is the modulation frequency (from 0.4 – 30 Hz at third octave intervals)

Qt is the directivity index of a human talker (see Table 2.3)

Q_l is the directivity index of the listener (stated to be 1.5 by the author [1])

r is the distance between the talker and the listener

r_c is the critical radius of the room

T is the reverberation time in seconds (assumed to be T_{20})

L_n is the background noise sound pressure level at the listener's location

$L_{A,s,1m}$ is the free-field speech pressure level of the talker at 1 m in front of the talker's mouth

However, this formulation of the modulation transfer function was intended to be used at the design level [1] and therefore does not use quantities that are measured when evaluating DL_2. In DL_2 evaluations, the only measured quantities are the reverberation time, background noise level, distance, and total measured sound pressure. The volume of the room is sometimes measured as well.

To circumvent this limitation, the assumptions employed in the development of Houtgast and Steeneken's formation were examined. In the derivation of the direct sound modulation transfer function, a squared impulse response (or echogram) for the room was assumed and is defined as follows:

$$r(t) = r_d(t) + r_r(t) \tag{4.5}$$

Where:

$r(t)$ is the total squared impulse response for the room

$r_d(t)$ is the direct sound contribution to the impulse response

$r_i(t)$ is the indirect sound contribution to the impulse response

The direct sound contribution to the impulse response is then defined as:

$$r_d(t) = \left(\frac{t}{r^2}\right)\delta(t) \tag{4.6}$$

Where:

t is time

r is distance

δ is the dirac-pulse function

and the indirect sound contribution is defined as:

$$r_i = \frac{1}{r_c^2}\frac{13.8}{T}e^{-13.8t/T} \tag{4.7}$$

Where:

T is the reverberation time

rc is the critical radius

Eq. (4.6) states that the direct sound is only a function of distance, and is identical to Eq. (1.5). Eq. (4.7) uses diffuse field theory to define the indirect sound. The direct and indirect sound contributions to the room impulse response appear in the modulation transfer function (Eq. (4.1) through (4.4)) as the distance between the talker and the listener (r) and the critical distance (r_c) of the room respectively. The total speech pressure level is then calculated as a function of distance and the critical distance.

As the direct sound modulation transfer function (Eq. (4.1)) was originally intended for design stage calculations, the use of diffuse field theory was expected. However as previously discussed, diffuse field theory rarely holds true for real rooms and the indirect speech pressure level also depends on distance, hence the proposition of DL_2 as a universal parameter.

To calculate the speech transmission index using Eq. (4.1) such that the reverberant speech pressure level may be defined, the critical radius must be defined such that it results in the measured reverberant speech pressure level.

The critical radius is defined as the distance where the direct speech pressure level is equivalent to the reverberant speech pressure level:

$$L_{p,direct} = L_{p,indirect} \tag{4.8}$$

The direct speech component is then defined using Eq. (1.4). By evaluating the direct speech at the critical radius, the following relationship holds true:

$$L_{p,direct} = L_w + 10log\left[\frac{Q_\theta}{4\pi r_c^2}\right] = L_{p,indirect} \tag{4.9}$$

Eq. (4.9) may then be rearranged to yield the critical radius as a function of known parameters:

$$r_c = \left(\frac{Q_\theta}{4\pi 10^{(L_{p,indirect}-L_w)/10}}\right)^{0.5} \tag{4.10}$$

The critical radius yielded by Eq. (4.10) allows the use of a user-defined reverberant speech pressure level in Eq. (4.1).

By defining the distance, r, to be infinitely large, Eq. (4.1) is expected to yield the same result as Eq. (2.1) for the same reverberant speech pressure level, reverberation time, and background noise level. This was verified by calculating the speech transmission index using a defined reverberant speech pressure level in Eq. (2.1) and comparing the results to a critical radius calculated using Eq. (4.10) in Eq. (4.1) for an infinitely large talker-listener distance.

It was noted that the background noise level term in Eq. (4.4) is modified by the talker's directivity. This was theorized to be incorrect as increasing the talker directivity is expected to increase speech intelligibility. However, if Eq. (4.4) is applied with the talker's directivity modifying the background noise level term, the calculated intelligibility decreases as the talker's directivity increases. It was then proposed that the talker directivity term be removed from the background noise level term of Eq. (4.4), resulting in the following:

$$C = \frac{q_t q_l}{r^2} + \frac{1}{r_c^2} + 10^{(L_n - L_{sp1m})/10} \tag{4.11}$$

By redefining the critical radius in terms of the reverberant speech pressure level, Eq. (4.1) may be used with parameters available from DL_2. In the case where the total sound pressure level is less than the expected direct speech sound pressure level, the total sound pressure level is assumed to be entirely indirect.

4.1.2 Experiment-Based Modifications to DL_2 Model

This chapter reiterates the findings from Chapter 3.1 as improvements to the DL_2 model. The original assumptions were made under the pretense that they would be adjusted using observations from data in real rooms. The assumptions employed in Chapter 2.1 that are applicable specifically to DL_2 are listed in Table 4.1.

Table 4.1 - Assumptions Employed in the Idealized DL_2 Model and their Conditions

Assumption	**Condition**
Sound Pressure Level at 1 m ($L_{p,1m}$)	The sound pressure level at a distance of 1 m from a sound source is assumed to be equal to that of what it is expected to be in a free field.
Uniform, Broadband Decay	The value for DL_2 is identical for all octave bands. Therefore, the A-weighted speech pressure level can be used as a representative term.
Linear Decay	The decrement of sound is expected to be linear. That is, a single value of DL_2 is sufficient to describe the decrement of sound at all distances form a sound source in a room.

4.1.2.1 Sound Pressure Level at 1 m ($L_{p,1m}$)

This assumption was assessed in Chapter 3.1.5. Sound pressure level data at 1 m from a dodecahedral loudspeaker array was collected in 53 rooms. As expected, it was found that the sound pressure level in rooms is rarely equal to the level expected in a free field environment. In the absence of other room furnishing information, it was assumed that all the rooms are normally furnished, and that room volume is the only factor determining the deviation from free-field behavior.

The data was sorted into octave bands and regressions were applied. Logarithmic regressions for the sound pressure level data at 1 m from the measurement loudspeaker produced the best r^2-value. The regressions are shown in Table 4.2.

Table 4.2 - Regression Equations Relating Sound Pressure Level at 1 m and Room Volume

Frequency [Hz]	Regression [dB]	Correlation Coefficient
125	$L_{p,1m} = -0.855 ln(V) + 7.2680$	0.1033
250	$L_{p,1m} = -1.059 ln(V) + 9.5802$	0.2442
500	$L_{p,1m} = -0.784 ln(V) + 7.2882$	0.2156
1,000	$L_{p,1m} = -1.014 ln(V) + 9.3390$	0.2737
2,000	$L_{p,1m} = -1.034 ln(V) + 9.0132$	0.2027
4,000	$L_{p,1m} = -1.148 ln(V) + 9.8664$	0.1626
8,000	$L_{p,1m} = -1.348 ln(V) + 8.7639$	0.1521

The regressions were then used to calculate the total sound pressure level at 1 m. This is the sound pressure level the DL_2 value is then applied to when calculating the sound pressure level at farther distances.

4.1.2.2 Uniform, Broadband Decay

The DL_2 data collected in all of the rooms were compiled and an A-weighted speech pressure level DL_2 value was calculated for each data set. For each data set, the difference between the octave band DL_2 value and the A-weighted DL_2 was evaluated. The average and standard deviations of the averages are compiled in both open plan offices and standard rooms in Table 4.3.

Table 4.3 - Average Difference for $DL_{2,f}$ - $DL_{2,s,A}$ for (1) Open-plan Offices and (2) Standard Rooms in dB/DD.

Open-plan Offices							
Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Average [dB/DD]	-2.5	-0.7	0.1	0.9	0.7	0.4	0.7
St. Dev [dB/DD]	1.4	0.7	0.3	0.6	0.8	0.9	1.0
Standard Rooms							
Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Average [dB/DD]	-0.1	-0.1	0.1	0.0	-0.1	0.2	0.9
St. Dev [dB/DD]	0.9	0.5	0.2	0.2	0.3	0.5	0.8

The DL_2 model was modified such that the user-input quantity is the DL_2 for the A-weighted speech pressure level. The DL_2 values for each octave band are then adjusted in accordance to Table 4.3. Since the spectral behavior of DL_2 was observed to vary between open plan offices and standard rooms, the room type will also determine which set of adjustments are to be applied.

4.1.2.3 Linear Decay

In standard rooms, the regression error between DL_2 from 1 – 16 meters and the measured sound pressure level was generally within 1 dB. This was considered acceptable by the author in terms of regression accuracy. As such, a single value of DL_2 was deemed to be acceptable for applications where there is a direct line of sight between a talker and a listener.

In open plan offices, the regression error depended largely on the presence of office dividers. The dividers were observed to systematically cause DL_2 regression underestimations in front of a workspace divider and overestimations behind a workspace divider. In the distance range of 4 – 8 m, the regression error was approximately 2 dB. This was accounted for by adding a 1 dB adjustment to the sound pressure levels at 4 and 8 m, and a 2 dB adjustment to the sound pressure levels at 5 – 7 m.

4.2 Model Construction

The model, as described in chapter 2.1.3, was then modified using the modified STI calculation scheme (direct sound), and according to experimental observations from chapter 3. A screenshot of the updated spreadsheet is shown in Figure 4.1.

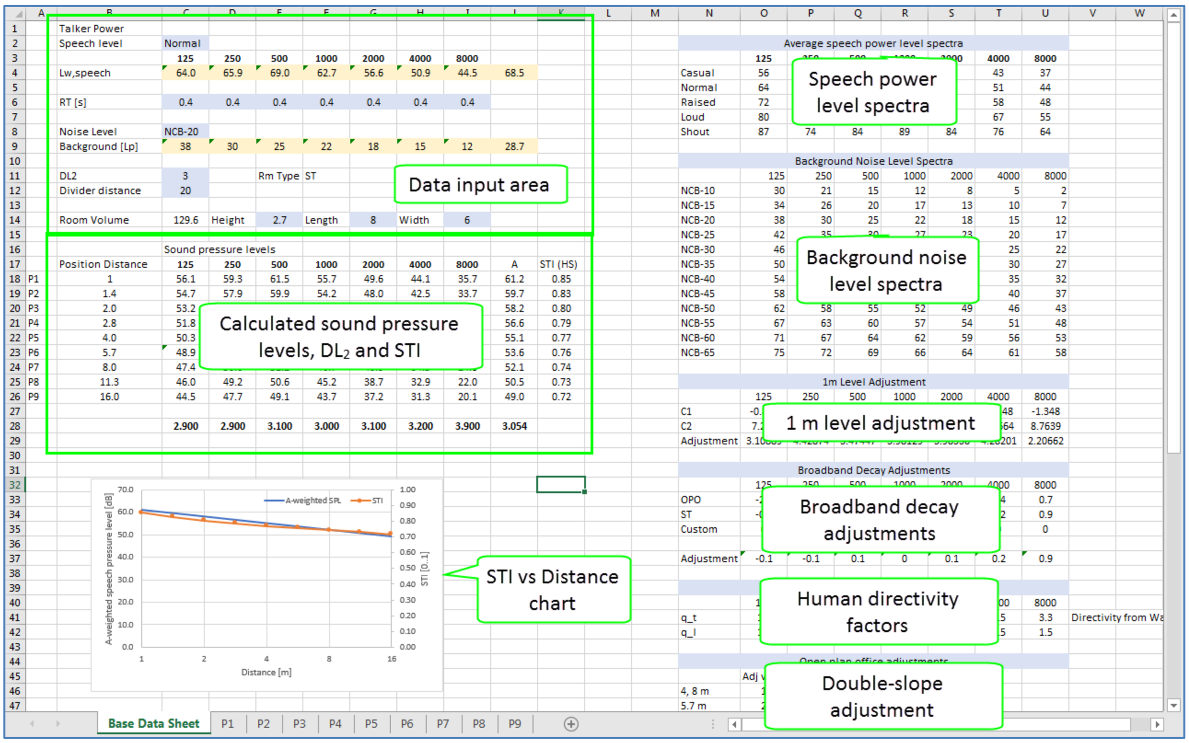

Figure 4.1 - Screenshot of Data Entry sheet of finalized DL_2 calculation tool

From the previous version, the common data sheet was merged with the data entry sheet. The NCB spectra for background noise were added and were referenced using a dropdown menu. Other than field labels, cells in blue require user input. That is, the user specifies the speech vocal effort level, the background noise level, the reverberation time, the broadband DL_2 value, the type of room, the room size, and the presence of a divider, if applicable.

The spreadsheet uses the speech vocal effort spectrum to calculate the 1 m speech pressure level, and adjusts it using the room volume according to Table 4.2. The speech pressure levels are then calculated at distances increasing by factors of 1.4 times using the user-specified DL_2 value (modified by the broadband decay adjustments in Table 4.3).

For open plan offices, 1 dB is added to speech pressure levels occurring at distances between 4 – 5 m, and 7 – 8 m, and 2 dB are added to speech pressure levels occurring at distances between 5 – 7 m.

The model is then formatted in two ways: an STI vs Distance format for examining how STI decays for a given set of conditions, and an STI vs DL_2 format for examining how STI varies with DL_2 at a fixed listener position.

While it was noted that dividers will result in higher sound pressure levels before the divider and lower sound pressure levels after, the effects were not examined in enough detail to be included in the model. In general, one can expect a 1 – 3 dB increase before a divider, and about a 1 – 3 dB decrease after a divider. This is not yet considered and needs to be manually accounted for by the user.

4.2.1 STI vs Distance

In this format, the DL_2 for the A-weighted speech pressure level is specified. The total speech pressure level is then calculated for each octave band after applying the DL_2 adjustment values in Table 4.3 to the specified A-weighted speech pressure level DL_2 value. The total speech sound pressure levels are then calculated at 1, 1.4, 2, 2.8, 4, 5.7, 8, 11.3, and 16 meters. The direct speech sound pressure level is then calculated at the same distances using Eq. (1.5). The reverberant speech sound pressure level is calculated by decibel subtraction using Eq. (1.6).

The calculated reverberant speech sound pressure levels are then used to calculate the equivalent critical radius, r_c, at each calculation position using Eq. (4.10). The input quantities are then applied to Eq. (4.1) to evaluate STI.

It was postulated that if the expected direct speech sound pressure level exceeds the total sound pressure level, the total sound is comprised entirely of indirect sound. At locations where this occurs, the distance term used in Eq. (4.1) is set to an infinitely large quantity such that Eq. (4.1) evaluates the reverberant speech STI.

For open plan offices, a +1 dB adjustment is added to the sound pressure levels at 4 and 8 m, and a +2 dB adjustment is added to the sound pressure levels at 5 – 7 m to account for the presence of the double slope. The adjustments translate to an approximate increase in STI of 0.03 and 0.06.

Figure 4.2 shows a sample STI vs Distance plot for a talker speaking at Normal vocal effort in an open plan office that is 2.7 m in height, 18 m in length, and 10 m in width. The reverberation time is 0.8 s, the background noise spectrum is NCB-30 and the DL_2 is 8 dB/DD.

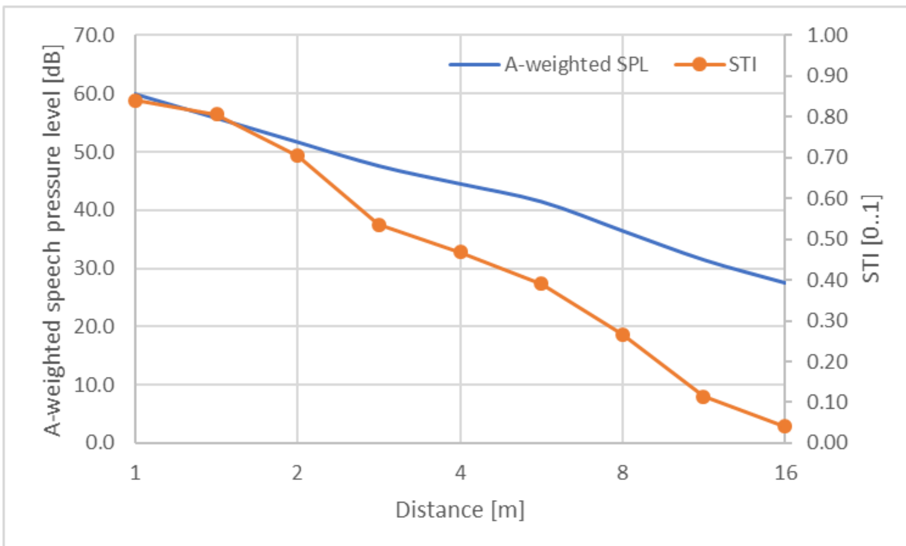

Figure 4.2 - Sample STI vs Distance plot for an Open Plan Office

Figure 4.3 shows a sample STI vs Distance plot for a talker speaking at Normal vocal effort in a standard room that is 2.7 m in height, 8 m in length, and 6 m in width. The reverberation time is 0.4 s, the background noise spectrum is NCB-20 and the DL_2 is 3 dB/DD.

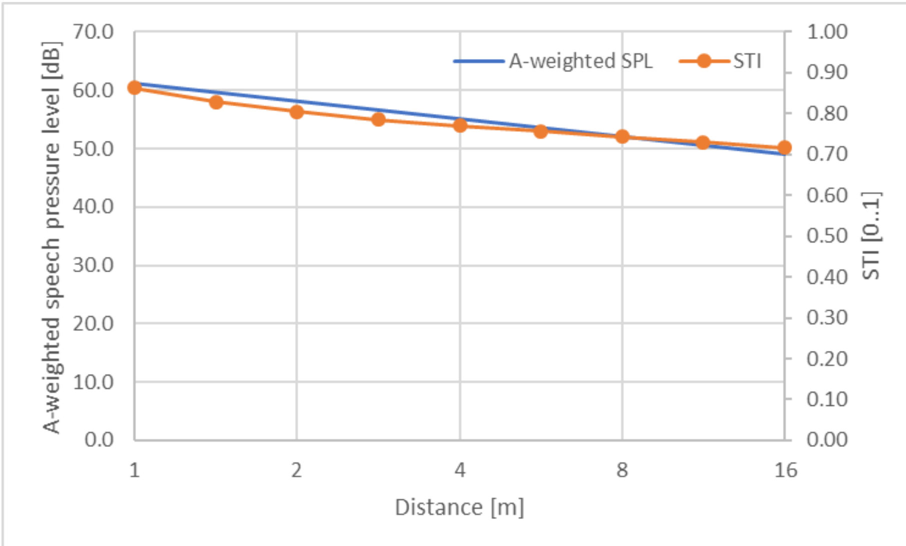

Figure 4.3 - Sample STI vs Distance plot for a Standard Room

4.2.2 STI vs DL_2

In this format, the evaluation distance is specified. The total speech pressure level at the specified distance is calculated for values of DL_2 between 1 – 14 dB/DD using the DL_2 adjustments in Table 4.3. If the distance is between 4 and 8 m in an open plan office setting, a +1 dB adjustment is applied to the total speech pressure level at 4 and 8 m, and a +2 dB adjustment is applied to the total speech pressure level at 5 – 6 m.

The direct speech pressure level is then calculated at the specified distance. The indirect sound is calculated by decibel subtraction of the direct speech pressure level from the total speech pressure level and is then converted to a critical distance value, r_c, value. Eq. (4.1) is then used to evaluate the STI.

Figure 4.4 shows a sample STI vs DL_2 plot for the same standard room as in Figure 4.3, evaluated at the transition distance of 4 m from a talker. However, there is an unexpected increase in STI around 6 dB/DD. This increase was theorized to be a result of a commonly recognized error in decibel subtraction as illustrated by the following example where sound pressure level 1 (L_1) is to be subtracted from sound pressure level 2 (L_2). As L_1 approaches L_2, the resulting sound pressure level approaches zero. This artefact is widely acknowledged in acoustical engineering and standards include provisions for a lower-limit estimation of the resulting sound pressure level. Clause 11.8.2

in ASTM Standard E336-14 "Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings" states that If L_1 is within 5 dB of L_2, the resulting sound pressure is approximate as being 2 dB lower than L_2 [19].

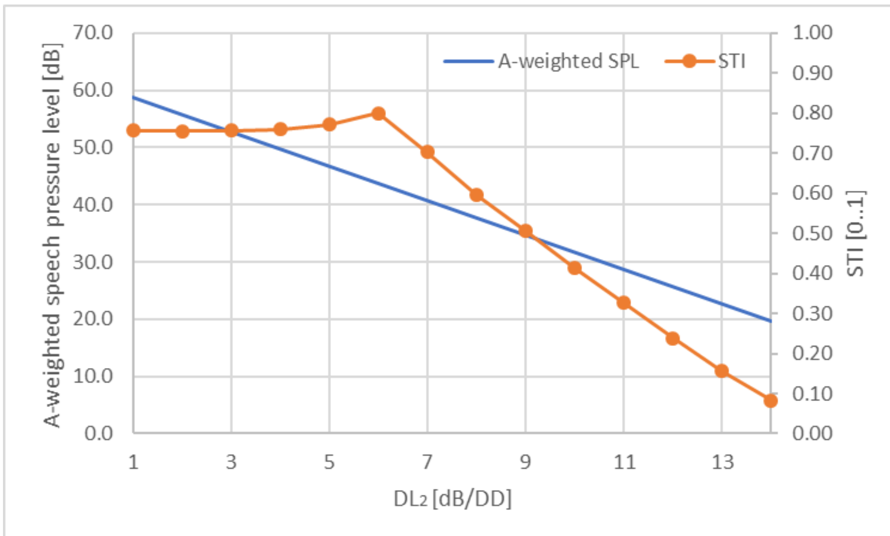

Figure 4.4 - Sample STI vs DL_2 plot showing Artefact of Decibel Subtraction around 6 dB/DD Range

Figure 4.5 results when approximating the reverberant speech pressure level as per E336 for situations where low signal to noise ratio is an issue. Contrary to the initial postulation that the increase in STI as DL_2 approaches 6 dB/DD, the increase in STI is still present. To diagnose the cause of the increase in STI, a sensitivity check was conducted by varying the critical radius in Eq. (4.1). It was found that STI increased as the critical radius increased, meaning that the reverberant speech pressure level reduces the speech intelligibility of direct speech.

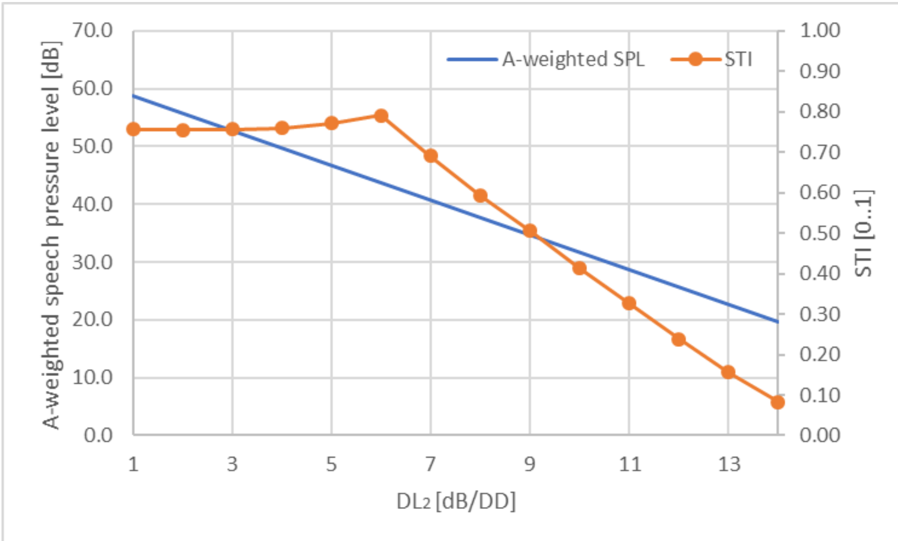

Figure 4.5 - Sample STI vs DL_2 plot with E336-15 Adjustment for Decibel Subtraction Approximation for Low S/N

As Figure 4.5 appeared to produce results that were similar to Figure 4.4 while accounting for the presence of reverberant speech pressure level, the E336-14 adjustments were made to the STI vs Distance model as well.

4.3 Sample Applications

In this section, the completed model will be used to evaluate theoretical rooms with the rating criteria formulated in Chapter 2 (Tables 2.7 through 2.9). This exercise is intended to give readers insight to how the models may be used and for the authors to identify any errors or logical fallacies in the formulation of the model through sample applications.

4.3.1 Case 1 (Intelligibility)

The STI vs DL_2 model was used to evaluate two theoretical classrooms: one which conforms to standards and one which does not. According to British Standard BB93 the maximum recommended background noise level is 35 dBA (approximately equal to NCB-25) and the maximum recommended reverberation time is 0.8 seconds for new classrooms [20]. The theoretical classroom was assumed to be 2.7 m in height, 10 m in width and 12 m in length. The talker was assumed to be speaking at a normal vocal effort.

The evaluation point, or transition distance, was chosen to be at the back of the classroom, at approximately 10 m from the talker. For quick reference, the quality ratings for Case 1 (intelligibility) rooms (Table 2.7) are provided below. Since an evaluation point is known, the STI vs DL_2 model was used.

Effort Rating	Listening Effort	STI Range	Intelligibility %	Acceptable	Rating
1	Very little effort	0.73 – 1.00	100	Yes	Excellent
3	Little effort	0.62 – 0.73	100	Yes	Good
5	Moderate effort	0.53 – 0.62	100	Yes	Poor
7	Considerable effort	0.43 – 0.53	100	Yes	Bad
9	Much effort	0.35 – 0.43	88%	No	N/A
11	Extreme effort	0.30 – 0.35	80%	No	N/A

Figure 4.6 shows STI as a function of DL_2 at 10 m from the talker for a compliant classroom. In classrooms, DL_2 will never exceed 6 dB/DD as 6 dB/DD is interpreted as an anechoic environment. For a classroom that is compliant with the limits specified by BB93, all DL_2 values below 5 dB/DD require little listening effort.

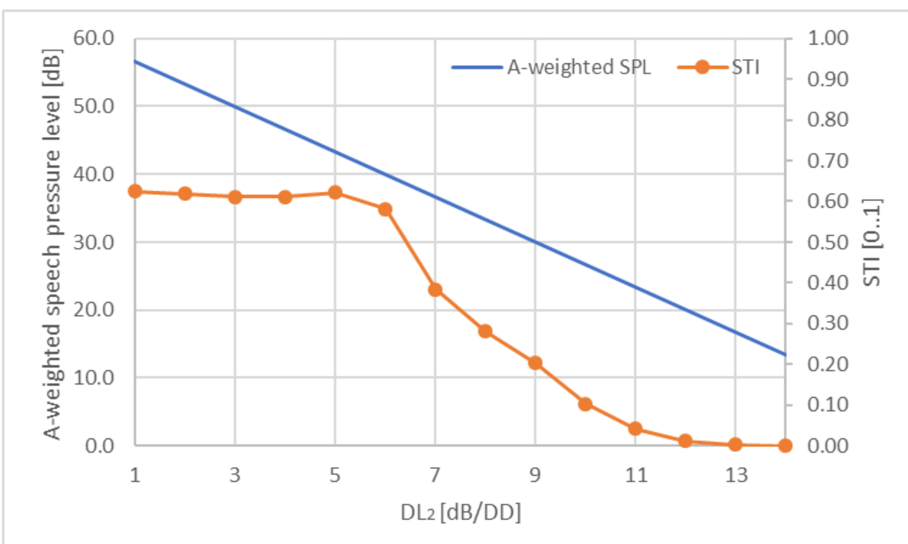

Figure 4.6 - STI vs DL_2 at 10 m from a talker for a compliant classroom (L_n = 35 dBA, T = 0.8 s)

Figure 4.7 shows STI as a function of DL_2 at 10m from the talker for a non-compliant classroom. The background noise level was chosen to be 40 dBA (NCB-30) and the reverberation time was chosen to be 1 second. At these conditions, the farthest listening position would require moderate or considerable listening effort.

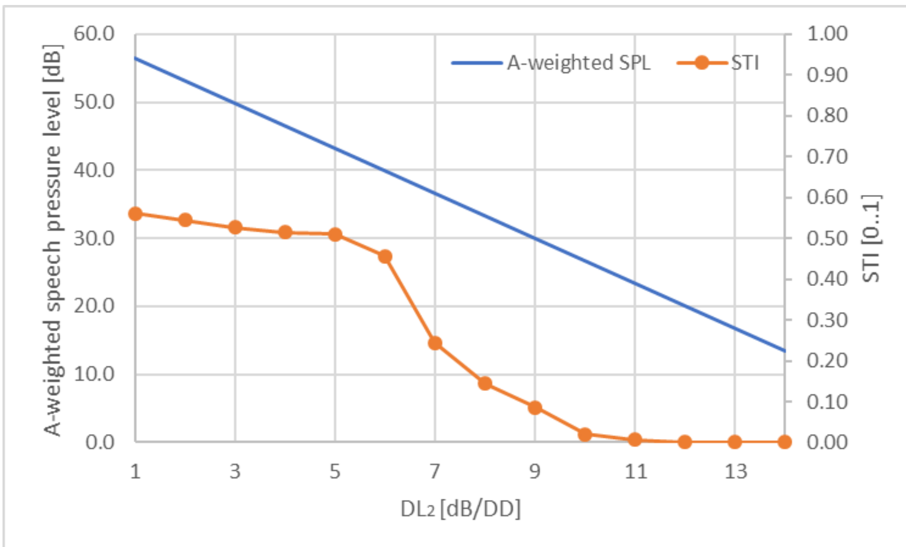

Figure 4.7 - STI vs DL_2 at 10 m from a talker for a non-compliant classroom (L_n = 40 dBA, T = 1.0 s)

When a classroom is evaluated for acoustical quality, the background noise level and reverberation time are typically measured. Should it be that the classroom is found to be non-compliant, a DL_2 measurement would help room users decide the maximum allowable seating distance.

Figure 4.8 shows STI vs Distance assuming a measured DL_2 of 3 dB/DD for the classroom in Figure 4.7. In this classroom, considerable listening effort is required at distances greater than 8 m.

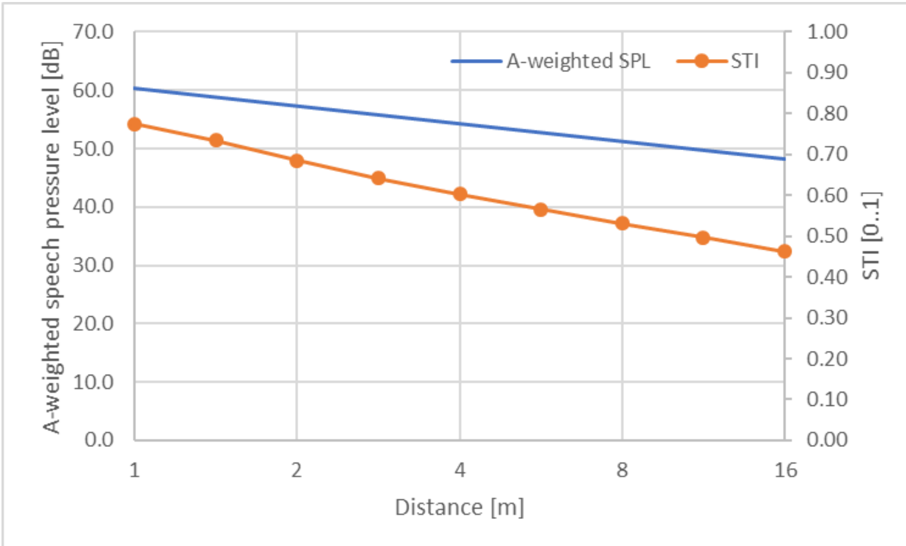

Figure 4.8 - STI vs Distance for hypothetical non-compliant classroom in Figure 4.7 (L_n = 35 dBA, T = 0.8 s)

4.3.2 Case 2 (Distraction)

Case 2 was used to evaluate a theoretical study room. This room was also modeled to be compliant with BB93, with a background noise level of 40 dBA (NCB-30) and a reverberation time of 0.8 s. The distraction percentages in Table 2.8 are provided below for reference.

Rating	Loss of Productivity [%]	STI
Excellent	0	0.00 – 0.20
Good	0 – 2	0.20 – 0.35
Fair	2 – 4	0.35 – 0.43
Poor	4 – 6	0.43 – 0.50
Bad	6 – 7	0.50 – 0.60
Unacceptable	> 7	> 0.60

The room was arbitrarily assumed to be 2.7 m in height, 25 m in length and 15 m in width and was assumed to contain dividers, such that the direct sound is not present. In this assessment, we were interested in the required DL_2 to reduce speech distraction at a nearby listening position. As this room was modeled to be a study environment, talkers were expected to be speaking at a lowered (casual) speech effort level.

Initially, the STI vs DL_2 was assessed at various distances to assess the possibility of reduced distraction. Since dividers are in place, the total sound reaching a distracted listener was assumed to contain no direct speech. Since the listener location is known, the STI vs DL_2 model was used.

Figure 4.9 shows the STI vs DL_2 for listener locations at 4, 6, 8 and 10 m from the talker. This theoretical study room may be considered as being similar to an open plan office due to the presence of desk dividers. According to Table 3.5, the observed value for DL_2 ranges from 4 – 9 dB/DD. At a DL_2 of 4 dB/DD, a listener located at 4 m can expect to suffer about 2 – 4% of productivity loss.

By knowing realistic DL_2 values and how to achieve them, this model can help designers determine the amount of furnishing and furnishing configuration to best reduce speech distraction.

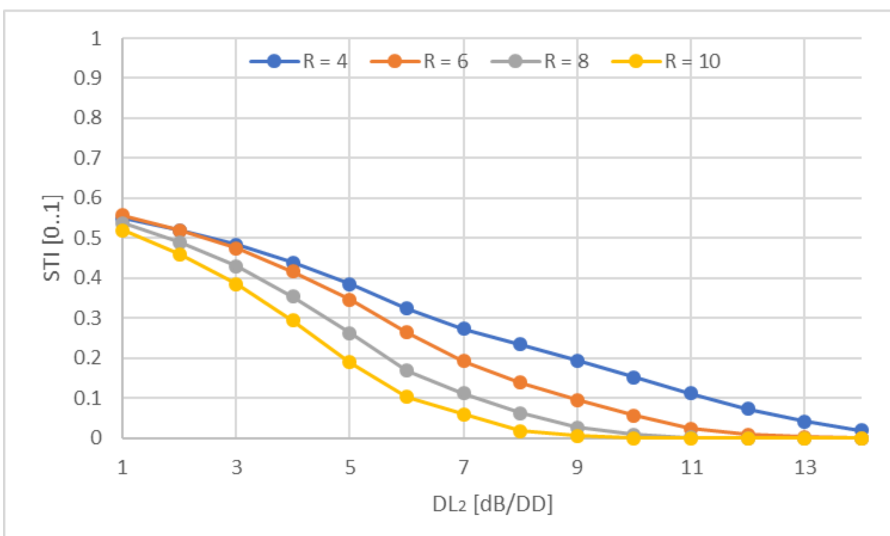

Figure 4.9 - STI vs DL_2 at distances of 4, 6, 8 and 10 m for a hypothetical study room (L_n = 30 dBA, T = 0.8 s)

4.3.3 Case 3 (Privacy)

Case 3 was used to evaluate a theoretical eating establishment for privacy from other patrons. The privacy rating values from Table 2.9 are supplied below.

Rating	Intelligible Speech [%]	STI
Excellent	< 50	< 0.15
Good	50 – 60	0.15 – 0.20
Fair	60 – 80	0.20 – 0.27
Poor	80 – 90	0.27 – 0.35
Bad	90 – 100	0.36 – 0.43
Unacceptable	> 100	> 0.43

The eating establishment was assumed to be similar to Dining Rooms according to BB93, which has a recommended background noise level of 45 dBA (approximately NCB-35) and reverberation time of 1 s. The eating establishment was arbitrarily assumed to be 2.7 m in height, and 15 m in width and length. Patrons in this setting were theorized to speak at normal vocal effort. Intended listeners were assumed to be located 1 m away, while the nearest unintended listener was assumed to be located 4 m away.

Since a listener position was known, the STI vs DL_2 model was used to evaluate the DL_2 required to provide good speech privacy. Figure 4.10 shows the expected STI vs DL_2 for an unwanted listener located 4 m from a talker.

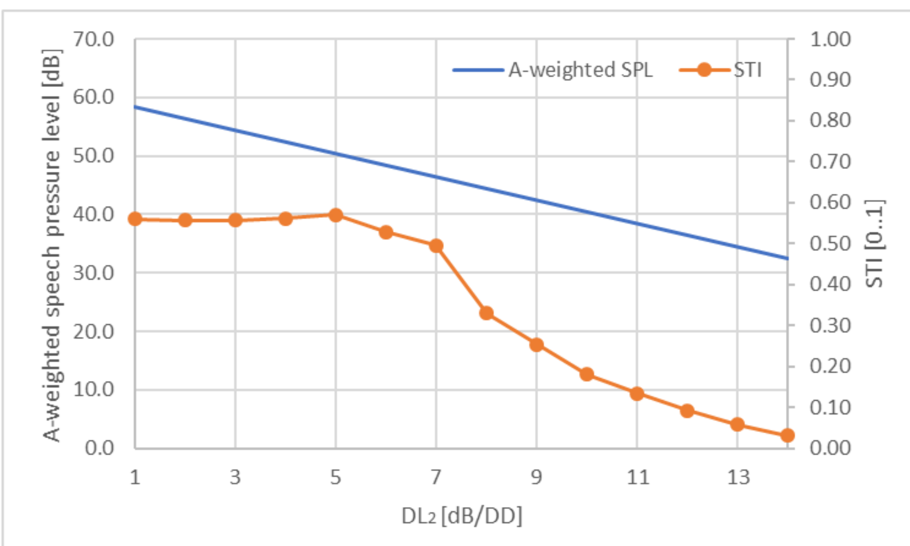

Figure 4.10 - STI vs DL_2 at 4 m for a hypothetical eating establishment without booths (L_n = 40 dBA, T = 1 s)

Without booths, restaurants are best modeled as standard rooms, which are generally expected to have DL_2 values between 1 – 5 dB/DD. For standard eating establishment conditions, an unintended listener is expected to be able to hear the entire contents of a conversation at normal vocal effort. Some eating establishments, such as pubs, overcome lack of speech privacy by playing loud music. However, this in turn causes patrons to raise their voices in order to be heard, and the eating establishment may become uncomfortably loud.

Figure 4.11 shows the same eating establishment with booths, with an unwanted listener located 4 m away, at different background noise levels. With booths in place, and by raising the background level to NCB-40 (50 dBA), good speech privacy (STI < 0.20) can be achieved with DL_2 values of around 6 dB/DD.

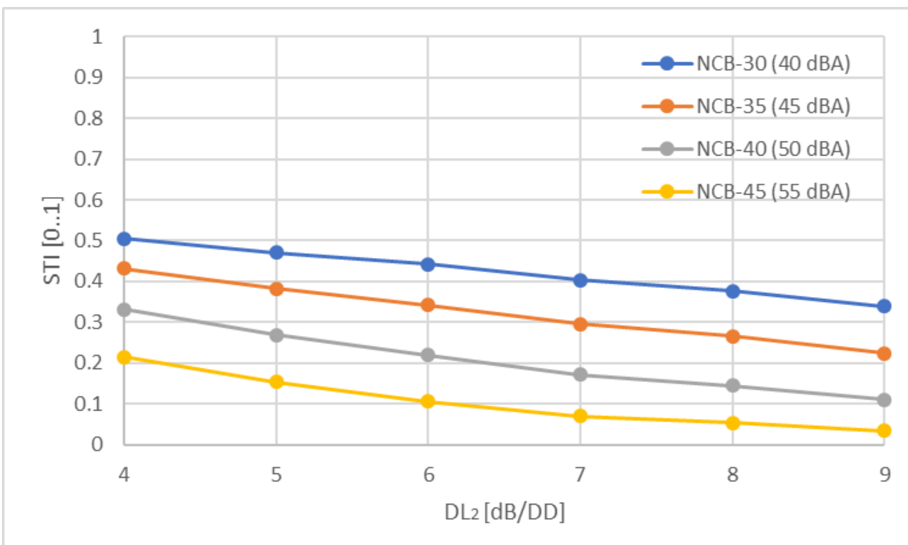

Figure 4.11 - STI vs DL_2 at 4 m for eating establishment with booths at varying noise levels (L_n = 40 dBA, T = 1 s)

4.4 DL_2 Observations

4.4.1 Case 1 (Intelligibility)

It was found that for a classroom of typical size, compliance with recommended reverberation time and background noise levels resulted in fully audible sentences at little listening effort for talkers speaking at a normal vocal effort level. In classrooms that are compliant with design standards, DL_2 provided little insight to the room's acoustical performance.

Additionally, STI calculations require that the reverberation time and background noise level be known. Without measuring these quantities for each room, STI cannot be predicted accurately. As the DL_2 quality rating brackets are based on STI, a standardized set of DL_2 quality ratings cannot be prescribed per room type.

However, in rooms where the reverberation time and background noise levels are known and are not compliant with standards, DL_2 is useful in determining the distance until which speech intelligibility is acceptable.

4.4.2 Case 2 (Distraction)

The sample analysis assumed that rooms where speech distraction is an issue contain seating dividers. In general, spaces where occupants intend to work without distraction either have subdivided spaces or enforce rules to limit speech levels.

In situations where the evaluation distance is unknown, the model may be used to generate a series of STI vs DL_2 graphs to present more insight than a single graph can. In this situation, the model was also more useful as a design tool than for evaluating rooms. The graphs grant designers insight to the amount of distraction expected at varying distances from a talker and allow designers to furnish the room to meet DL_2 values that limit distraction to acceptable amounts.

Perhaps most importantly, the model predicts that speech distraction targets are achievable with DL_2 values observed in real rooms. While factors that are expected to influence DL_2 (such as divider density, height, and absorptivity) were not studied specifically, the model gives designers more realistic expectations for the performance of a room.

4.4.3 Case 3 (Privacy)

For rooms where privacy is desired, the model predicted that speech privacy is only achievable in rooms with partial dividers when listeners are nearby. The sample setting was an eating establishment where increases in background noise levels are acceptable to promote better speech privacy.

In cases where adjusting DL_2 alone is not sufficient to provide satisfactory amounts of speech privacy, and the nearest listener location is known, the model could also be used to evaluate the level of background noise required to achieve the required amount of speech privacy. These conditions also vary by eating establishment, and designers may opt to use a combination of seating booths, greater distances between tables, and higher background noise levels if allowed by design constraints.

4.4.4 General Model Use Guideline

Through the sample applications, the model was found to be best suited for design or acoustical improvement analysis as opposed to being a standardized metric.

By specifying the relevant room parameters (background noise level, reverberation time, speech vocal effort level, and room dimensions), the model will generate either a STI vs DL_2 or STI vs distance chart.

The STI vs distance chart is useful to determine, at a glance, if the STI targets for the room are being met. If STI targets are not met, users can modify the background noise level, the reverberation time, or both, to obtain the proper STI at various distances.

Background noise level reduction can be achieved by proper HVAC system balancing or mitigating noise sources in a room. Conversely, background noise levels can be increased either by playing music or using a sound masking system. Reverberation time is mainly adjusted by introducing or removing acoustic absorption.

Alternatively, if the room setting permits, the user may choose to investigate the installation of dividers in their space.

The STI vs DL_2 chart lets users focus on a single, critical location to identify the DL_2 required to achieve the desired STI targets.

The tool ultimately allows users to adjust room parameters to determine the type and extent of work required to achieve either ideal or acceptable room conditions. The user can then determine costs before committing to lengthy and possibly expensive mitigation work.

4.5 Conclusions

The initial model developed in Chapter 2 was updated according to experimental observations made in Chapter 3. Additionally, by modifying the inputs to the full speech transmission index calculation scheme, sound pressure level data may be used. The full STI calculation scheme was also implemented in the DL_2 model.

The refined model was used to assess a hypothetical room of each room type. The background noise level and reverberation times were specified according to BB93 for each room. The model was used to analyze or design each room.

For intelligibility cases, DL_2 was found to provide redundant information if the room meets recommended reverberation time and background noise levels specified in design standards. However, DL_2 is useful in rooms where recommended reverberation time and background noise level are not met as it allows for optimized use of a suboptimal room.

In the distraction case, the model was used to produce STI vs DL_2 curves for a range of distances. The model recommended DL_2 values of greater than 6 dB/DD for productivity loss of 2% at 4 m. In rooms where dividers are present, DL_2 values range from 4 – 9 dB/DD. The recommended values are plausible and may be used by designers to achieve speech distraction requirement targets.

In the privacy case, the model concluded that good speech privacy is not possible at small distances (e.g. 4 m) if internal dividers (e.g. booths) are absent. However, by producing STI vs DL_2 curves for varying levels of background noise levels, the model produced a chart of recommended DL_2 values to meet user-specifiable privacy targets.

The model was found to be most useful in analyzing rooms as opposed to prescribing set DL_2 values corresponding to quality ratings. This is due to the variability of reverberation time and background noise levels from room to room.

5 Conclusion

DL_2 was proposed as a universal room acoustics parameter with the intent to establish a standardized rating system. An initial model was built based on the foundation work that resulted in ISO 3382-3, which related DL_2 to the speech transmission index (STI) to facilitate specifying rating criteria. The initial model was built to calculate STI considering only reverberant speech and assumed the behavior of sound in rooms. While inherently inappropriate for rooms where direct speech is present, the model was used as a base that was to be improved using experimental data and proper STI calculation algorithms.

While DL_2 is a parameter that is evaluated the same way regardless of room type, the rating schemes to assess room acoustic quality depend on how rooms are used. Three room use cases were identified: Case 1 (intelligibility) rooms where good speech intelligibility is desired throughout the space, Case 2 (distraction) rooms where good speech intelligibility is desired near a talker and distracts unintended recipients, and Case 3 (privacy) rooms where good speech intelligibility is desired near a talker and is meant to be confidential to nearby unintended listeners.

The room type categorization helped determine appropriate rating schemes. Case 1 requires that speech be fully intelligible to the intended audience and rates rooms based on listening effort. Case 2 requires that speech be fully intelligible at short distances, and the room rating is based on the percent of productivity loss caused at unintended listener locations. Case 3 requires that speech be fully intelligible at short distances, and the room rating is based on the percentage of the sentence intelligible at unintended listener locations. The quality rating brackets were derived from existing research relating STI ratings to the impact on human listeners.

Experimental data were then used to modify the initial model such that it would better reflect the behavior of sound in real world conditions. The linearity of sound decay, the sound pressure level at 1 m from a sound source, and the frequency variation of DL_2 were studied. It was found that DL_2 can be assumed to be reasonably linear if the evaluation range is limited to 16 m, the sound pressure level at 1 m in rooms is usually higher than in free-field environments, and DL_2 is generally less in low frequency bands and higher in high frequency bands. The trends evident in the data were then implemented in the initial model.

Finally, the STI calculation algorithm was modified such that it would accept the inputs available from DL_2 measurements, specifically the total speech sound pressure level. The modified STI calculation algorithm was then implemented, resulting in a final DL_2 model.

The complete model was then used to evaluate hypothetical rooms for each case. The rooms were modeled based on conditions specified by standards used in acoustical engineering. The rating schemes were then applied to their respective cases.

Through the sample applications, it was found that DL_2 is more useful as a design tool than as a standardized quality metric. To prescribe standardized quality ratings using only DL_2, the reverberation time and background level for each type of room will need to be assumed. Since reverberation time and background noise levels are known to vary greatly between rooms of the same type (e.g. classrooms), the same DL_2 value in two rooms of differing reverberation time and background noise level will produce different STI vs Distance graphs. Thus, standardized quality ratings based only on DL_2 are expected to have unreasonably large errors. However, if the reverberation time and background noise level are known, DL_2 can be used to gain deeper insight on how a room can be optimized for its intended use.

6 Future Work

The following sections outline aspects that the authors identified as work that can be done to further improve the DL_2 design tool.

6.1 Speech Distraction

Figure 2.6 of chapter 2, the loss of productivity versus STI curve is based on a wide variety of speech signals from foreign languages to contextual speech. In the case of typical workplaces, it is reasonable to assume that speech would be in the listener's native language and the topics are contextualized and are of interest to the listener.

It is therefore of interest to assess the loss of productivity due to conversations directly relevant to the listener. This, however, may have ethical repercussions and would be difficult to execute if the tests used speech signals that are directly relevant to the daily lives of the listeners.

Given the difficulty of simulating the conversations in a typical workplace environment, the distraction curve presented in Figure 2.6 may be the best approximation at the time this thesis was completed.

6.2 Workplace Dividers

In chapter 3.1.4, the effects of workplace dividers on the sound pressure level were observed. However, the data collected were not sufficient to understand how sound is diffracted, transmitted, or reflected around a divider, or how factors such as divider reflectivity, transmissivity, absorptivity, and geometry affect the sound pressure level in the immediate vicinity of a workplace divider.

It is hypothesized that the distance from the previous divider and the distance to the next divider also contribute to the sound pressure level before and after the divider of interest.

As the pre-existing data were not collected at sufficiently fine intervals before and after a divider for various heights, the specific effects of dividers were not included in the DL_2 tool. As of this thesis, the best approximation for divider effects would be to assume that the sound pressure level is 1 – 3 dB higher than the predicted sound pressure level before a divider, and 1 – 3 dB lower than the predicted sound pressure level after a divider.

However, the mechanisms dictating the magnitude of the over and underestimation in the vicinity of dividers are yet unclear and warrant further investigation.

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Appendix

B1-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	75.6	91.1	93.7	89.2	92.4	91.6	88.7	61.1
2	64.6	79.7	82.5	79.4	79.0	81.6	77.6	50.1
4	63.8	79.2	77.9	75.5	76.9	77.2	72.1	46.6
6	61.8	73.0	74.6	73.6	72.5	73.8	68.6	43.1
8	59.5	70.3	68.9	64.1	63.5	63.1	60.1	36.9
10	57.1	71.0	71.9	63.9	61.4	61.6	56.3	38.7
DL2 [dB/DD]	4.8	5.9	6.8	7.3	8.6	8.7	9.1	6.8

B1-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	70.5	86.1	90.8	86.4	89.2	89.4	85.4	58.0
2	69.3	82.5	79.1	78.7	76.5	79.7	77.0	48.9
5	61.9	72.3	72.1	68.2	69.7	73.2	71.5	40.2
9	55.5	71.9	71.0	64.2	67.0	68.7	64.8	38.6
14	54.2	59.6	63.4	63.7	66.3	66.1	61.9	32.8
22	51.1	52.3	51.5	52.4	59.3	60.9	57.7	23.2
DL2 [DB/DD]	4.7	7.3	7.6	6.9	5.9	6.0	6.0	7.0

B1-3								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	76.3	89.7	93.2	88.8	91.7	93.1	86.9	60.5
2	69.4	81.5	83.5	79.0	80.1	79.4	74.5	50.8
4	64.1	79.9	80.9	77.2	78.2	77.8	70.4	48.6
8	59.0	73.6	71.2	66.7	69.4	72.7	65.1	39.8
16	55.7	62.6	63.0	52.9	56.9	58.2	51.2	29.9
DL2 [DB/DD]	5.2	6.2	7.3	8.4	8.0	7.7	8.1	7.2

B2-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1.5	68.0	85.2	87.4	80.8	85.2	81.2	78.5	54.3
3	63.5	78.5	81.3	77.3	80.6	79.2	76.3	48.8
5.5	60.9	75.1	79.0	72.6	74.8	73.9	71.6	45.6
7.5	61.8	70.4	73.2	69.0	74.3	72.3	70.6	40.9
10.5	52.8	67.9	71.5	66.0	69.3	66.4	63.3	38.4
12	55.7	65.4	68.9	63.5	67.3	64.4	63.3	35.9
DL2 [DB/DD]	4.3	6.4	5.9	5.7	5.8	5.6	5.3	5.9

B3-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	72.6	88.5	92.1	88.0	92.6	88.2	90.7	59.6
2	69.7	83.2	85.0	80.9	84.3	82.3	80.4	52.6
4	67.6	79.2	80.8	77.0	82.7	79.9	76.7	48.8
8	58.9	75.0	76.0	70.4	75.6	73.6	69.2	43.5
12	57.5	70.4	72.4	66.0	69.7	68.3	65.0	39.4
DL2 [DB/DD]	4.5	4.8	5.3	5.9	5.9	5.2	6.8	5.4

B3-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.8	88.4	92.9	87.5	90.2	88.4	88.5	59.7
2	70.8	83.2	85.1	79.4	81.4	81.1	77.2	52.2
4	63.4	76.6	80.9	75.7	78.2	80.3	75.3	47.9
6	64.0	73.3	75.5	69.7	72.7	74.6	69.6	42.7
8	61.5	67.2	69.6	66.0	69.4	70.3	66.3	37.5
12	54.7	66.9	64.7	60.6	62.8	64.5	63.4	33.3
16	53.6	61.9	64.2	56.0	61.1	61.5	59.1	31.0
DL2 [DB/DD]	5.3	6.6	7.5	7.6	7.2	6.6	6.8	7.3

B4-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	75.6	91.5	92.5	88.3	93.1	89.7	86.4	60.3
2	68.7	86.2	87.4	84.1	87.9	86.0	83.2	55.4
5	64.2	79.4	80.9	76.4	77.1	76.1	73.0	48.3
9	55.6	71.2	71.7	68.1	68.8	68.3	66.8	39.5
13	51.2	68.1	67.6	60.8	62.9	60.7	57.3	35.0
16	49.9	60.7	62.1	57.0	59.5	57.9	53.7	29.5
24	48.0	57.6	57.3	53.1	58.3	55.2	52.1	25.5
DL2 [DB/DD]	6.3	7.5	7.7	8.0	8.3	8.1	8.2	7.8

B4-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	71.8	90.2	93.1	88.6	94.0	91.3	91.1	60.7
2	69.3	83.7	87.3	81.3	85.9	84.0	81.2	54.2
5	61.6	76.4	78.2	73.2	77.2	77.6	72.9	45.7
12	58.3	75.3	77.0	71.2	74.7	75.8	72.6	44.3
DL2 [DB/DD]	4.0	4.3	4.7	4.9	5.5	4.3	5.2	4.7

B4-3								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	69.2	85.7	87.9	82.7	87.3	84.4	80.9	55.2
2.5	66.9	82.2	85.5	79.7	82.7	81.5	79.6	52.4
3.5	63.2	78.1	83.0	75.8	80.5	79.1	76.7	49.5
DL2 [DB/DD]	3.0	3.9	2.5	3.5	3.7	2.8	2.0	2.9

B5-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	72.6	89.9	92.7	88.4	91.2	91.5	87.3	60.1
2	71.9	83.2	85.3	80.4	81.7	81.5	78.1	52.5
4	64.4	79.5	81.6	75.2	76.7	77.6	73.3	48.5
6	66.8	76.7	79.9	72.7	75.5	75.3	69.2	46.5
8	65.7	72.8	72.7	66.7	69.5	70.2	66.6	40.3
12	59.6	72.9	70.6	64.3	66.0	66.5	62.4	38.7
16	60.7	64.7	64.9	57.3	61.5	61.4	60.5	32.3
20	58.0	63.8	63.6	56.1	59.3	59.6	56.7	31.0
22	57.3	62.5	59.9	53.8	59.3	58.3	55.8	28.6
DL2 [DB/DD]	3.5	6.0	7.0	7.6	7.1	7.2	6.8	6.8

B5-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	68.6	84.8	85.8	82.2	83.6	82.9	78.9	53.6
2	72.8	82.5	84.8	81.0	81.7	83.3	80.4	52.3
4	63.1	76.4	79.9	77.7	79.1	79.3	74.9	47.8
6	67.0	75.7	78.0	74.4	75.5	75.8	71.3	45.6
9	64.0	71.0	71.6	67.6	70.9	70.2	67.8	39.6
13	59.8	67.9	68.7	65.0	65.5	66.8	63.4	36.5
15	60.0	65.2	64.4	58.9	62.5	63.7	62.1	32.5
19	59.1	65.8	62.5	57.9	62.4	62.0	59.3	31.6
DL2 [DB/DD]	2.8	4.9	5.8	6.1	5.5	5.4	5.1	5.6

B6-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	70.5	88.8	92.9	88.7	91.7	90.0	90.9	60.2
2	62.2	90.0	87.6	84.2	86.8	85.9	84.3	56.4
4	60.5	76.2	76.3	71.6	73.7	72.7	70.8	44.0
7	56.6	72.7	68.2	61.7	66.8	64.8	62.3	37.3
DL2 [DB/DD]	4.6	6.6	9.0	9.9	9.3	9.4	10.5	8.6

B6-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	70.5	88.8	92.9	88.7	91.7	90.0	90.9	60.2
2	66.1	82.1	83.4	79.5	80.6	79.0	76.7	51.0
4	58.3	75.3	80.3	75.4	76.7	74.9	73.7	47.1
6	59.3	73.5	76.5	69.1	71.5	70.0	67.3	43.1
8	58.0	67.1	70.1	65.2	67.4	66.2	65.4	37.2
11	53.1	65.3	69.9	62.9	64.0	61.3	59.6	36.3
14	52.9	60.7	61.8	57.6	59.7	59.6	57.0	29.5
DL2 [DB/DD]	4.6	7.1	7.3	7.8	7.9	7.8	8.3	7.4

B7-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	70.8	88.4	90.4	88.1	91.0	87.0	86.8	58.5
2	67.1	85.4	85.3	78.3	79.6	77.8	76.4	52.5
4	62.9	77.5	81.5	75.3	76.6	75.1	71.0	48.1
8	61.1	73.4	73.8	67.7	69.0	68.6	65.3	41.1
10	61.1	68.7	73.4	65.6	68.3	66.9	62.5	39.7
17	57.4	62.0	61.7	53.9	56.3	55.6	52.9	29.1
24	59.2	56.7	53.0	44.5	51.7	50.3	47.0	23.2
30	57.1	55.8	52.8	45.1	53.2	51.7	48.9	22.4
DL2 [DB/DD]	2.7	7.0	8.0	8.9	7.9	7.4	7.9	7.6

B7-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	75.1	88.5	91.3	86.9	90.6	89.6	86.7	58.7
2	69.8	83.1	83.6	77.7	81.0	80.4	79.3	51.0
4	65.0	76.3	81.7	74.8	76.6	74.7	73.5	48.0
6	63.1	71.5	74.4	67.8	70.5	71.1	66.2	41.2
8	60.3	72.5	72.9	66.4	68.2	70.0	64.6	40.2
10	57.4	68.8	71.1	62.1	64.3	65.9	62.3	37.6
14	57.4	63.0	64.9	55.7	58.8	58.5	55.0	31.5
18	57.8	60.4	59.7	51.3	55.4	53.7	52.1	27.4
DL2 [DB/DD]	4.5	6.6	7.1	8.1	8.2	7.9	8.2	7.1

B8-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	70.5	86.4	89.6	84.7	91.8	86.0	84.0	57.2
2	68.2	80.6	80.8	74.4	80.9	77.2	73.4	48.4
5	56.5	64.3	67.9	62.0	67.1	63.1	56.0	34.9
7	55.6	68.4	66.2	60.7	66.1	62.6	57.1	34.6
10	53.0	58.2	57.6	55.6	59.1	55.4	50.6	26.5
12	51.4	58.9	60.1	56.6	60.8	57.9	53.6	28.1
16	49.0	51.4	52.7	46.7	52.6	48.7	45.1	20.3
18	49.2	55.4	53.0	48.7	53.0	49.1	45.0	21.8
DL2 [DB/DD]	5.5	8.1	8.9	8.5	9.2	8.8	9.1	8.7

B9-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	81.5	92.3	93.2	84.3	85.7	80.0	74.8	59.9
2	73.9	91.5	87.0	80.4	81.5	76.4	68.8	55.9
4	71.1	82.5	82.6	73.4	72.5	68.0	60.2	49.5
6	62.9	79.9	78.4	67.3	66.4	63.5	55.0	45.6
9	64.9	76.5	72.2	61.8	62.2	58.9	50.7	40.8
12	59.3	69.9	70.6	58.4	58.6	53.8	46.6	37.1
DL2 [DB/DD]	5.8	6.2	6.4	7.5	7.9	7.4	8.0	6.4

B10-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.8	89.4	91.3	87.2	93.6	88.2	85.5	59.2
2	63.8	82.7	79.5	75.7	81.0	77.7	71.5	48.6
6	55.1	65.6	65.6	55.3	59.5	55.9	51.2	32.5
14.1	52.8	60.2	58.1	47.8	53.8	50.0	44.4	25.9
DL2 [DB/DD]	5.7	8.1	8.7	10.7	10.8	10.5	11.0	8.9

B10-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.4	91.2	93.5	89.0	92.7	90.9	86.1	60.9
2	67.3	84.2	88.4	84.7	90.5	87.5	83.0	56.2
5	64.2	75.2	77.2	73.0	75.9	74.9	70.5	44.7
8	59.0	75.4	75.0	71.8	77.1	74.3	65.5	43.5
16	56.2	62.9	62.3	54.5	59.8	57.7	51.2	29.9
32	48.1	54.8	55.4	45.8	56.8	53.2	45.6	22.9
44	43.8	48.8	45.8	39.7	51.0	49.9	41.3	15.6
DL2 [DB/DD]	5.2	7.6	8.5	9.3	8.0	8.0	8.7	8.3

B10-3								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	76.4	88.3	94.1	88.5	93.7	90.9	84.5	61.0
4	72.1	87.4	88.9	82.2	86.8	84.1	77.1	56.0
8	66.3	80.0	81.9	74.7	78.9	76.5	69.0	48.8
16	62.5	80.4	74.0	65.8	72.3	69.0	62.0	44.0
DL2 [DB/DD]	3.5	2.3	4.9	5.5	5.4	5.4	5.6	4.3

B10-4								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
2	72.9	83.9	88.7	84.8	91.0	88.8	80.9	56.4
4	68.6	80.8	80.2	75.9	79.2	77.2	69.0	48.2
8	59.2	73.5	74.0	64.7	67.4	67.3	55.8	40.8
16	53.2	63.6	62.0	50.6	56.6	54.7	46.7	29.4
20	49.0	61.5	58.5	47.7	54.7	52.6	44.1	26.6
DL2 [DB/DD]	7.2	7.1	9.0	11.5	11.1	11.0	11.2	9.0

B11-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
2	72.9	83.9	88.7	84.8	91.0	88.8	80.9	56.4
4	68.6	80.8	80.2	75.9	79.2	77.2	69.0	48.2
8	59.2	73.5	74.0	64.7	67.4	67.3	55.8	40.8
16	53.2	63.6	62.0	50.6	56.6	54.7	46.7	29.4
20	49.0	61.5	58.5	47.7	54.7	52.6	44.1	26.6
DL2 [DB/DD]	7.2	7.1	9.0	11.5	11.1	11.0	11.2	9.0

B11-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	70.4	89.2	92.7	89.8	93.2	90.6	82.3	60.5
1.5	62.3	80.2	81.2	76.6	80.7	81.6	72.9	49.0
4.1	59.7	71.9	78.5	72.3	77.9	78.3	71.7	45.3
6	58.9	68.3	68.9	63.7	71.6	70.7	62.1	37.1
8.5	52.2	68.7	69.4	59.7	65.5	64.6	55.0	36.3
DL2 [DB/DD]	4.6	6.6	7.0	8.6	7.5	7.3	7.4	7.1

B12-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	72.6	88.6	94.1	88.9	94.0	91.5	88.2	61.1
2	63.1	82.9	83.8	76.7	79.8	78.7	75.3	50.8
3.8	60.4	75.0	74.8	69.8	71.7	72.3	67.2	42.5
5.8	57.1	69.8	70.2	64.4	65.9	66.0	61.4	37.6
7.7	53.9	71.6	64.3	59.9	59.7	60.5	54.9	35.1
9.4	52.8	65.5	63.2	54.5	57.3	55.6	49.5	31.0
11.5	51.0	61.5	62.3	52.0	53.1	52.9	47.0	28.9
13.3	52.7	59.0	56.0	49.3	50.2	49.4	43.7	24.5
15.5	54.3	61.6	56.8	48.4	50.1	48.1	41.8	26.0
20	53.7	54.8	54.4	47.3	51.9	50.2	43.1	22.3
DL2 [DB/DD]	4.5	7.7	9.3	10.0	10.5	10.4	11.2	9.0

B12-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	73.0	86.9	92.5	88.3	94.0	91.3	84.1	59.9
2.3	68.2	81.2	82.0	75.0	80.1	76.8	73.9	49.2
6.4	62.2	69.0	74.9	64.9	69.2	65.5	59.3	40.8
8.1	64.3	63.4	62.3	59.6	66.3	60.9	56.6	32.0
11.8	59.2	61.9	60.0	51.9	55.8	53.8	47.2	28.2
13.7	60.5	57.8	54.0	46.2	52.9	49.0	44.0	24.3
18.8	58.5	55.7	54.1	44.3	50.8	47.5	41.4	23.0
20.5	58.6	51.5	48.9	39.1	42.4	42.3	35.9	20.1
25	57.0	51.0	45.7	36.4	41.9	42.2	35.9	18.5
27	59.2	48.7	45.4	36.4	39.8	40.0	33.0	19.4
30	57.3	49.3	44.9	43.5	48.9	47.6	37.8	18.8
DL2 [DB/DD]	3.1	8.2	10.1	10.6	10.8	10.2	10.6	8.8

B13-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	78.1	88.7	95.7	89.7	93.6	93.0	83.8	62.3
2	66.8	80.4	81.6	76.5	77.8	76.4	70.5	48.9
4	58.2	74.9	77.5	69.8	74.2	76.7	67.3	44.3
6	62.7	72.6	70.3	61.0	68.8	72.2	62.4	38.5
7.6	62.1	65.6	68.6	56.2	62.0	64.8	54.2	34.9
9.4	64.3	63.1	62.2	52.8	59.6	60.3	50.6	30.5
12.4	64.6	60.9	61.2	48.0	55.8	55.9	47.2	29.3
14	63.4	55.2	56.6	48.8	53.8	53.8	45.4	26.0
15.6	60.5	56.4	58.7	49.3	54.8	54.6	45.5	26.2
DL2 [DB/DD]	2.9	8.3	9.3	10.7	9.7	9.5	9.7	8.9

B13-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.3	90.3	95.3	90.6	92.5	92.0	84.4	62.2
2	69.3	83.7	84.3	82.1	81.8	81.5	76.3	52.5
5	60.7	76.7	81.2	74.0	76.5	77.0	69.0	47.6
6.9	61.3	71.3	71.4	71.0	72.7	75.3	67.6	40.8
9.8	53.9	64.1	67.9	60.9	64.3	67.3	56.8	34.6
11.6	53.1	63.1	63.2	55.6	60.0	59.2	51.7	30.5
DL2 [DB/DD]	5.9	7.7	8.3	9.1	8.3	7.7	8.4	8.3

B14-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	76.4	91.1	92.6	88.0	93.5	90.9	87.3	60.3
2.5	67.2	86.4	89.7	82.9	89.5	85.3	77.9	56.6
3.5	71.8	86.5	88.7	82.2	87.9	86.5	79.5	55.8
6.4	64.0	72.9	76.2	68.7	71.9	70.0	61.1	42.8
8.5	62.5	72.1	72.7	66.2	69.2	66.6	58.9	39.9
10.1	63.6	72.7	73.0	66.3	70.7	66.8	59.6	40.4
12.7	62.2	65.6	64.8	56.3	58.9	56.2	49.0	32.4
14.7	61.1	62.4	62.3	54.5	59.0	54.0	47.8	30.0
16.1	60.5	61.0	64.6	53.9	59.1	54.5	49.6	31.0
19.4	54.4	55.0	54.0	45.0	49.1	45.7	38.9	21.9
21.1	52.6	50.7	50.5	41.6	49.4	44.9	38.7	18.7
23.4	54.8	57.0	52.9	43.1	50.2	46.7	38.8	22.2
DL2 [DB/DD]	4.7	9.0	9.9	10.9	11.0	11.3	11.6	9.7

B14-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	75.0	90.5	92.3	89.4	95.1	90.9	86.3	60.6
3.8	62.9	83.6	86.1	78.9	87.2	82.1	76.3	53.2
5.3	67.8	75.1	75.1	71.9	74.5	71.1	64.0	43.3
9.5	61.1	72.5	74.9	69.9	74.4	71.3	63.4	42.2
12.2	59.8	70.1	64.8	57.5	62.2	56.8	50.4	34.3
14.9	59.9	71.3	68.0	58.8	63.7	59.6	54.9	36.3
19	60.3	64.1	64.6	54.9	60.0	55.9	50.2	31.7
DL2 [DB/DD]	3.6	5.9	6.9	8.3	8.7	8.6	8.9	6.9

B15-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	70.4	87.4	89.8	86.5	91.9	89.8	80.8	57.9
2	65.7	86.5	84.9	81.2	84.3	82.6	77.7	53.3
3.7	60.6	79.7	81.4	76.0	78.5	78.5	70.8	48.6
5.5	61.0	73.9	78.1	67.4	71.6	71.5	64.8	44.1
7.5	61.4	71.9	70.9	64.4	68.8	67.3	62.8	38.7
DL2 [DB/DD]	3.3	5.8	5.9	7.8	8.0	7.6	6.6	6.3

B15-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.7	86.1	91.3	88.0	91.2	91.0	79.8	58.8
2.9	70.5	80.7	82.5	80.2	84.3	83.3	73.0	50.9
4.7	62.4	74.9	79.5	77.7	79.7	81.1	70.2	47.6
8	60.2	75.9	74.8	69.3	75.8	74.2	62.3	43.0
9.7	59.2	70.6	73.2	68.2	73.5	73.6	62.6	40.7
14.4	56.7	65.3	68.6	61.2	68.6	68.2	56.2	35.6
DL2 [DB/DD]	5.0	5.0	5.7	6.8	5.7	5.8	6.0	5.8

B16-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	77.6	88.4	94.4	89.8	94.3	91.8	88.5	61.5
1.9	68.3	79.9	86.0	80.2	85.4	82.7	77.8	52.8
3.2	66.2	75.9	81.1	76.2	81.3	79.9	73.3	48.3
5.2	62.9	72.5	76.2	73.3	78.0	75.3	71.6	44.2
8.6	58.8	67.9	70.2	65.0	70.8	68.8	63.6	37.7
9.9	58.6	69.0	69.0	63.2	70.9	67.7	64.1	37.0
11.9	54.5	63.9	65.4	57.0	65.7	63.2	57.7	32.6
13.5	55.7	63.4	63.9	56.7	66.4	63.9	58.6	31.8
15.5	53.6	61.0	59.9	54.1	61.9	60.2	54.7	28.3
16.8	55.3	59.3	58.9	53.9	61.4	58.7	53.6	27.4
DL2 [DB/DD]	5.4	6.5	8.4	8.8	7.7	7.7	8.0	8.1

B16-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.9	89.4	94.9	88.3	94.8	92.3	91.1	61.7
2.6	67.3	80.2	87.1	81.1	86.6	84.3	79.5	53.8
4.5	64.8	72.7	75.0	69.6	76.3	76.9	71.5	42.7
7.4	56.6	76.6	73.5	68.5	73.7	71.8	67.7	42.3
9.1	56.8	71.0	68.9	59.1	66.4	66.8	62.0	36.8
11.6	57.4	68.7	64.8	55.6	62.9	63.4	57.6	33.5
DL2 [DB/DD]	5.5	5.4	8.5	9.2	9.0	8.2	9.2	7.9

B17-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.5	91.2	91.4	88.0	94.6	87.9	84.6	59.9
4.3	58.6	76.1	77.3	69.6	76.2	70.4	67.2	44.4
6.2	54.4	72.2	72.0	65.0	75.8	68.0	64.7	40.1
8	53.4	74.2	74.1	67.5	73.8	68.0	64.8	41.7
11.5	51.8	63.3	63.7	56.4	63.3	56.6	53.5	31.1
13.5	51.4	63.0	68.4	56.4	64.2	58.4	54.7	34.3
15.4	51.5	57.3	57.8	50.6	60.9	55.5	54.0	25.8
17.3	53.4	58.8	59.9	52.2	61.7	57.3	54.1	27.5
24	52.3	53.7	56.1	50.2	62.9	58.7	54.1	25.1
DL2 [DB/DD]	4.9	8.3	7.8	8.7	7.7	7.2	7.3	7.9

B17-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	77.5	89.0	93.0	88.4	95.5	87.7	85.1	60.6
2.6	64.0	84.7	89.1	81.0	90.3	83.4	80.6	55.9
4.4	60.5	74.8	78.0	70.3	75.8	70.7	65.8	44.6
7.1	55.7	70.7	70.5	68.5	73.5	66.4	64.3	39.3
9	56.9	71.8	74.0	65.6	72.0	65.5	61.6	40.7
11.7	53.5	68.3	69.3	63.5	67.9	61.9	58.6	36.6
13.6	54.1	67.3	64.4	60.3	67.7	62.0	57.1	33.6
16.3	54.0	63.1	63.9	58.9	69.3	60.5	55.5	32.5
DL2 [DB/DD]	5.7	6.3	7.7	7.4	7.5	7.4	7.8	7.3

B17-3								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.6	92.1	92.0	88.0	93.1	89.2	82.3	60.1
4.9	63.4	78.1	79.5	75.0	77.2	74.4	69.6	46.9
6.9	59.6	71.3	72.8	69.4	73.5	71.8	68.1	40.8
10.5	57.0	67.3	67.3	64.4	68.2	65.5	62.0	35.7
12.4	57.1	68.1	69.1	61.9	67.1	64.4	59.1	36.3
15.5	59.7	63.0	65.4	57.1	66.1	63.0	57.2	32.6
DL2 [DB/DD]	4.4	7.2	6.8	7.6	7.1	6.8	6.3	7.0

B17-4								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.6	88.0	92.0	88.1	93.6	88.7	86.1	59.6
2.9	64.1	79.1	82.7	76.6	80.2	74.5	72.0	49.5
6.1	64.9	77.9	75.4	73.9	77.2	72.9	69.7	44.8
8.4	55.9	68.6	70.9	62.5	66.3	61.8	57.6	37.5
12	57.6	69.8	71.3	62.0	65.9	62.1	58.7	37.9
13.8	58.3	64.5	65.0	56.0	62.1	57.8	53.8	32.1
17.5	57.1	61.3	62.5	54.8	62.0	57.7	52.8	29.8
DL2 [DB/DD]	4.2	6.1	6.9	8.1	7.9	7.6	8.1	7.0

B18-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	67.4	89.2	89.3	83.0	82.7	77.3	71.7	56.5
2	63.4	79.3	80.0	74.0	74.6	70.0	61.9	47.1
4.5	59.9	76.8	76.3	69.0	68.5	64.3	57.6	43.5
7.6	56.5	70.8	68.9	62.2	62.3	57.9	50.5	36.7
11.9	48.8	66.4	62.8	54.4	54.4	50.9	41.9	31.1
16.2	47.5	61.7	59.1	48.1	48.1	44.6	35.6	26.8
20.5	42.9	60.5	55.2	45.0	46.5	41.9	32.2	24.3
24.8	40.6	54.7	53.1	41.1	43.7	38.8	31.6	20.4
DL2 [DB/DD]	5.8	6.7	7.7	8.9	8.5	8.3	8.9	7.4

B18-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	65.4	86.9	87.4	82.9	82.2	77.8	70.9	54.9
2	64.6	81.0	78.4	70.2	71.8	64.4	59.8	46.3
5	59.3	68.5	71.7	66.0	66.0	60.3	56.0	38.5
9	57.5	63.5	62.3	57.3	59.4	58.5	50.3	30.4
13	49.5	59.5	58.6	52.8	54.2	50.3	41.2	26.3
16	50.2	57.2	55.1	49.9	52.0	49.4	40.1	23.4
DL2 [DB/DD]	4.1	7.6	7.8	7.7	7.2	6.3	7.2	7.7

B18-3								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	67.4	89.2	89.3	83.0	82.7	77.3	71.7	56.5
2	63.4	79.3	80.0	74.0	74.6	70.0	61.9	47.1
4.5	59.9	76.8	76.3	69.0	68.5	64.3	57.6	43.5
7.6	56.5	70.8	68.9	62.2	62.3	57.9	50.5	36.7
11.9	48.8	66.4	62.8	54.4	54.4	50.9	41.9	31.1
16.2	47.5	61.7	59.1	48.1	48.1	44.6	35.6	26.8
20.5	42.9	60.5	55.2	45.0	46.5	41.9	32.2	24.3
24.8	40.6	54.7	53.1	41.1	43.7	38.8	31.6	20.4
DL2 [DB/DD]	5.8	6.7	7.7	8.9	8.5	8.3	8.9	7.4

B18-4								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	70.5	84.6	85.7	80.4	81.3	73.2	69.7	52.9
1.6	66.3	78.2	77.1	70.7	68.4	64.2	54.9	44.6
2.7	63.5	77.7	81.2	72.6	72.6	66.5	60.3	47.4
4.3	57.7	76.6	73.9	69.6	66.2	60.7	52.1	42.3
5.4	58.7	72.0	73.2	67.1	66.3	61.6	55.8	40.2
7.2	57.6	69.7	69.1	60.8	59.9	57.7	48.5	36.3
7.9	58.2	69.8	67.9	63.3	63.5	60.6	53.7	36.1
DL2 [DB/DD]	4.4	4.6	5.2	5.3	5.4	4.1	4.8	5.1

B18-5								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	69.9	85.1	89.2	82.4	82.9	77.2	69.8	55.6
2	66.3	78.4	78.6	74.9	73.2	69.4	64.7	46.3
4	58.7	75.5	75.8	68.5	69.2	66.4	61.0	42.8
6	58.3	71.6	72.5	66.2	68.0	63.2	56.7	39.6
7.5	58.0	71.3	71.2	64.5	65.6	59.6	56.1	38.5
DL2 [DB/DD]	4.5	4.7	5.8	6.1	5.5	5.5	4.8	5.7

B19								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	75.5	92.8	94.1	87.0	86.5	79.9	78.3	60.9
2	67.4	86.9	83.3	72.8	74.2	66.6	64.7	51.5
4.9	64.8	79.3	80.1	69.8	69.0	63.3	58.9	46.7
8.5	54.8	70.3	69.0	58.7	57.6	51.7	47.7	36.2
10.6	54.7	66.3	64.4	52.4	52.9	48.4	41.6	31.8
13.6	52.0	67.7	63.7	52.6	56.2	49.9	45.2	32.1
16	46.8	59.6	57.9	47.0	48.4	44.6	38.5	25.3
19.2	44.8	63.4	55.0	45.7	49.2	44.4	38.2	26.2
21.2	45.4	57.2	53.8	44.4	48.4	45.7	37.0	22.1
DL2 [DB/DD]	6.9	7.9	8.9	9.4	8.6	7.9	9.2	8.5

B20-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	73.9	91.0	91.9	91.8	93.9	91.8	82.4	61.1
4	60.3	82.1	86.7	84.1	87.5	84.3	75.2	54.5
6	64.0	79.8	85.1	83.2	86.7	84.0	74.4	53.2
8	62.3	79.9	83.9	83.1	85.9	82.6	72.2	52.5
10	60.9	75.6	82.6	81.0	85.8	82.2	72.3	50.9
12	58.3	78.6	81.2	81.0	84.1	81.5	70.9	50.3
16	57.5	76.7	80.6	79.3	82.9	80.7	69.3	49.1
DL2 [DB/DD]	3.8	3.7	2.9	3.0	2.6	2.7	3.2	3.0

B20-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	70.2	89.8	93.5	91.2	91.9	88.7	84.0	61.2
2	63.6	84.4	85.2	79.7	81.6	77.6	66.8	52.5
4	57.6	78.6	82.0	76.0	77.2	74.5	65.4	48.7
6	59.0	79.0	80.2	73.7	74.6	71.7	61.2	47.2
8	58.6	77.2	74.9	69.9	72.6	70.3	60.3	43.2
10	57.2	72.7	73.3	67.7	69.1	68.7	60.4	40.6
13	54.3	68.2	71.5	65.9	68.6	63.8	56.1	38.4
16	50.8	64.2	68.4	63.3	65.6	62.0	55.0	35.3
19	55.9	64.1	66.5	62.5	64.3	61.0	55.2	33.9
21	52.7	64.2	65.3	62.4	64.2	62.5	54.4	33.3
DL2 [DB/DD]	3.6	6.1	6.2	6.3	6.0	5.8	5.8	6.2

B21-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	74.0	89.3	92.2	89.9	92.8	89.4	84.2	60.2
2	69.7	88.4	89.0	87.3	89.8	87.3	82.5	57.6
4	67.2	82.9	87.7	84.5	87.9	85.7	79.7	55.3
8	61.8	80.7	85.1	80.9	84.1	82.5	75.6	52.3
12	63.8	79.0	83.7	79.8	83.0	79.1	73.1	51.0
DL2 [DB/DD]	3.2	3.1	2.3	2.9	2.8	2.7	3.1	2.6

B21-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	71.0	88.7	93.6	88.8	91.7	89.6	82.0	60.6
2	68.3	85.2	89.2	84.5	87.6	85.3	78.1	56.3
4	68.3	84.6	85.6	81.7	85.0	82.5	75.2	53.4
8	65.4	83.9	83.2	79.1	81.3	79.5	71.6	51.2
16	60.2	77.2	80.9	74.1	78.5	74.8	67.8	47.6
DL2 [DB/DD]	2.5	2.4	3.1	3.5	3.3	3.5	3.5	3.1

B22-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	81.8	94.0	97.0	90.2	87.6	87.3	85.8	63.5
1	77.2	90.3	91.6	85.1	83.6	79.6	76.9	58.5
2	73.3	88.8	88.9	83.5	81.8	76.8	72.2	56.2
4	72.8	84.1	89.2	82.5	80.1	76.0	69.9	55.5
6	73.8	87.1	89.4	82.4	80.3	75.4	69.1	56.0
DL2 [DB/DD]	2.3	2.3	2.0	2.0	2.0	3.1	4.5	2.0

B22-2-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	79.4	91.9	96.2	89.0	86.8	82.8	77.7	62.5
1	75.0	90.2	91.8	85.8	83.2	80.5	71.2	58.7
2	73.8	91.2	91.6	84.3	83.3	78.0	68.9	58.6
4	74.9	89.1	89.4	83.4	81.8	76.4	67.4	56.6
DL2 [DB/DD]	1.5	0.7	2.1	1.8	1.5	2.2	3.3	1.8

B22-2-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	83.5	96.8	99.7	92.1	89.6	83.8	81.0	66.1
1	78.8	90.3	94.9	87.4	85.2	79.4	75.8	61.1
2	73.2	88.8	90.7	85.1	83.5	78.0	71.6	57.6
4	70.8	87.3	88.9	83.8	81.7	75.7	68.9	56.0
6	70.3	87.0	90.0	83.6	80.9	74.7	67.7	56.5
8	72.2	88.7	90.0	82.5	81.2	74.6	67.0	56.7
DL2 [DB/DD]	3.1	2.0	2.4	2.2	2.0	2.2	3.4	2.3

B22-3-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	82.3	94.7	98.0	91.3	87.8	82.5	78.6	64.5
1	79.8	93.0	92.3	87.5	85.8	79.4	75.3	60.0
2	76.5	90.0	92.8	85.2	84.2	79.2	72.0	59.2
4	63.6	81.5	82.8	77.8	75.3	69.5	59.7	49.9
7	62.7	79.3	82.4	76.6	74.8	68.8	59.0	49.1
10.2	58.6	74.6	78.1	73.3	69.5	64.0	53.4	44.9
13	57.8	75.3	76.9	70.7	69.4	63.7	52.8	43.8
13.3	54.1	71.6	74.6	68.9	66.1	60.4	49.0	41.3
20	52.3	70.7	72.9	67.2	65.4	59.9	48.1	39.7
22.4	50.6	66.3	71.3	65.1	62.5	56.8	44.8	37.6
25.2	51.5	67.7	70.2	64.0	62.0	56.3	44.2	36.9
28.5	47.4	64.9	68.9	63.0	60.9	55.6	42.7	35.4
31	43.6	63.4	67.8	61.5	59.8	53.5	41.0	34.2
35	44.8	61.5	67.1	61.6	58.9	53.3	41.3	33.5
DL2 [DB/DD]	6.4	5.6	5.1	5.1	5.0	5.0	6.5	5.2

B22-3-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	80.5	93.9	97.8	90.6	89.8	86.1	77.5	64.1
1	77.0	89.2	91.1	83.3	83.3	78.5	70.6	57.7
2	74.3	89.2	91.4	83.9	82.2	78.3	71.4	57.9
4	73.0	86.1	86.6	82.1	80.0	75.0	67.9	54.0
7	69.6	84.4	86.4	79.0	77.5	72.6	63.9	53.0
10.2	66.6	81.6	82.6	76.9	75.1	70.3	62.5	49.7
13	63.9	79.9	81.3	76.0	74.0	69.2	59.6	48.4
13.3	65.2	78.9	80.0	73.5	72.6	67.3	57.8	46.9
20	62.2	74.0	78.6	72.4	71.0	64.8	56.2	45.0
22.4	62.5	75.6	78.2	71.4	69.7	63.9	54.5	44.8
25.2	59.6	74.3	75.2	69.2	68.2	62.9	52.1	42.3
28.5	59.0	71.9	73.8	67.8	66.3	60.8	50.9	40.6
31	58.2	71.0	72.7	67.1	65.1	60.6	49.1	39.7
35	56.6	70.6	72.3	66.4	64.2	59.5	48.4	39.2
DL2 [DB/DD]	3.8	3.8	3.9	3.6	3.8	4.0	4.5	3.8

B22-3-3								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	81.0	93.5	97.2	90.0	89.2	86.2	77.3	63.6
1	76.4	92.8	92.4	85.6	84.8	80.9	72.0	59.7
2	76.7	92.3	91.1	84.9	83.0	79.8	70.9	58.7
4	67.6	83.8	83.6	77.0	75.4	70.0	60.0	50.8
7	66.6	81.9	83.9	77.5	75.8	70.8	61.4	50.6
10.2	57.4	76.9	77.9	71.2	69.4	64.2	52.9	44.8
13	62.5	75.9	78.7	72.3	70.7	66.1	55.4	45.3
13.3	56.4	71.3	72.9	66.8	64.4	59.1	47.5	39.8
20	55.6	71.3	74.8	67.9	64.9	59.7	48.7	41.2
22.4	50.2	68.5	70.1	64.0	60.4	55.2	42.5	36.9
25.2	51.4	66.9	70.2	63.9	62.6	57.5	44.2	36.8
28.5	46.3	65.8	68.4	61.5	58.5	53.0	40.3	34.9
31	48.1	64.4	68.9	61.8	58.9	54.5	41.7	35.1
35	43.9	61.3	66.7	60.4	57.3	51.5	39.2	33.0
DL2 [DB/DD]	6.0	5.5	5.0	4.9	5.3	5.6	6.4	5.1

B22-4-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	83.4	96.0	99.2	92.1	92.7	88.9	80.6	65.7
1	75.5	92.7	90.5	86.7	84.6	81.0	73.1	58.8
2	75.9	88.6	90.4	83.1	82.2	78.1	68.7	57.1
4	75.8	87.6	88.6	81.3	79.7	74.7	65.9	55.4
6	73.5	87.0	85.6	81.4	79.2	74.0	64.6	53.6
8	72.2	84.6	87.2	80.7	78.8	73.3	64.1	53.8
DL2 [DB/DD]	2.2	2.6	2.8	2.7	3.2	3.7	4.0	2.7

B22-4-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	84.4	98.0	100.0	92.5	88.7	89.9	86.0	66.6
1	74.8	91.6	93.3	85.7	84.7	79.9	76.6	59.9
2	73.1	89.2	89.3	82.9	81.5	75.5	69.0	56.5
4	74.3	87.7	88.2	80.9	79.7	73.2	65.5	55.1
6	72.6	87.4	87.3	80.3	78.1	72.1	64.9	54.4
8	75.6	83.5	86.7	80.3	78.9	72.2	64.2	53.3
DL2 [DB/DD]	1.9	3.0	3.1	2.9	2.5	4.1	5.3	3.0

B22-4-3								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	80.7	92.9	98.6	90.4	88.1	84.1	81.5	64.6
1	79.4	93.2	98.2	86.6	88.6	81.5	78.1	63.9
2	74.0	89.2	92.0	85.2	82.4	78.0	72.9	58.5
4	73.1	85.4	87.7	81.2	81.4	74.4	68.4	54.4
6	72.6	86.1	87.4	80.8	79.2	72.8	64.8	54.3
8	70.0	86.5	87.8	80.6	79.0	72.7	64.0	54.6
DL2 [DB/DD]	2.6	2.1	3.3	2.5	2.6	3.1	4.6	3.0

B22-4-4								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	80.7	94.6	96.5	89.9	88.7	85.4	75.2	63.2
1	76.9	91.1	92.8	85.9	84.7	79.7	71.9	59.5
2	74.5	90.7	90.0	84.4	81.8	75.1	67.8	57.5
4	73.5	87.7	88.1	80.9	79.4	72.7	64.3	55.1
6	71.9	87.1	87.0	79.9	77.5	72.3	62.6	54.1
DL2 [DB/DD]	2.3	2.0	2.6	2.7	3.0	3.7	3.6	2.5

B22-5-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	83.2	96.9	99.2	92.3	91.3	84.5	77.8	65.8
1	74.0	90.7	94.4	85.8	83.7	77.6	72.6	60.5
2	70.8	86.8	88.9	80.2	78.3	74.8	67.5	55.3
4	68.8	82.6	83.4	76.5	75.9	72.0	63.3	50.3
6	66.7	82.0	80.4	75.9	73.2	68.4	62.1	48.4
8	62.9	78.0	78.9	73.6	71.4	66.5	58.6	46.1
DL2 [DB/DD]	4.4	4.3	5.2	4.5	4.7	4.2	4.6	4.9

B22-5-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
0.5	80.8	94.4	98.1	90.6	87.6	82.2	78.4	64.4
1	73.3	89.2	91.9	84.6	84.0	77.8	74.2	58.4
2	73.6	86.9	89.0	80.9	78.1	73.2	69.0	55.5
4	72.1	84.3	86.1	80.1	78.8	72.0	68.2	53.0
DL2 [DB/DD]	2.6	3.3	3.9	3.5	3.2	3.5	3.6	3.7

B22-6-1								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	73.3	90.3	92.1	84.6	83.3	79.7	71.4	58.7
2	71.0	87.7	87.7	81.3	80.1	75.4	67.6	54.9
4	69.5	84.8	86.3	79.2	77.8	73.9	65.2	53.0
8	66.5	85.5	83.9	78.6	76.4	71.3	62.8	51.7
16	61.3	79.5	80.7	75.9	74.4	68.7	59.1	47.9
DL2 [DB/DD]	2.9	2.4	2.7	2.0	2.2	2.6	2.9	2.5

B22-6-2								
Distance [m]	**125 Hz [dB]**	**250 Hz [dB]**	**500 Hz [dB]**	**1000 Hz [dB]**	**2000 Hz [dB]**	**4000 Hz [dB]**	**8000 Hz [dB]**	**$L_{p,s,A}$ [dB]**
1	73.1	89.9	92	84.3	83.2	79.2	71.2	58.5
2	68.4	85.9	88.6	81.5	80.7	75.3	67.8	55.1
4	67	83.4	86.7	79.2	78.3	73.8	65.4	53.1
8	67.1	85.1	84.1	77.6	76.4	71.5	62.2	51.6
16	63.9	79.8	82.1	74.8	73.7	68.2	58.7	48.7
DL2 [DB/DD]	2.0	2.1	2.4	2.3	2.3	2.6	3.1	2.3