SOUND LIVING IN VANCOUVER'S LANEWAY HOUSING

by

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Abstract

Laneway housing is an innovative higher density housing form introduced to meet the City of Vancouver's EcoDensity Charter. This form of residential occupancy was introduced without specific acoustical standards for construction. Noise concerns generally accompany increasing urban density, particularly in housing located close to transportation and activity centers. Laneways and laneway housing have environmental and architectural features that can contribute to noise levels exceeding criteria for healthy living. To advance the state of practice, this research first explores the sonic environment of laneways, including sound propagation, urban canyon effects, and sound sources. Second, this research investigates the acoustics of the laneway house, including outdoor-indoor sound insulation of facades, architectural features, and floor plan layout in relation to environmental noise sources. Empirical field measurements, the CMHC road traffic noise model and software modelling programs are used to investigate the acoustical environmental quality of laneway housing. Findings from case study investigation of four laneways and six laneway houses are evaluated against the CMHC noise criteria for healthy living. The various research tools are evaluated for accuracy and practicality as acoustic design tools for Vancouver laneways and laneway housing. The results of this study can inform laneway development planning (including benefits of laneway vegetation), laneway house design, building envelope construction, and policy guidelines as the City of Vancouver continues in its plans for sustainable densification.

Keywords: acoustics of small buildings, urban canyon effect, road traffic noise, laneway house acoustics

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Glossary and Abbreviations

Acoustic barriers— a built structure, usually a wall, of sufficient acoustical impedance, height, thickness, and length to block line of sight between source and receiver. For example, a thick berm along the side of a highway.

Acoustical Insulation Factor (AIF) — rating system developed by CMHC for exterior envelope sound insulation capacity of each room against transportation noise.

AFOITC— apparent field outdoor-indoor transmission class.

AFOITL—apparent field outdoor-indoor transmission loss.

AGS (architectural greenery systems) — see AVS below.

AVS (architectural vegetation systems) — vegetated green walls, green roofs, living fences and other vegetated building components.

Attenuation— decrease in sound levels or sound energy, used interchangeably with decay.

BPN— building practice notes, published by NRC

BRN— building research notes, published by NRC

Canyon— a narrow urban street, resembling a canyon, gorge or channel, enclosed on both sides by buildings with acoustically hard surfaces, functioning like a wave guide or open tunnel for sound travel

CMHC— Canadian Mortgage and Housing Corporation; also used to reference the organization's traffic noise model, *Road and Rail Noise: Effects on Housing* (1981)

CMHC criteria— road traffic noise exposure limits for residential spaces: 55LAeq24 for outdoors, 45 for kitchen or bath, 40 for living room and 35 for bedroom. See Appendix 1: Acoustical criteria for residential spaces.

CoV— City of Vancouver (municipal government)

dBA— weighted decibel levels tailored to human sensitivity, discounting low frequency sounds

ΔdB/dd— decay or attenuation per doubling of distance; decay rate; the rate of attenuation in sound propagation over distance.

Decay— sound level decrease: progressive decrease in sound pressure level as sound propagates over distance; used interchangeably with attenuation.

DNL— day-night sound level, the A-weighted equivalent sound level for a 24 hour period with an additional 10 dB imposed on the equivalent sound levels for night time hours of 10 p.m. to 7 am.

Diffraction— where acoustical waves bend over and around barrier edges

Diffusion— where acoustical waves become “scattered” when reflected; used interchangeably with “scattering”

EPA— the U.S. Environmental Protection Agency

FAA— U.S. Federal Aviation Administration

Facade— a vertical enclosure to an indoor space, consisting of exterior wall, and any windows or doors set within.

FFR— facade to floor area ratio: area of facade divided by enclosed room floor area, in %.

FHWA— U.S. Federal Highway Administration

Flutter echo— a distinct “ringing” sound effect caused by sound waves ricocheting between two parallel reflectors

FSTC—field sound transmission class. See STC.

Hard— a material surface property of having high acoustical impedance and low absorptivity. The term “hard” is used interchangeably with “opaque.” The opposite of acoustical hardness is acoustical softness, transparency or absorptivity.

HOSANNA— European project for mitigating urban noise, acronym for “Holistic and Sustainable Abatement of Noise by optimized combinations of Natural and Artificial means”

Insertion Loss (IL) — attenuation achieved by inserting acoustic measures such as source enclosures and acoustic barriers; the WHO defines it to be the difference between levels before and after an alteration (placement or removal of a construction) [1].

Leq(N), LAeq— equivalent continuous noise level over N hours of a source that realistically fluctuates over time; dBA

Level reduction (LR) — sound level difference between source and receive on either side of a partition.

Lmax, LAmax— maximum sound level of a single noise event to describe time-varying noise sources; LAmax indicates A-weighting.

LWH— laneway housing and/or laneway house. LWHs = laneway house*s*.

Mass-air-mass resonance (M-A-M) — an acoustical phenomenon where layered panels resonate and increase sound transmission levels at specific frequency, depending on panel width.

LWH model— model for facade transmission loss

Multi-family residential building (MFRB) — a housing classification where multiple housing units are contained within one building or several buildings within one complex. A common form is an apartment building.

Noise reduction (NR) — reduction in noise level between a source and receiver

NRC or **NRCC** — National Research Council of Canada (not to be confused with noise reduction criteria, which is not used in this paper)

Obstacle— in CMHC, other buildings that are in the sound path blocking the sound waves are called obstacles.

Opaque— (acoustical) see "hardness"; acoustical material surface property of being 0% absorptive or 100% reflective.

OSB— oriented strand board, a construction material used in wall assemblies made of compressed wood fiber or wood chips and glue.

Outdoor-Indoor Transmission Class (OITC) — rating system for building facade protection against exterior noise intrusion, including road traffic noise.

Real time analyzer (RTA) — an acoustical instrument that measures and records dB levels across frequency spectrums over time and computes a number of required parameters.

Reverberation time (RT) — the time it takes for sound levels to attenuate by 60dB within a space, representative of room absorption.

RS— single family dwelling zones in Vancouver.

Scattering— see "diffusion."

Shielding— a building can shield some of its own facades from sound sources; these facades are referred to as being "shielded" in CMHC. Shielding is generally used in acoustics as the shadow effect of having obstacles such as other buildings or a hill blocking direct sound path to the receiver.

Specular reflection— angular reflection of sound waves by smooth mirror-like surfaces, with minimal diffusion.

Soundscape— term first introduced by Murray R. Schafer (Simon Fraser University) to describe a sonic environment as perceived and interpreted by human observer

Sound pressure level (SPL) — the common term for measure of magnitude of sound, in logarithmic units of dB, often A-weighted to tailor to human experience.

ΔSPL— attenuation, decay, or sound level drop at receiver distance x from reference distance x_o close to source.

ΔSPL/dd—see **ΔdB/dd**

Sound transmission class (STC) — an integer rating of how well a building partition attenuates airborne sound from speech and human activity

Traffic Noise Modelling (TNM) — standard procedures used by acoustic and traffic engineers to predict traffic noise levels

Transmission coefficient (τ) — coefficient used in building component insulation performance: $\tau = \frac{Wreceiver}{Wsource}$; $\tau = 10^{-TL}/_{10}$

Transmission Loss (TL) — decrease in source-to-receiver sound level achieved by a partition's sound insulation performance.

VGS (vertical greenery systems) — green wall and vegetated fence systems

Wall—exterior walls. Interior walls are referred to specifically.

WHO— the World Health Organization

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Dedication

To the City of Vancouver

To residents, designers and builders of small architecture

To God and to everyone He has blessed me with in the making of this work

CHAPTER 1: Introduction

1.1 Research context

1.1.1 Correlation between urban density and noise level

Vancouver, a high-density city of limited land area, lies at the center of a region anticipated to grow in population by one million in the next thirty years [2]. The City of Vancouver (CoV) plans to meet demands for growth and affordable housing by "sustainable densification" as described in official development plans. The EcoDensity charter (adopted 2008), the Greenest City 2020 Action Plan (2010) and the Regional Context Statement (2013) all place foremost priority on creating a compact urban area [2]. The EcoDensity charter introduced Laneway Housing (LWH) in 2009 as one of the key strategies to achieve sustainable densification and affordable housing goals within Vancouver city limits.

The laneway house (LWH) is a smaller-sized detached house, also known as an accessory dwelling unit, permitted to be built at the rear yard of a single family residential (RS) lot in the space conventionally allotted to garages, facing the back lane. Since the LWH program's implementation in 2009 and the first LWH completed that same year, more than 1100 laneway house permits have been issued and more than 500 laneway houses have been completed throughout Vancouver's RS zones[1] [3].

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[1] Vancouver's residential zoning districts are categorized into One-Family Dwelling zones (e.g. "RS-7"), Two-Family Dwelling zones (e.g. "RT-11"), and Multiple Dwelling zones (e.g. "RM-9N") [77]. Commercial District zoning (e.g. "C-2C" [77]) is also relevant in one of the case studies.

The LWH strategy in combination with secondary (basement) suites triple permitted density on single family (RS) zoned lots. The RS-zone covers up to 70% of Vancouver's land area [4] [5]. This can potentially bring one hundred thousand new occupants into Vancouver's laneway environment [6]. While this compact infill housing development pattern supports the City's sustainability and walkability goals, acoustics is a significant concern for a high-density environment [7] [8].

It has been established that the degree of urban density directly correlates to urban noise levels [7]. The Levels Document for residential sound exposure by the U.S. Environmental Protection Agency and CoV's Noise Control Manual (*Sound Smart*) suggest that Vancouver's anticipated growth and changing "density-to-noise designation" will increase community noise levels to the 65-75 LAeq range[2], greatly exceeding tolerable outdoor levels of 55-60LAeq for similar *dense urban* settings [7] [8] [9].

Attenuation by distance (geometric divergence) and ground absorption (significant areas of soft soil and vegetation) are the two primary means for sound levels to drop naturally in open space. Both these devices are scarce in a high density urban setting. Furthermore, buildings and paved roadways act as reflectors that can increase noise levels.

Higher noise levels affect living quality in specific and personal ways. Compact development entails that people live closer to noise sources like transportation nodes, possibly with insufficient distance for necessary noise attenuation. While living in a small-footprint, compact and walkable community has strong merits for convenience and sustainability, higher noise

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[2] US EPA ratings are specified in DNL, which includes a +10dB correction factor above LAeq24 for 9 nighttime hours. The actual amount varies by hour, e.g. DNL – Leq = 19.4 dB for 4am [17, p. 133]. DNL is roughly Leq24 + 10dB; for example, 70dB DNL ≈ 60dB Leq24. The ratings are then updated to reflect present-day conditions by applying a 10dB increase every 20 years [8]

levels must be anticipated and accounted for in planning, building design and construction. Residential property values drop by 0.5-2.5% per dB increase in average sound level, indicating that people do consider noise to be undesirable and value quietness as an asset [7]. Connelly points out that the World Health Organization (WHO) considers community noise a public health problem that is increasing in significance with urban densification [10, p. 2]. Traffic noise in particular directly impacts residential health and is regulated by governments worldwide [11].

1.1.2 Road traffic noise in Vancouver

In an urban setting, road traffic is often the most significant noise source impacting the largest numbers of city dwellers [8]. Traffic noise is the number one noise source generating residential complaints across Vancouver, followed by sirens and parties (see Figure 69 in Chapter 3) [12]. Babisch et al. and Selander et al. have published research on the relationship between traffic noise exposure and risk of myocardial infarction in *Epidemiology*, and Gan observed associations between road traffic noise and cardiovascular disease [11].

Although it is important to distance urban dwellings or recreational areas from traffic noise sources, high density residential developments are increasing near transit and transportation for convenient access, proximity and to encourage walking. An example is the Cambie Street corridor, where more than a dozen blocks of single family lots flanking Cambie Street and along W. King Edward are rezoning for multi-family development. In Vancouver, some Two-Family Dwelling and Multiple Dwelling districts located along major arterial road corridors and intersections, e.g. portions of Kingsway, Knight St., Broadway, and Commercial Dr., have been assigned the “N” designation (e.g. “RT-10N” and “RM-7N”) to indicate need for noise-mitigation [13]. Livability pilot studies and traffic mitigations strategies for reducing noise were suggested by public workshops back in 1997 to be implemented along First Avenue [12, p. "traffic solution"]. However, a large number of RS-zoned areas sited along or within 100m of busy road corridors are still currently exposed to significant traffic noise and without noise-mitigation regulations, including segments along Granville St., Cambie St., Knight St., King Edward Ave. and 41st Ave. Zoning for N-designation may need updating to reflect present-day noise levels.

Traffic noise levels in an urban residential environment sited on or near arterial roads can be as high as 75LAeq24, about eleven times louder and noisier than a quiet living room [8, p. 8]. Residents in such a situation are often impacted by noise in the form of speech and sleep interference. In worse cases, outdoor spaces are generally not useable, recreational areas may need to be sheltered, and indoor spaces require adequate sound insulation [8, p. 8] [14, p. 9].

Even in urban residential areas *away* from major roads and having a more acceptable outdoor LAeq24 of 50-55dBA (about three times as loud/noisy as a quiet living room), noise can still be a problem [8, p. 8]. Some noise events of lower intensities may become more noticeable and annoying due to the reduced masking effect of lower ambient noise [7]. The DNL community noise metric developed by the U.S. EPA and adopted by the Federal Aviation Administration (FAA) incorporates a +10dB LAeq correction factor during the nine sensitive hours from 10pm to 7am due to higher annoyance and lower masking ambient levels [9]. In quieter environments and during quieter times of day, breakthrough noises become more noticeable and annoying—a moving car may go unnoticed on a busy street but stir up attention in a quiet residential area.

1.1.3 Standards for acoustical health

There are criteria in place to protect residential health from excessive noise levels. The World Health Organization (WHO) recommends that community noise in residential spaces be limited to 30LAeq in bedrooms at night for uninterrupted sleep, and 35LAeq during daytime [1]. Single sound events should not exceed 45LAmax [1]. Outdoor levels adjacent to residences, such as on patios, should be no more than 40 – 55LAeq.

Outdoor living areas of new developments must be under 40LAeq in most European countries. In general, outdoor levels should be under 50LAeq to prevent *moderate* annoyance and under 55LAeq to prevent *serious* annoyance [1, p. 61]. For people who enjoy outdoor-oriented living, such as leaving windows open and spending lots of time on patios or in gardens, the outdoor sound level should be on the lower end of the criteria spectrum [7]. The difference between the outdoor and indoor criteria is expected to be achieved by standard construction providing about 10-25dB in noise level reduction.

The Canadian Housing and Mortgage Corporation (CMHC) provides similar criteria for acoustical health in residential spaces: outdoor living area, kitchen/bath, living room, and bedroom should be at or under 55, 45, 40, and 35LAeq, respectively. The National Research Council of Canada (NRC or NRCC) recommends indoor levels 5 points below CMHC criteria, at 40, 35, and 30LAeq for the respective indoor spaces, and noise events should be no more than 5dB over ambient noise levels [15]. The City of Vancouver adopts the CMHC criteria in its Sound Smart Noise Control Guide and thus, CMHC, the most lenient of all criteria listed above, is the reference for this study [8].

Domestic acoustical health criteria by WHO, CMHC, and NRC can be found in Appendix 1: Acoustical criteria for residential spaces. Note that standard noise criteria include noise emitted from all sources that affect a residential space, including road, rail and air traffic, industries, construction, public works, and the neighborhood [1]. Therefore, road traffic noise contribution should ideally be well below criteria to accommodate contributions from other noise sources.

For readers who are unfamiliar with acoustics, it is necessary to note that sounds of different frequency bands are perceived differently by humans, and that different types of noise sources are governed by different frequency ranges. Roughly speaking, higher frequency sounds generally give the impression of being higher pitched compared to lower frequency sounds, which give impression of being lower pitched. For example, of road traffic noise ranging from 63Hz to 8000Hz [16], the low engine rumble of trucks contain more low frequency sounds (e.g. 64Hz to 150Hz). High-pitched sirens, metal-screeches and tire-squeaks contain more high frequency sounds (e.g. 700Hz to 2000Hz). Human conversation is around 200Hz to 3000Hz, and humans are generally most perceptive to sounds of the 2000-5000Hz frequency range [17, pp. 83, 547].

In a context of increasing road traffic and urban noise levels, LWH is an interesting subject for acoustical investigation. Firstly, being situated within the laneway invites acoustic exploration. Secondly, LWHs have unique architectural properties that contribute to unique acoustical behaviour.

1.1.4 Laneways

There are several factors unique to laneways that affect acoustics of the living environment within them. These are: position in relation to streets (noise source), the urban canyon effect, and noises inside laneways. A laneway's orientation with respect to road traffic noise sources and how neighboring buildings interact with sounds determine noise exposure. Laneways abutting high-traffic streets can channel noise, and keep levels relatively high by building reflections—a phenomenon called the "urban canyon effect." The degree to which a laneway exhibits the urban canyon effect depends on the characteristics of its surfaces, primarily the ground surface and surface of the rows of buildings flanking each side of the laneway.

Unique noises in laneways are also a concern. Laneways were originally designed as a service space and have unique functions that are noisy, most notably garage use, yard work, lane traffic, and garbage and recycling activities. Laneways are also much narrower than the street, placing people and sound sources (such as moving vehicles) much closer to each other. Unique sounds, close proximity to source, and any urban canyon effects contributing to noise buildup inside the laneway affect the living environment for LWH residents. Chapter 2 and 3 explore the acoustics and sounds inside laneways.

1.1.5 Laneway house

The laneway house (LWH) is architecturally and dimensionally different from the main house such that noise may be an increased threat. In contrast to Vancouver's typical single-family house, LWH is acoustically more vulnerable in several ways: closer noise sources, smaller dimensions and lower mass.

1.1.5.1 Close to noise sources

Laneway houses can be very close to noise sources; they are adjacent to the laneway which is a service space with many potentially noisy functions and activities. In some cases, laneway houses (LWH) are close to the street, transit nodes and busy intersections.

A standard Vancouver RS house is often separated from laneway noise sources by the full length of the back yard, about 15.24m (50ft) for the majority of Vancouver RS zoned lots, and typically shielded by the garage. But for LWH, there is only a minimum 0.9m (3ft) setback from the lane.

At such a close distance to laneway noise sources, the lane house occupant is practically in the acoustical near-field and will need protection—to be provided by the building envelope—from laneway noises.

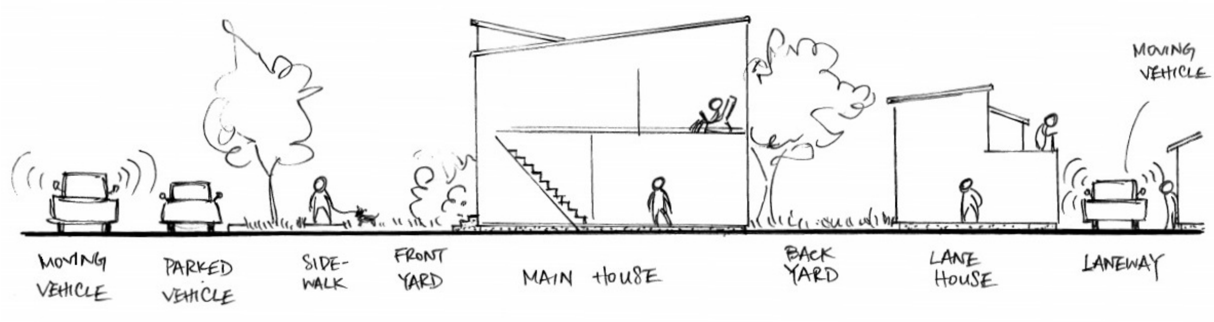


Figure 1: Lengthwise section view of LWH position adjacent to laneway (on right).
A main house occupant is more than 15.24m (50ft) from the lane and is shielded by lane-side structure.
The LWH is shielded from the front street traffic (on left) but not from laneway traffic.

For LWH on a corner lot, two facades are close to noise sources: the street-facing facade is only a side-yard distance—as close as 1.5m or 5ft Footnote 3—from the street, while the lane-side facade is close to and exposed to both the street and the laneway. In comparison, for corner block main houses, the front facade is at a full front-yard distance from the street (e.g. 6m or 20ft), the back facade is a back-yard distance (e.g. 15m or 50ft) from the laneway—only the lengthwise facade facing the side street is close to street traffic. As shown in Figure 2 and 3, a corner lot laneway house is exposed directly to noise from both the flanking street and the lane.

[3] Side yards are generally a minimum 10% of the lot width. The City Engineer specifies setbacks of 1.8m to 12.m for specific streets [133].

Figure 2: Laneway house site at noisy intersection (Google Earth image).
Side yard distance is about 1.5m (5ft) and much narrower than the front yard of 6m (20ft). Both roads have high traffic volume. There is a bus stop on Knight St., which can be both convenient and noisy.

Figure 3: Corner lot LWH flanking W33rd Avenue and laneway (Google Earth image).
The lot fronts Cambie St. (Google Earth image). Cambie St. is a six-lane arterial road and W33rd Ave. is a thoroughfare with higher traffic volume and speed than standard residential streets.

EcoDensity encourages high density development along transit corridors for easy transit access and to reduce personal vehicle traffic and commute time. It is possible to see higher rates of

LWH development in convenient locations along transit nodes, transportation corridors and activity centers. This consequently places some laneway houses closer to noise sources with higher exposure levels. In Figure 2, the potential LWH site is close to a major intersection with several bus stops and two shopping plazas with stores that open until midnight, all of which are significant noise sources in addition to any noises from the lane.

1.1.5.2 Smaller size

LWHs are generally small in size, ranging from 19m^2 (204sf) to 84m^2 (900sf), and averaging 52m^2 (560sf). One-storey LWHs under 4.6m (12-15ft) are encouraged over taller 1.5-storey versions up to 6.1m (20ft) maximum[4] [18].

In the event of noise intrusion, one of the most immediate human responses is to move away from the source. The LWH is not only sited closer to noise sources, it also confines occupants to a smaller enclosure than does the standard house. With little room or distance for occupants to escape from noise, the LWH must be able to provide adequate noise protection in other ways, such as by room absorption and by transmission loss of the building envelope, which have to do with room and facade size.

Sound attenuation by absorption in an interior space is proportional to room volume, room contents and absorptive surface area. The smaller a space and less absorptive its indoor surface area, the louder a noise will remain in the space. Also, smaller spaces allow for less furniture in the room to absorb sound. As new homes built 2009 onwards, LWH typically use modern and minimalist interior finishing with hard reflective surfaces that do not absorb sound. With more

[4] CoV prefers one-story LWHs in version 2.0 due to concerns for neighborhood privacy and blockage of sunlight by taller LWHs.

reflective surfaces and lighter furnishing, sound energy that would otherwise be absorbed can remain and build up in the room.

Because of the small building size, there is a tendency for LWH designers to employ open space plans and loft layouts to enhance a sense of spaciousness. In these cases, there are less partitions indoors to function as sound barriers and it may be harder to create quiet spaces in LWH for concentration or rest.

1.1.5.3 Lightweight construction

In terms of construction and the building envelope, LWHs are "expected to be built to the same or higher standard than the main house [19]," although only from the standpoint of energy efficiency and moisture control. The smaller size of LWH equates to smaller facade surface areas to place windows and doors, smaller indoor spaces, and lower mass of construction, all of which can reduce sound insulation effectiveness of the building envelope and place a heavier noise load on an interior receiver. Some LWH have even lower mass than the standard lightweight timber-frame building envelope, as lighter modular envelope components are used to reduce building time, shipping and handling costs, and to increase energy performance. Low-mass, non-absorptive, energy-efficient structural-insulated panel (SIP) wall systems that use EPS (expanded polystyrene) and XPS (extruded polystyrene) are recommended by one award-winning LWH design-builder [20]. In terms of acoustics however, mass and absorption are major sound-attenuating characteristics. A LWH built of lightweight, reflective construction material may not provide adequate noise protection compared to a larger house.

The combined effects of proximity to noise sources, smaller building size, and lighter envelope assemblies raise concern for the acoustical comfort and health in the LWH living environment.

1.1.6 Insufficient noise regulation for LWH

LWH are a higher-density dwelling form currently without stated acoustical regulations that apply to other high-density and multi-family settings. Current construction code for detached single-family houses and their accessory dwelling units (includes LWH) does not regulate acoustics. One exception is a clause stating that air-source heat pumps are prohibited from venting to the side yard to minimize noise to neighbors [19]. Venting to the rear yard will affect a LWH and silencing devices may be necessary. Official guidelines on LWH design and construction do not yet address acoustical performance. There is no mention of acoustics or even noise in the *Laneway Housing Design Guide* and the *Laneway House (LWH) Guidelines*, the official publications and reference documents on LWH issued by CoV [18] [21]. In fact, some non-acoustical design recommendations may conflict with acoustical performance, such as encouraging larger windows on the lane-side and street-side facades to protect yard side privacy [18] [22]. In public discussions of LWH development, focus has been placed upon many important aspects of livability except for acoustics. The noise issue was occasionally raised in citizen letters to City Council, but never directly addressed [23].

This is in contrast to official acoustical recommendations for multi-family residential settings, such as those in place for all RM-zone and other multi-family residential buildings and for secondary suites [24] [25] [26]. RM-zone buildings near arterial streets require special exterior wall treatment to meet CMHC criteria outlined in RM-9/9N District Schedule 4.15.1 [25], and interior party walls need to have STC65 [26]. Comprehensive rezoning is required to comply with CMHC criteria for maximum allowable traffic noise in the units [27]. In an apartment building, walls of occupied living spaces adjacent to the elevator shaft, garbage chute, and vehicle access must meet sound insulation requirements [24] [28]. Laneways are comparable in function to the garbage chute and the parking entry path in bigger buildings and are exposed to similar noises. The same applies to LWH living spaces adjacent to the garage. These gaps in protective acoustical specifications for LWH deserve attention.

Given the above factors of increased noise levels and closer proximity to noise sources in a context of urban densification, the architectural and environmental uniqueness of LWH, and missing construction requirements for LWH acoustics, a higher level of preventative acoustical planning, design and construction may be called for. The purpose of this research is to ensure that the regulatory framework for LWH design and for acoustical health are compatible, to advance the state of practice and current knowledge, and to validate tools for assessment.

1.1.7 Problem statement

This research explores the acoustical environment and the construction of LWH to answer several questions. First, whether the indoor and outdoor acoustical living environments of LWH comply with health standards for high density residential settings. Contributing factors to the results are investigated, such as any urban canyon effect, the types and characteristics of noises within laneways, and sound insulation of current LWH construction. Second, investigative tools and standards used in the process are evaluated for capacity to adequately predict problems and anticipate solutions for LWH.

1.1.8 Hypothesis

Whether or not a LWH can meet CMHC criteria depends on multiple factors: location, canyon effect, architectural layout, and facade construction. A LWH's location in terms of distance and orientation to noise sources is the most important factor. LWHs located in noisy areas, especially those on corner lots and exposed to road traffic, will not comply and will need further regulatory intervention. Building effects are another important factor. Most LWHs adequately shielded from road traffic by main houses will meet criteria with standard exterior wall construction and fenestration, except where the laneways are very reflective. Highly reflective laneways exhibiting the urban canyon effect—based on surface materiality, building density, building height, and degree of vegetation—are expected to have lower sound decay through the lane. This translates to higher outdoor noise levels for LWHs inside very reflective laneways.

It is anticipated that more activity sounds will be heard inside laneways, especially yard work and garage related noises, close vehicle approach noises, and special equipment operations including garbage trucks. These laneway noises may require LWH to have more careful architectural planning and higher construction insulation. The same standard construction that will suffice for one location may not be adequate for another—even if they are different lots on the same block; the same wall may work for one room size but not for another, for one room usage but not another. More detailed hypothesis will be described in relevant sections.

1.2 Research framework and methodology

This research adopts the case study method, a practical learning tool widely used in architecture, building science and engineering. Case study research can be both qualitative and quantitative, allowing exploration of a more dynamic range of topics and phenomena within the real-life context of Vancouver laneways and laneway houses [29] [30]. Multiple sources of evidence are drawn from, including empirical measurements, to yield practical context-dependent knowledge [10, p. 109] [29]. Standardized field measurements, numerical models, and computer models are applied to the case studies. Results obtained by the different investigative methods are compared and the methods are evaluated for practicality and effectiveness.

In order to effectively manage the multiple aspects of the problem, this thesis project is organized into two major parts: the first on the laneway, covering two chapters, and the second on the laneway house forming the remainder of the discussion.

Laneways

The study first investigates and evaluates the sonic environment in laneways both quantitatively and qualitatively, respectively organized into Chapter 2 and 3. Chapter 2 looks quantitatively at road traffic noise propagation through laneways in relation to the physical characteristics of the laneways. Sound propagation is empirically measured, predicted by standard traffic noise model, and modelled by software. Trends of change in magnitude (attenuation) and related factors will be analyzed and discussed. This segment of study also predicts LWH outdoor noise levels to check for CMHC criteria compliance.

Chapter 3 takes inventory of some laneway sounds, identifying and categorizing sources. Quantitative and qualitative observations on duration, amplitude, frequency spectrum, and other relevant information pertaining to the laneway sonic environment is presented.

Laneway Houses

The study then evaluates the LWH by focusing on facade transmission loss. Study of sound transmission loss involves multiple subject categories in acoustics, including:

- comprehensive traffic noise modelling from outdoor source to indoor receiver;

- room absorption (relating to interior space dimensions, room contents, surface materials and air conditions);
- facade (surface area, components like windows and doors, and exterior wall assembly materials and details); and
- use designation of the space.

CMHC criteria compliance of case study laneway house living spaces (outdoor and indoor) is determined from this segment of study. Chapter 4 more comprehensively investigates LWHs acoustics from source to receiver, and includes discussion of sound insulation properties of high R-value rigid foam thermal insulation products, which are anticipated to increase in LWH application.

Each part of this study makes use of a set of real case studies from Vancouver's RS zones. Empirical measurements are taken from case studies per standardized procedures. Industry modelling tools are then used to simulate the case studies, and data by different investigative methods are compared. Modelling tools are evaluated, findings and uncertainties are discussed, and any recommendations for mitigation are presented.

The next section provides contextual information on the case studies investigated in each part of the study. Chapter 2 and Chapter 3 results are based on case study laneways; Chapter 4 results are based on case study laneway houses.

1.3 Case Study Laneways

Four Vancouver laneways were selected for study of laneway sound propagation. Each case study laneway spans one residential block, ranging from 90m to 180m. The width-to-height ratio of RS-zone laneways in Vancouver is generally estimated at around 1:1:30 (w:l:h). Various laneway layouts are investigated. One case study is shared back-to-back by a commercial block and an RS residential block. One case study is a T-block.

1.3.1 Charles lane

This laneway is located in East Vancouver. The block was redeveloped approximately in the late 1980s to early 1990s. The houses are all of similar size, form and material. The garages are near identical, with 2 car metal overhead doors. There is no vegetation inside the laneway at the time of study.

Table 1: Charles laneway attributes

Charles lane information			
Dimensions	W:7.4m H: 5.1m L:82m H:W ratio: 0.69		
Physical attributes	**Geometry:** T-block and shielded from west side arterial road. **Form & buildup:** Close to maximum vertical buildup (90% of max height allowed). Minimal gaps between buildings are covered by hard gapless fencing. **Surface material:** Complete, smooth asphalt pavement, stucco and metal garage facade. Homogeneous and reflective surfaces. **Vegetation:** none inside laneway.		
Dominant road traffic noise source	On west	Field test air conditions	20°C; 65%RH

Figure 4: Google Map street view down Charles lane

Figure 5: Google Earth aerial map of Charles block

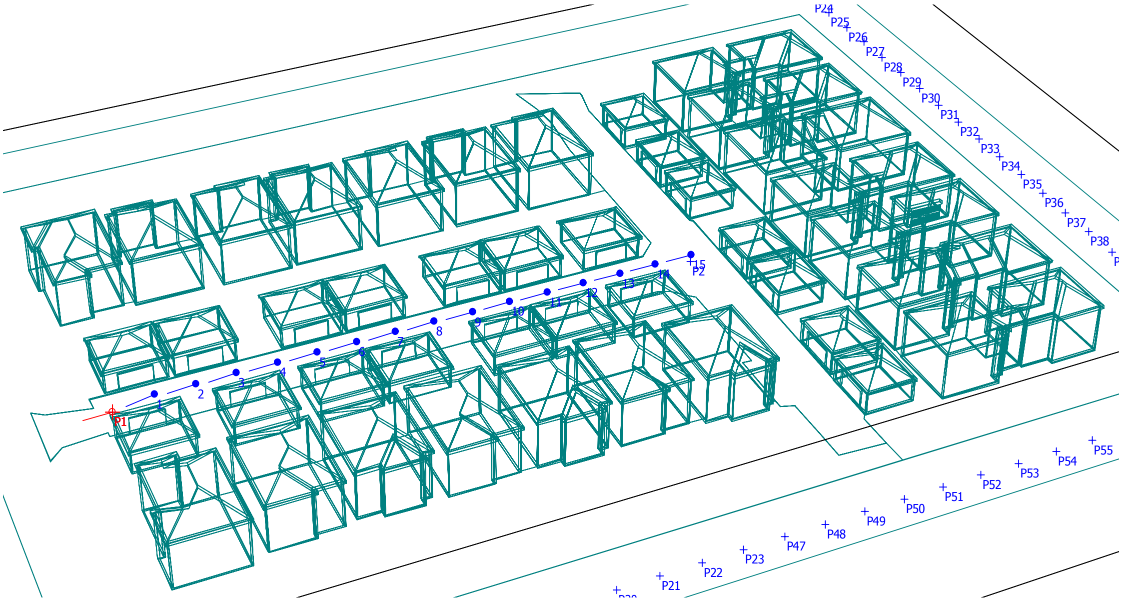


Figure 6: Sketchup2Odeon 3D model of Charles block

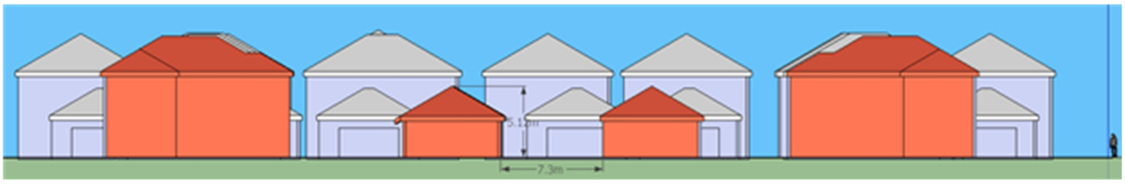


Figure 7: Sectional elevation of Charles laneway

1.3.2 E. Hastings lane

East Hastings is a laneway shared back-to-back by a single family (RS-1) zone residential street and a commercial street (C-2C). Mixed-use buildings are taller (up to four storeys) and built continuously along the laneway without setback, except one with uncovered parking spaces on the lane side. Multifamily apartments have residential windows and patios facing the laneway. The residential houses mostly have paved carports and garages on the lane side.

Table 2: E. Hastings laneway attributes

<table>
<tr><th colspan="4">E. Hastings lane information</th></tr>
<tr><td>Dimensions</td><td colspan="3">(effective) W:10m H: 9m L:173m H:W ratio: 0.9</td></tr>
<tr><td>Physical attributes</td><td colspan="3">Geometry: Shared commercial-RS1 block with taller continuous buildings on one side.

Form & buildup: Exceeds vertical buildup for RS zones on one side and relatively open on other side. Lane pavement is narrow, at 4.6m wide. However, most RS lots have paved carports and the laneway is not built up vertically along the rear property line on the RS side. Therefore, the lane has an effective width of 10m.

Surface material: Complete, smooth asphalt pavement over all grounds, including open carports in RS rear yards and parking lots on either side of lane at east end. Vertical surfaces are concrete 4-storey mixed-use multifamily building on the north commercial side; stucco and wood RS buildings on the south residential side.

Vegetation: minimal. Small gardens spotted throughout backyard areas, some vines on the 4-storey building and a small patch of lawn near the east end.</td></tr>
<tr><td>Dominant road traffic noise source</td><td>On north</td><td>Test air conditions</td><td>24°C; 45-50%RH</td></tr>
</table>

Figure 8: Google Map street view down E. Hastings lane

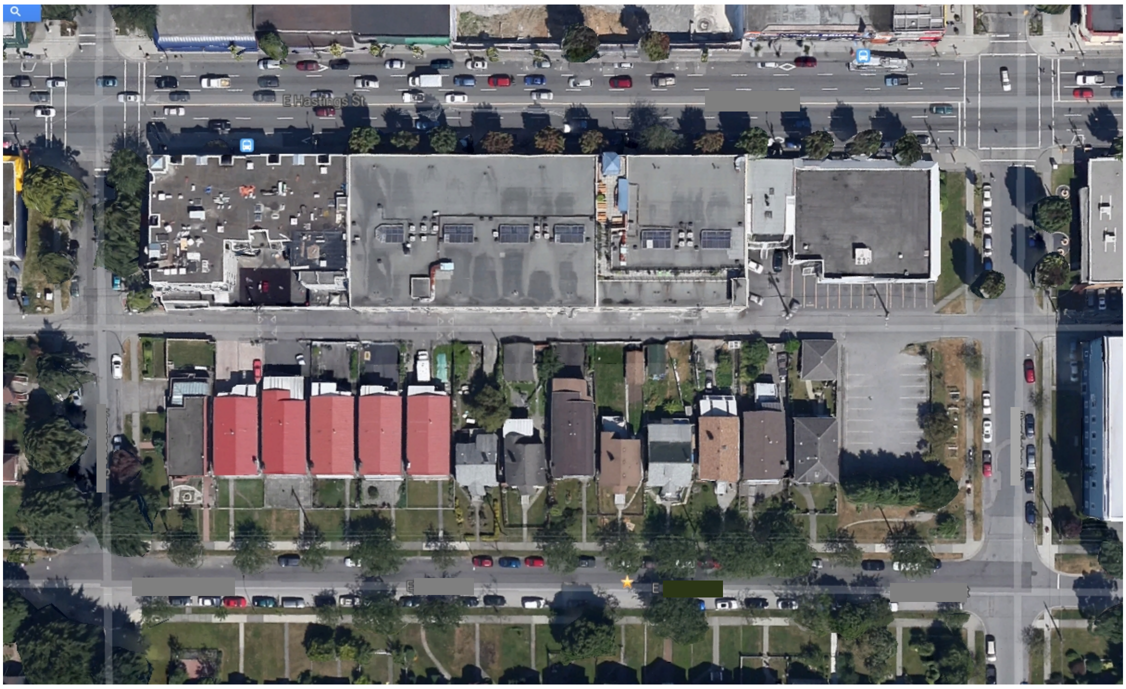


Figure 9: Google Earth aerial map of E. Hastings block

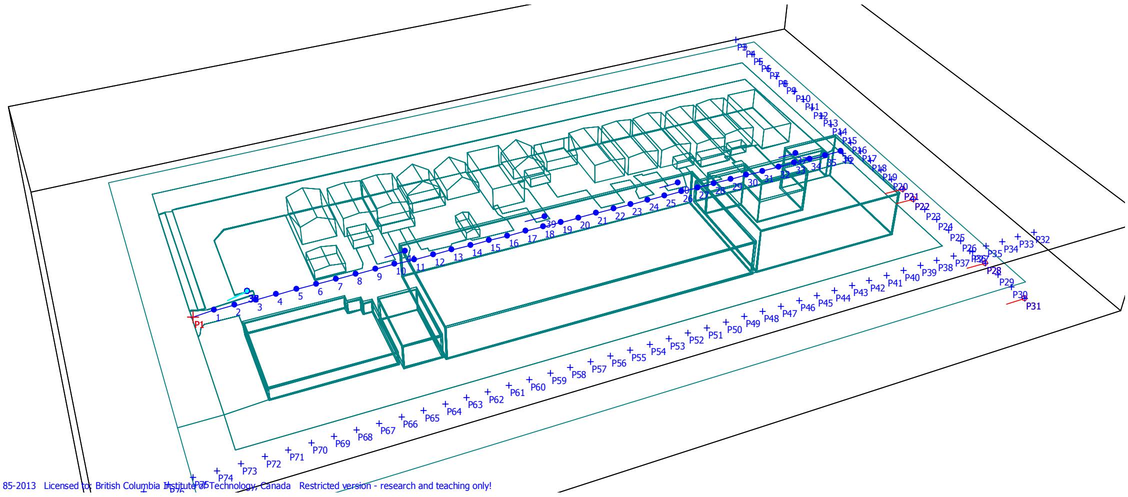


Figure 10: Sketchup2Odeon 3D model of E. Hastings block

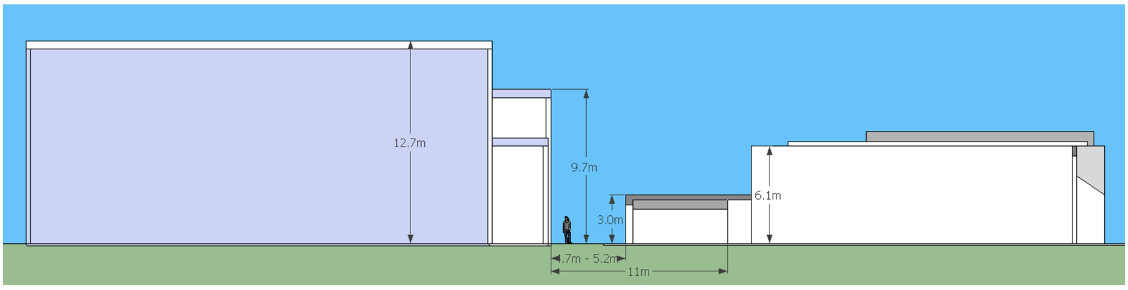


Figure 11: Sectional elevation of E. Hastings lane

1.3.3 William lane

William lane is the most common example of a Vancouver laneway; it is fully paved, with little vegetation, and lined with smaller, lower-height garages on both sides. Some garages have older surface material. There are some open unbuilt spaces of residential backyards with gardens and lawns.

Table 3: William laneway attributes

William lane information			
Dimensions	(effective) W:5m H: 3.7m L:171m H:W ratio: 0.74		
Physical attributes	**Geometry**: Standard residential block laneway. **Form & buildup**: Some gaps between buildings are covered on the lane side by fencing. **Surface material**: Complete, smooth asphalt pavement. Low height garages on both sides consistently through the laneway. Some material are worn and less reflective than Charles garages and E. Hastings mixed buildings. **Vegetation**: minimal through laneway. A few lots have smaller garages, revealing backyard lawns. Some open backyards have lane side fences.		
Dominant road traffic noise sources	Two major roads each two blocks from the east and west sides	Test air conditions	23-25°C; 55%RH; no wind

Figure 12: Google Map street view down William lane

Figure 13: Google Earth aerial map of William block

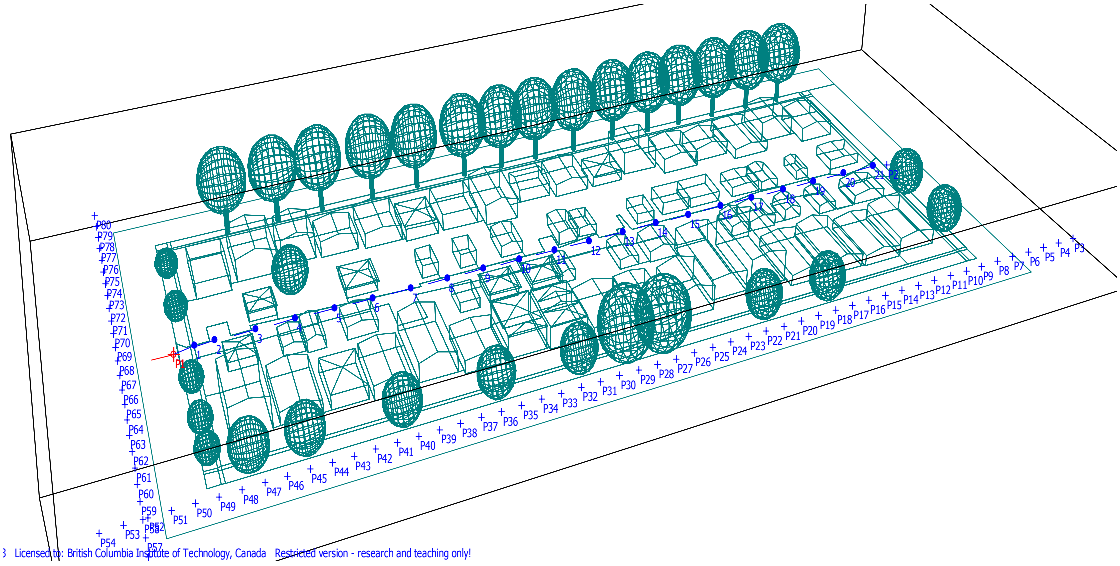


Figure 14: Sketchup2Odeon 3D model of William block

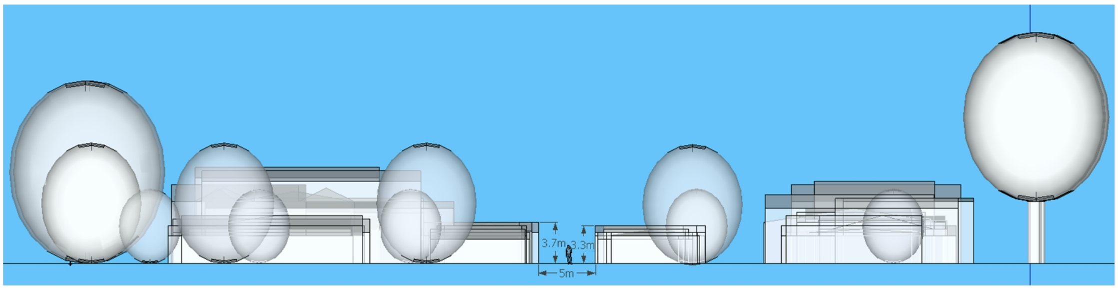


Figure 15: Sectional elevation of William lane

1.3.4 W34th lane

W34th lane is a particularly verdant laneway close to the west border of Vancouver near the Endowment Lands. The laneway drive path is partially paved, with majority dirt and gravel surface. Abundant vegetation growing from residential backyards extends into the laneway.

Table 4: W.34th laneway attributes

W34th Avenue			
Dimensions	(effective) W:5m H: 3.6m L:180m H:W ratio: 0.7		
Physical attributes	**Geometry**: Standard residential block laneway. **Form & buildup**: fairly “open.” Wider separation between garages along the laneway due to larger lots (15.2m). Gaps are fenced or foliaged. **Surface material**: Broken asphalt pavement, mostly dirt with a bit of gravel, some parts are overgrown with grass. Vertical surfaces are mostly foliage or fencing. **Vegetation**: heavily foliaged through laneway with notable vertical coverage. Foliage extends into airspace over the drive path.		
Dominant road traffic noise source	Access road on west	Test air conditions	13-15°C; 72%RH

Figure 16: Google Map street view images down W34th lane

Figure 17: Google Earth aerial map of W34th block

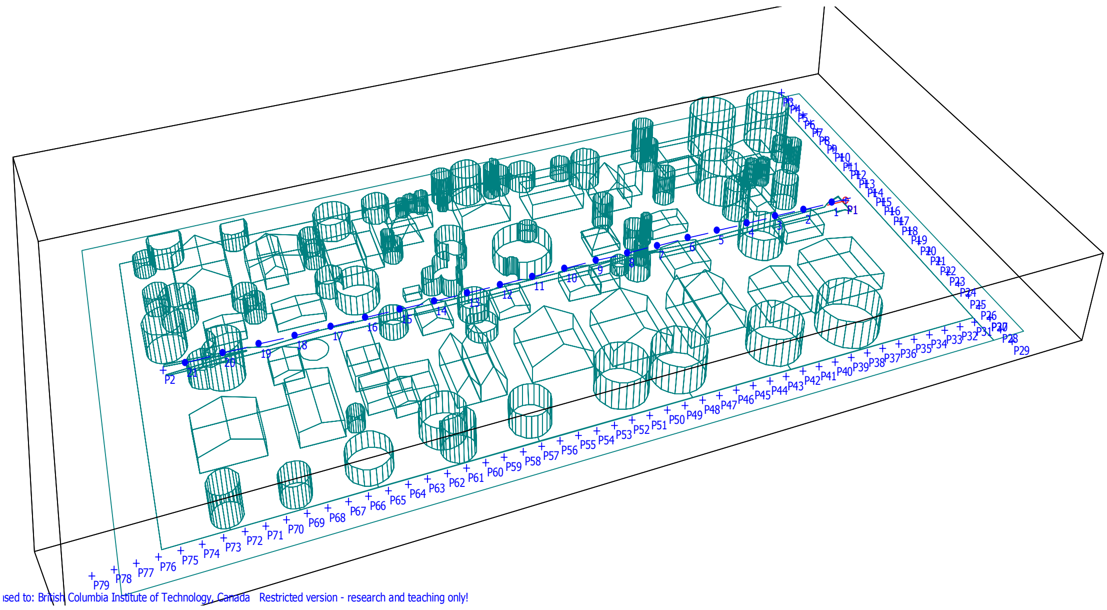


Figure 18: Sketchup2Odeon 3D model of W34th block

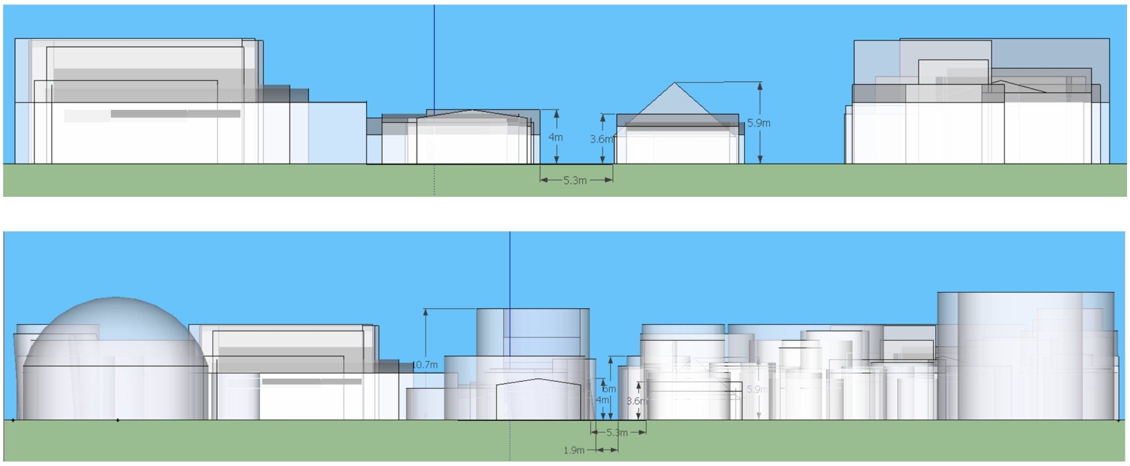


Figure 19: Sectional elevation drawings of W34th lane for buildings only (top) and including vegetation (above)

1.3.5 Summary of Case Study Laneways

The laneways are categorized based on acoustical response. The various laneway characteristics affecting sound propagation may be considered in terms of acoustical reflectivity/absorptivity. These include surface materiality and vegetation (reflectivity, absorptivity and diffusivity), height of canyons, and degree of build-up or percent coverage by buildings. This is approximated by considering air space as a 100% absorber, vegetation and soil as partial absorbers, and buildings and paved road surfaces as non-absorptive reflectors. A closed laneway with negligible gaps between buildings has more building surface area to reflect sound waves, and so it is more reflective than an open laneway. A taller laneway is covered to a greater height by buildings, and so is more reflective than a lower height laneway. A highly vegetated laneway with lots of trees, shrubs and associated air space instead of buildings is more diffusive and absorptive. Reflective is sometimes referred to as being acoustically “hard,” such as in the description of ground effects [14] [17]. Note that the term “hard” specifically refers to the property of acoustical reflectivity or non-absorptivity and does not always correlate to tactile hardness.

The case study laneways are ranked by reflectivity in Table 5, the values are estimated through site measurements.

Table 5: Summary of all laneways with acoustical reflectivity ranking

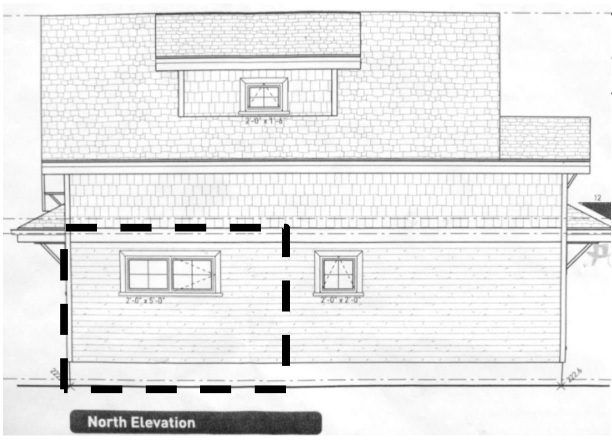
	Lane	**Paveme nt**	**Open Space**	**Vegetation**	**Reflect ivity**	**Absorptivity**	**Short descriptor**
1	Charles	100%	<10%	0%	90%	10%	Highly reflective
2	E. Hastings	100%	16%	4%	80%	20%	Highly reflective
3	William	100%	20%	20%	60%	40%	Somewhat reflective
4	W34th	50%	60%	60%	35%	65%	Absorptive

1.4 Case Study Laneway Houses

Six laneway house owners/residents responded to request letters and participated in the field test segment; these LWHs are adopted as the case studies for this chapter. Five of the case study LWH were completed 2012-2013. One is a heritage building estimated to be built in the early 1900s. The location and architectural information for each LWH are summarized below. Test facades are marked by a dashed box.

1.4.1 Case Study A

For Case Study A, the daily traffic volume on the dominant road source is approximately 25,738, with an estimated 12% heavy vehicles (buses and trucks). Road traffic noise levels are high.



Test facade: north (east half of the north) facade enclosing the ground level study. This facade faces the yard, the main house, and the major road which is a significant noise source.

Building notes: 1.5-storey tall. Bedrooms on 2nd floor; bedroom decks face lane on south. Indoor partitions are insulated by Roxul Safe and Sound and in some places with Acoustiblok (loaded vinyl sheet attenuator). Brand new without indoor room furnishing. Hardwood floors on first floor; carpet on stairs and on second floor. An HVAC is located just outside the north east facade and it is quite loud. Indoor levels exceed criteria when HVAC is on. HVAC is off for acoustic tests.

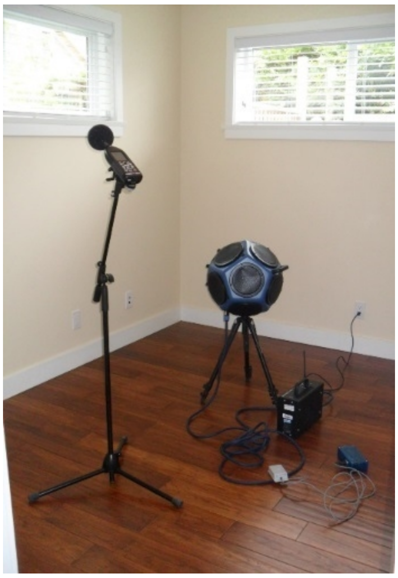


**Figure 20: Aerial Google Earth image of LWH A location (top of previous page),
Test Facade A at north west (second from top on previous page and above left on this page) and associated indoor space (above right).**

1.4.2 Case Study B

For Case Study B, the daily traffic volume on the dominant road source is approximately 25,738, with an estimated 12% heavy vehicles (buses and small trucks). There is significant road traffic noise levels and LWH B is closer to the intersection than LWH A above.

Test facade: south (enclosing kitchen, west of garage door). Inside covered by kitchen sink counter, cupboards and refrigerator in addition to window. Facing laneway, with low hedges.

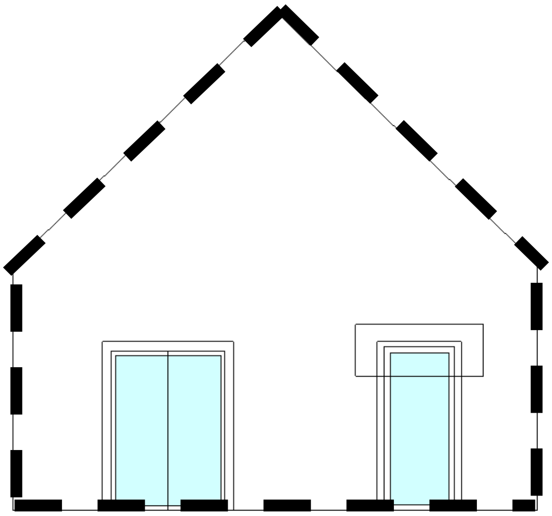
Building notes: this LWH is identical in architectural layout and design to A, possibly with identical wall construction and fenestration specifications. They are neighbors on the same block. B is closer to the corner whereas A is a midblock LWH; the two LWHs are four lots apart. The exterior color, landscaping, interior finishes and furnishing are different.

This LWH has hardwood floors throughout both levels with no carpet; it is fully furnished, including a large canvas painting on the wall. Indoor partitions are insulated by Roxul Safe and Sound; all walls are sealed with acoustic caulking with special treatment at electric penetrations.

Figure 21: Aerial Google Earth image of LWH A location (image on previous page), Test facade B at south west (top and above left) and associated indoor space (above right).

1.4.3 Case Study C

For Case Study C, the daily traffic volumes on the dominant road sources are approximately 18,000 and 19,000. In this area, heavy vehicles (bus and small trucks) are estimated at 2%. The LWH site is shielded by surrounding buildings from streets.



Test facade: south facade enclosing the living area. This facade faces a small terrace courtyard with wood fencing, tiered gardens, and other townhouses in the development.

Building notes: This is a detached coach house on the lane-side, sitting over the garage entry of a multi-family development project. The building is 6.2m tall, consisting of one level of double height living spaces under cathedral ceiling, with open floor plan except for bed and bath. The kitchen sits directly over motorized garage gates and the remainder of living space is over garage; part of the bedroom is over garbage area; the north side (lane side) is at about 1.83m above grade.

Figure 22: Aerial Google Earth image of LWH C location (first image on previous page), Test Facade C at south (second image on previous page and three on top of this page), lane side view (above left) and associated indoor space (two above right).

1.4.4 Case Study D

For Case Study D, the daily traffic volume on the dominant road source is approximately 52,000; heavy vehicles are estimated at 9%. This corner lot LWH is also exposed to side street traffic.

Test facade: north (west half of the north) facade enclosing the ground level living room. This facade faces the lane and the neighbor's completely open backyard.

Building notes: This is a heritage house from the early 1900's. The building is approximately 6m tall; sleeping area is on 2nd level "attic" space under cathedral ceiling. There is significant mechanical equipment (heater) noise from kitchen area and an intermittently buzzing fish tank in living room. On the east side (where outdoor levels are highest) there is a storage area and on the south entry there is a vestibule. These architectural elements insulate interior living spaces. The wall assembly composition, apart from the outermost layers, is unknown.

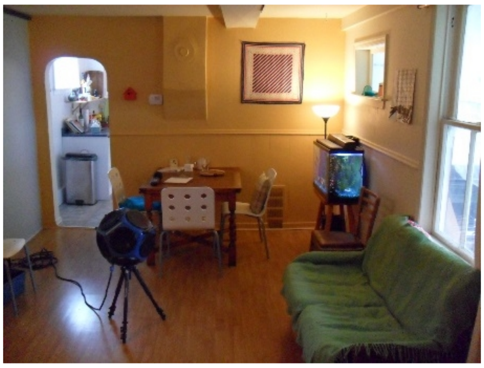
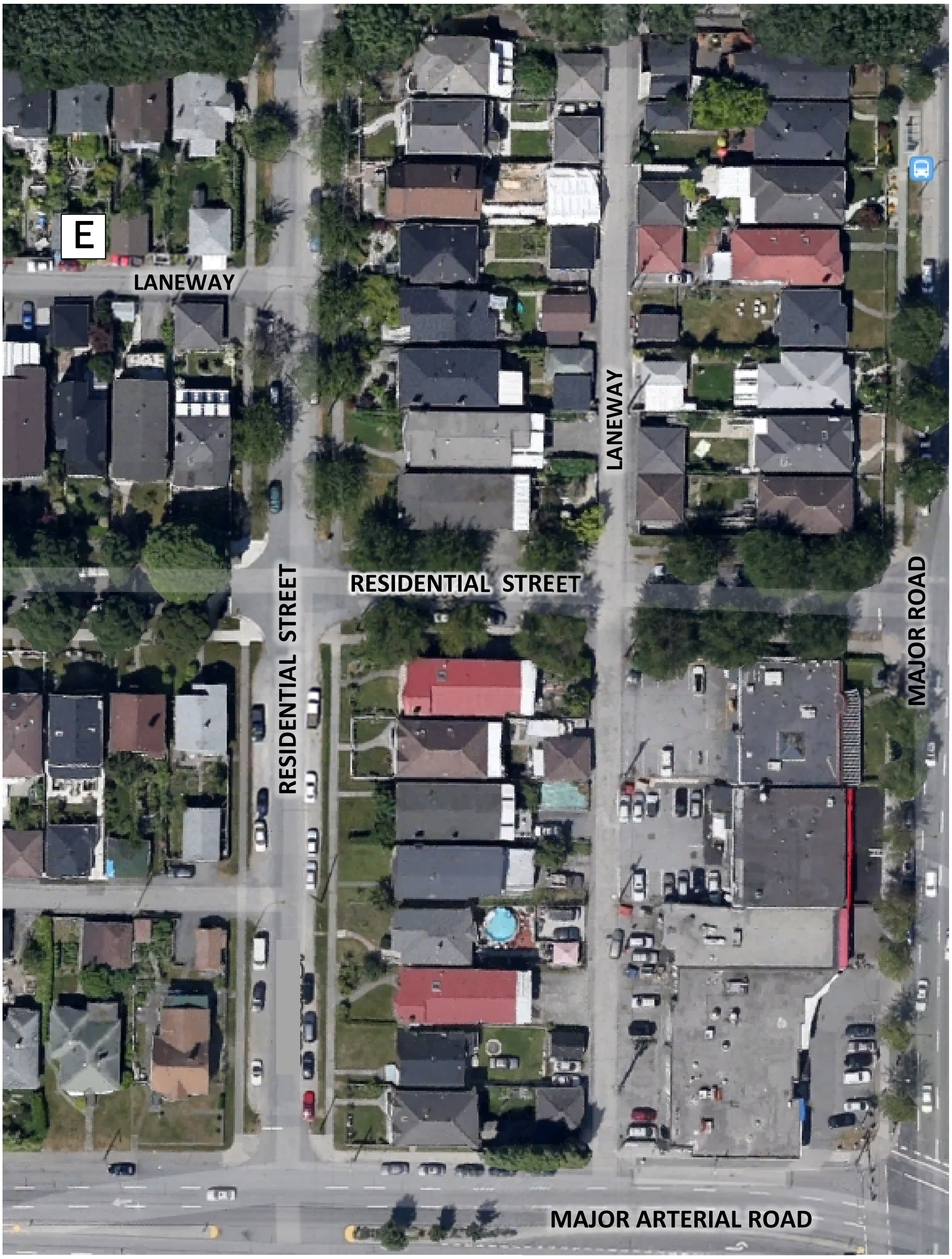
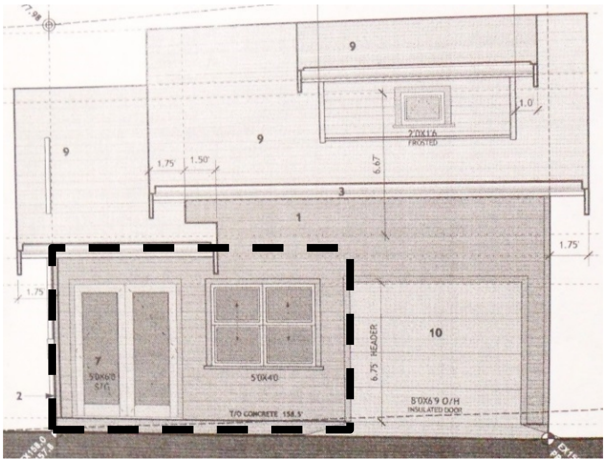


Figure 23: Aerial Google Earth image of LWH D location (first image on previous page), Test Facade D on north (second image on previous page), outdoor views (above right and above) and associated indoor space (above left).

1.4.5 Case Study E





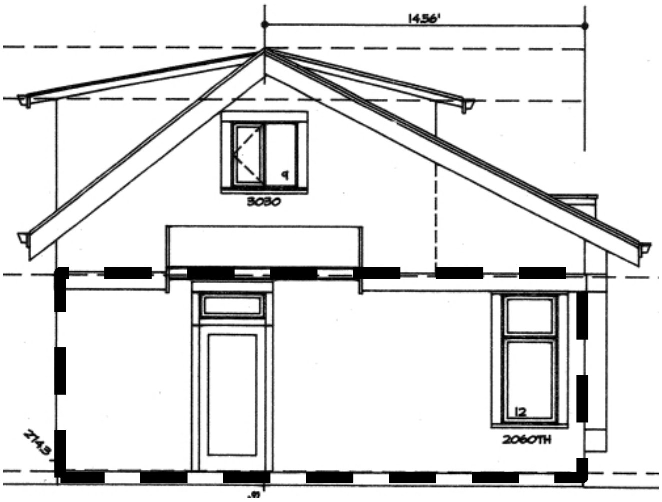
For Case Study E, the daily traffic volumes on the dominant road sources are approximately 57,565 and 27,464; heavy vehicles are estimated at 13% and 7% respectively.

Test facade: south facade (west of garage door) enclosing the ground level semi-lofted living room and kitchen. This facade faces the lane and neighbor's garage.

Building notes: This LWH has a "real" loft, which means there are no partitions separating the sleeping quarters from the kitchen and living space. Mechanical equipment and kitchen appliances operate intermittently at a notable level. Smooth coated concrete flooring on first level and carpet on stairs and 2nd level. There is large gap underneath the glazed double doors separating garage space and living room. The living room has two sets of glazed double doors and two large windows.

Figure 24: From top to bottom: aerial Google Earth image of LWH E location, Test Facade E at south west and associated indoor space.

1.4.6 Case Study F



For Case Study F, the daily traffic volumes on the dominant road sources are approximately 16,000 and 65,000; heavy vehicles are estimated at 10% and 21% respectively.

Test facade: west facade enclosing the ground level semi-lofted living room and kitchen. This facade faces the side yard and lot-partition fence towards the neighboring lot.

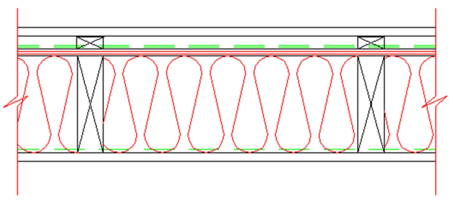
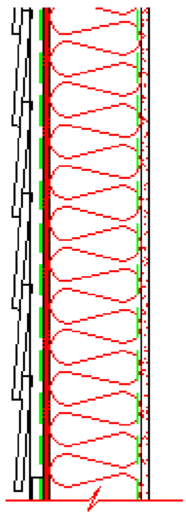
Building notes: The interior (plumbing and appliances) and landscaping of this LWH were under construction, so testing required extra coordination. The living area has a partial double height lofted ceiling; bedrooms are on second level with doors, one has a deck facing the lane. Hardwood flooring throughout. Buildings on the south side of the laneway are below grade due to site gradient, which means less barrier attenuation from southern sources like SE Marine Drive.

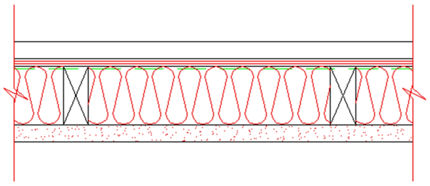
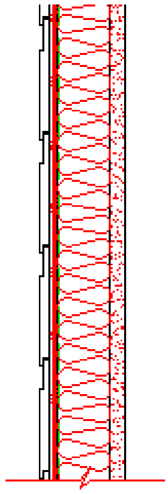
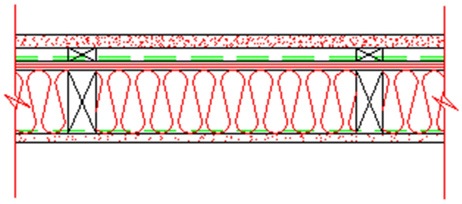
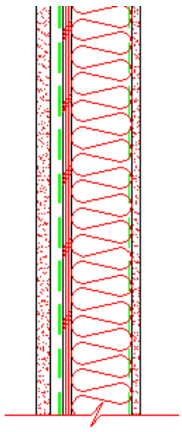
**Figure 25: from top to bottom: Aerial Google Earth image of LWH F location
Test Facade F on west side, and associated indoor space (images on top row of this page).**

1.4.7 Exterior wall sections

Four out of the six case studies have standard 140mm (2x6") wood frame exterior walls with lapped horizontal panel siding. Two LWHs A and B have fiber cement boards, and two LWHs C and E have painted wood panels. LWH D's wall assembly is approximated based on general information given by a builder experienced with old home renovations [31]. All exterior walls have a 12.7 to 25.4mm (½" to 1") rainscreen cavity between exterior siding and rest of wall assembly (at D, this is assumed). These wall systems reflect common residential construction in Vancouver. Wall section diagrams are presented below.

Table 6: Typical exterior wall sections of the six case study LWHs

Typical wall section (A, B, C, and E)			
Horizontal section	Vertical section	Assembly details	
		13mm	fiber cement board or wood cladding
		19mm	rainscreen cavity, with 38mm strapping @ 406mm o.c.
		0.5mm	2-ply asphalt building paper
		13mm	plywood sheathing
		140mm	studs (2x6") @ 406mm o.c. R-22 fiberglass batt insulation in cavity
		0.15mm	polyethylene air barrier
		13mm	gypsum wall board

D wall section (heritage from early 1900s)			
Horizontal section	Vertical section	Assembly details	
		19mm 0.5mm 13mm 101.6mm 25mm	painted wood siding tar paper plywood sheathing full 2x4" studs @406mm o.c.; assume cavity insulation fiberglass batt but generally no insulation from that time period 1" plaster
F wall section (crushed stone stucco siding on 89mm (2"x4") studs)*			
Horizontal section	Vertical section	Assembly details	
		19mm 6.4mm 19mm 0.3mm 13mm 89mm 0.15mm 13mm	stone dash stucco, painted wire mesh strapping and rainscreen cavity building paper plywood sheathing 2x4" studs @406mm o.c. with fiberglass batt insulation polyethylene air barrier gypsum wall board *requires additional insulation, by spray-foam or rigid board, to meet R-22 code requirement.

1.4.8 Summary of test facades and room specifications

Table 7 below summarizes specifications and information for the six LWH test facades.

Table 7: Test facade and room specifications for six case study LWHs

Test facade and room specifications						
Case Study ID	**A**	**B**	**C**	**D**	**E**	**F**
Test facade size (m^2)	7.6	7.8	28.8	13.9	10.1	20.0
Fenestration/facade ratio	12%	24%	22%	0%	51%	19%
Test room floor area (m^2) (approx. ±1 m^2)	7.2	19.0	30.0	20.7	19.5	27.0
Façade/floor area ratio	106%	41%	96%	67%	52%	74%
Test room volume (m^3) (approx. ±2.5m^3)	17.5	42.9	122.0	44.4	65.1	57.5
Test room use	Study	Kitchen-living	Living-dining-kitchen	Living-dining	Living-dining-kitchen	Living-dining-kitchen
Room condition	Empty	Furnished	Furnished	Furnished	Empty	Empty
Other		Open plan	Open plan, double height cathedral ceiling		Open plan + loft, open to sleeping area	Open plan + double-height ceiling

Four of the six case studies feature open plan living spaces. Three of the six case studies feature double height or lofted ceilings. Each case study test facade is referenced by its respective LWH letter.

1.5 Scope & limitations

Scope is limited to budget, timeframe, and available resources. This section provides a general overview of items beyond scope. More detailed treatment will be given in pertinent sections throughout the text.

In this study, focus is given to road traffic noise. Transportation noises not from road traffic, such as those from aircraft, water vessels, and light-rail/subway, will not be addressed except those observed and inventoried in Chapter 3, Section 3.3.1 and Appendix 2: *Laneway sound categories and descriptions*. Vibration, ground transmission and impact noise are also beyond the scope. Psychoacoustics and psychological and emotional aspects of sound will not be addressed. Models assume laneways are flat; slope gradient and curvatures in sound path are beyond scope.

Room acoustics beyond those addressed in Chapter 4 are beyond scope, including indoor partition transmission loss, indoor noise sources such as resident activity, indoor equipment and household appliances, speech articulation, and speech privacy. Contribution of LWH to community noise is also beyond scope, although this is a conscious concern in citizen letters to City Council [32] [33]. The main house is also beyond the scope of this study except where it serves as a noise barrier or source for laneway sounds.

CHAPTER 2: Road traffic noise propagation through laneways

This section explores the acoustics of laneways. The laneway is adjacent to the outdoor and indoor living spaces of LWH and thus is an important noise source to investigate. In comparison to the yard-side, the lane-side is exposed to noise sources that have greater acoustical impact on the LWH dweller than on the main house resident. Laneways are connected to larger streets and form a part of the road network that traffic and traffic noise originate from and travel through. Laneways are publicly accessible, and are the designated space for various engineering services including garbage and recycling.

Moreover, the geometry and physical characteristics of a laneway influence its sonic environment in ways that may be unfavorable to LWH occupants. This is particularly true in terms of urban canyon effects resulting from increasing built surfaces in the laneway. This section explores sound propagation through the laneway to observe environmental factors affecting the sound environment.

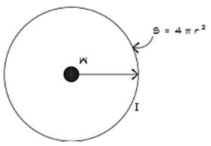
2.1 Literature review

Literature review for this section is organized as follows: (1) sound propagation theory for point and line sources, (2) road traffic noise, and (3) sound propagation in urban canyons.

2.1.1 Sound propagation theory and outdoor environmental effects

Many factors influence sound propagation, starting with source characterization. The fundamental theory governing sound energy divergence in free field (without reflection or absorption) is based on the point source and the line source [17, pp. 66, 185].

For a point source, spherical spreading of sound energy away from the source results in sound level dropping exponentially, starting at a distance *beyond the near field*, at a rate of 6dB per doubling of distance (6dB/dd). The sound pressure level at a receiver *r* meters *beyond the near field* is given by Eq. (1) [17, p. 66]:



$$L_p = L_w + 10log\frac{1}{4\pi r^2} \qquad \textbf{Eq.(1)}$$

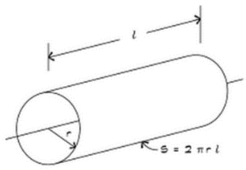
Eq.(1) reduces to:

$$L_p = L_w - 11 - 20\log(r) \qquad \textbf{Eq.(1b)}$$

where the expression $-20\log(r)$ yields the -6dB/dd. L_p is the sound pressure level at *r* meters away from a reference point (here set to 1m) near the source, and L_w is the sound power level of the source.

The near field is the range of space very close to the source where sound level does not attenuate according to this theory; the near field range changes depending on source characteristics. In practice, the reference point is a point beyond the near field.

Line source fall off in free field is 3dB per doubling of distance (3dB/dd), as per Eq.(2) below [17, p. 70] [34, p. 115]:



$$L_p = L_w + 10log\frac{1}{2\pi rl}$$

Eq.(2)

Assuming l >> *r* and approaches infinity, Eq.(2) reduces to

$$L_p = L_w - 8 - 10\log(r)$$ **Eq.(2b)**

where the expression $-10\log(r)$ yields -3dB/dd. L_p is the sound pressure level at *r* meters away from a reference point (here set to 1m) near the source, and L_w is the sound power level of the source. The expression $-10\log(r)$ yields the -3dB/dd.

In practice, geometric divergence (more commonly called attenuation or decay) between source and receiver is only one of several factors affecting sound propagation in outdoor environments. Other influences include:

- Ground effect (interaction between ground surface and sound waves)
- Barriers, buildings and heavy vegetation
- Atmospheric absorption (air temperature and humidity)
- Wind effects, atmospheric turbulence and refraction
- Day/night air temperature gradient refraction close to the ground, especially during the winter [35] [17]
- Sloped ground interaction (intervention by berms and hills)

Among these, this study focuses only on ground effect, degree of vegetation, barriers and buildings. Other factors such as meteorology and sloped ground are beyond the scope of this study.

2.1.2 Traffic noise modelling

Road traffic noise is the primary noise source investigated in this study. Traffic noise models (TNM) are used in industry to predict residential acoustic conditions. In these models, ground surface materiality (reflective or absorptive) is important. In literature, non-absorptive ground is commonly referred to as "hard" and absorptive ground is referred to as "soft."

The equation for decay of a single moving point source over flat open ground—applicable to any moving noise source in and around laneways including single vehicles, *with ground correction*, is [17, p. 185] [36]:

$$\Delta L_R = 10\log(\frac{d_r}{r})^{\frac{\xi+4}{2}} \qquad \textbf{Eq.(3)}$$

where ΔL_R = drop in sound level due to distance (dB)

d_r = distance where reference level is measured, usually 15m

r = distance between source and receiver

ξ = 0 for hard site

ξ = 1 for soft site

Moving point source decay is 6dB/dd for a hard site and 7.5dB/dd for soft site, an additional 1.5dB/dd for ground attenuation [17]. The corresponding line source (a line of traffic such as a road) falloff rate is 3dB/dd for a hard site and 4.5dB/dd for a soft site and is given by [17, p.

185]:

$$\Delta L_R = 5\log(\frac{d_r}{r})^{\frac{\xi+4}{2}}$$ **Eq.(4)**

where

ξ = 0 for hard site

ξ = 2 for soft site

These are theoretical appropximations. In reality, an example of a hard site is a concrete paved plaza, or long smooth asphalt road. Examples of soft ground include areas of soft soil, heavy foliage, shrubs and/or other very absorptive ground surface such as thick layer of fallen leaves or snow. In line source prediction, areas with some building attenuation are also considered soft ground [17].

For line sources, Long suggests that, more often, the 4.5dB/dd “soft ground approximation” is used; 3dB/dd is used only in special circumstances, such as where source and receivers are both 3m above ground, or when the ground is hard without any intervening structures [17, p. 185].

The Canadian standard for residential road traffic noise modelling is CMHC’s *Prediction of Outdoor Noise from Road Traffic* model, Part 3 of *Road and Rail Noise: Effects on Housing* [14]. For road traffic noise, CMHC only considers line sources. NRC Building Research Note 146 (BRN 146) presents the theories and principles used in the CMHC standard in greater depth and elaborates on modelling considerations [15]. The NRC TNM attenuation by distance equation is equivalent to hard ground line source decay, using a reference distance of 30m [15, p. 10]:

$$Attenuation\ with\ distance = 10log\frac{r}{30}$$ **Eq.(5)**

J.D. Quirt, author of the NRC TNM and one of the national authorities on the subject who collaborated on the CMHC standard, also produced a NRC report, Building Practice Note 56 (BPN 56), that uses a simplified residential TNM with slight variations including consideration for angle of noise incidence [37]. He considers the CMHC model "the simplest and most accurate TNM available [ibid]." The Canadian TNMs are comparable to the Federal Highway Administration (FHWA) method [35]. In the US, the FHWA noise prediction methodology has been incorporated into computer programs like SNAP, STAMINA, and OPTIMA [35, p. 344].

In traffic noise modelling, source, path and receiver characteristics are examined to predict noise level at the receiver, which is usually the property line, building line or building facade.

At the source, traffic noise level from a road is determined by posted speed, traffic density or volume per day in both directions, percentage of heavy vehicles, road gradient, road width, and road surface conditions (to consider wheel-to-pavement interaction and reflections between road surfaces and the bottom of cars) [14] [15] [38]. Flow pattern, such as whether the traffic is continuous and constant or interrupted and at varying speeds, is another influence. Urban intersections are a point of interest because of the acceleration and deceleration patterns of traffic near intersections. Interrupted flow characterizes driving within Vancouver; there are frequent traffic lights, stops and intersections. Proximity to a street intersection (within 150m) contributes to higher traffic noise levels [14] [15] [38]. Source directivity or angle of sound approach is included in Quirt's NRC report (BPN 56) but not in CMHC [37].

The second part of TNM takes into account factors pertaining to path and receiver:

- distance between source and receiver, which is the path length;
- receiver height, to consider magnitude of any soft ground effects based on angle of incidence;

- ground conditions along the propagation path: sound absorptivity in terms of soft or hard ground surface, scattering objects are included in soft ground approximation;
- obstacle correction for building or row(s) of buildings blocking the sound path;
- barriers with height, length, width, distance, and various ratio calculations; and
- shielding (by the building's own mass) [14] [15] [35].

In the FHWA TNM, path length and ground condition are calculated by Eq.(3), which applies beyond the near field [36]. A reference distance d_r beyond near field is used, usually set to 15m [17, p. 185]. Canadian standards CMHC and NRC use 30m from the source as the reference point.

Figure 26 compares the line source decay equation (with ground correction) with attenuation by distance values used in Table 3.5 of CMHC's numeric TNM. In addition, Odeon software was also evaluated and its line source propagation behavior over hard and soft ground is modelled for comparison.

It can be seen from Figure 26 that for hard ground attenuation, the different TNMs are consistent with one another. NRC is congruent to theory (Eq.(2), Eq.(4)-hard, and Eq.(5)) and is thus not shown. CMHC is slightly less than theory by about 0.3dB in SPL which is unnoticeable to the human ear. On the other hand, Odeon hard ground line source approximation exceeds Eq.(4)-hard starting at 40m and progressively increase at a higher rate, to ΔSPL of -4dB at 180m. The Odeon soft ground approximation lies between theory for soft ground correction Eq.(4)-soft and CMHC-soft, to a difference (ΔSPL) of -2dB from Eq.(4) and +5dB from CMHC-soft at 180m. Odeon overestimates hard ground attenuation and underestimates soft ground attenuation in comparison to theory and standard models.

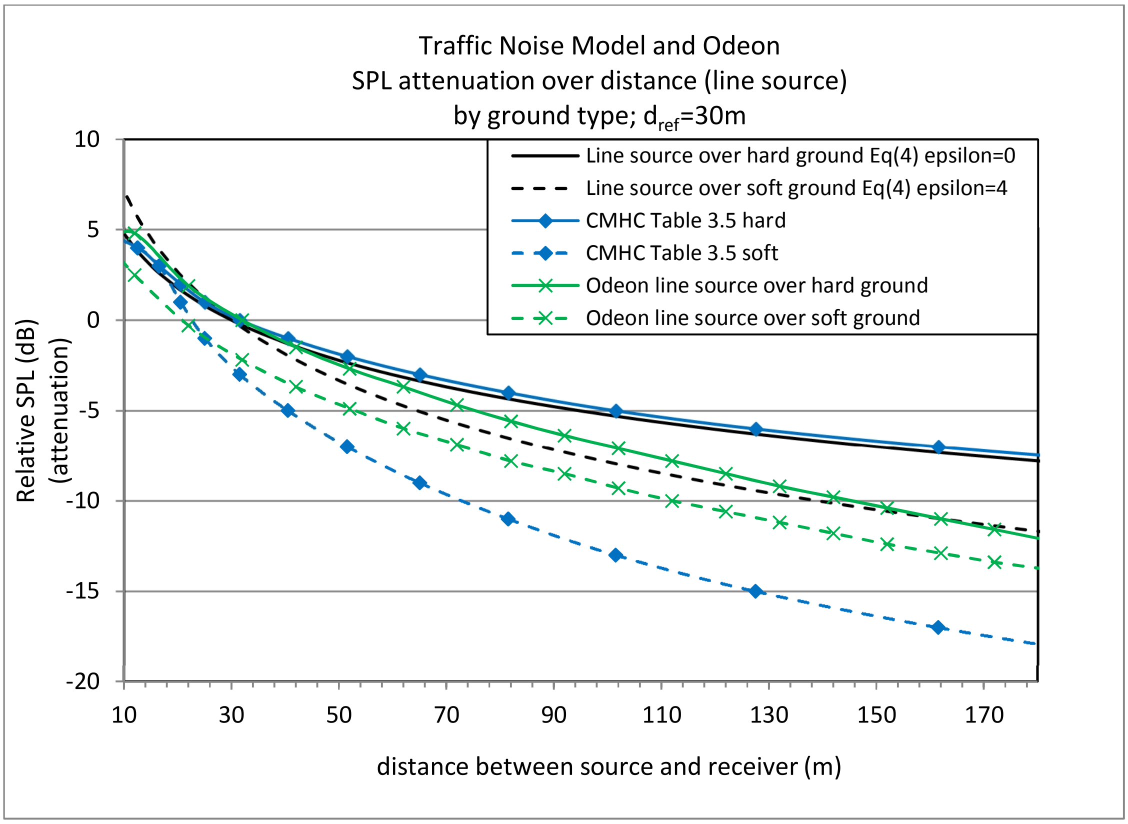


Figure 26: Comparison of TNMs for line source decay over distance with ground correction.

Table 8 below summarizes all sound propagation theories discussed in this section; most adhere to the open field model [37, p. 5].

Table 8: Summary of sound propagation theory and traffic noise model bases.

<table>
<tr><th></th><th colspan="2">Point Source</th><th colspan="2">Line Source</th></tr>
<tr><td></td><td>Equation</td><td>Decay rate</td><td>Equation</td><td>Decay rate</td></tr>
<tr><td>Theory: free field Eq.(1) & Eq.(2) [17, pp. 69,70]</td><td>$L_p = L_w + 10log\frac{1}{4\pi r^2}$
$\Delta L_R = L_S - 20\log(r)$</td><td>Δ6dB/dd</td><td>$L_p = L_w + 10log\frac{1}{2\pi rl}$
$\Delta L_R = L_S - 10\log(r)$</td><td>Δ3dB/dd</td></tr>
<tr><td>Traffic Noise Model (FHWA)

Eq.(3) & Eq.(4) [17, p. 185]</td><td>Moving point source decay with ground correction:
$\Delta L_R = 10\log(\frac{r_o}{r})^{\frac{\xi+4}{2}}$

r_o= reference distance or d_{ref}
ξ = 0 for hard site
ξ =1 for soft site</td><td>Hard:
Δ6dB/dd

Soft:
Δ7.5db/dd</td><td>Line source decay with ground correction:
$\Delta L_R = 5\log(\frac{r_o}{r})^{\frac{\xi+4}{2}}$

ξ = 0 for hard site
ξ = 2 for soft site</td><td>Hard:
Δ3dB/dd

Soft:
Δ4.5dB/dd</td></tr>
<tr><td>CMHC</td><td>N/A</td><td>N/A</td><td>N/A
Decay rate derived from trend-line of Table 3.5 values.
Reference distance 30m</td><td>Hard
Δ2.7dB/dd

Soft
Δ5.1dB/dd</td></tr>
<tr><td>Odeon</td><td>$L_p = L_w - 10log\frac{1}{4\pi r^2}$
$+raytracing$
$+\ image\ source\ meth$
$+absorption$
$+scattering$
$+static\ air\ condition$</td><td>Eq.(6)</td><td>Model as a series of point sources 5m apart to mimic a line of bumper-to-bumper traffic. Decay rate from plotted trendlines are approximately:</td><td>Hard:
Δ3.9dB/dd

Soft:
Δ4.0dB/dd</td></tr>
</table>

In theory, soft ground attenuation (Eq.(4)-soft) is greater than hard ground (Eq.(4)-hard) by 1.5dB/dd, with ΔSPL increasing and becoming more noticeable over distance, to -4dB from hard ground levels at 180m (the approximate length of one residential block). A greater discrepancy exists between methods of predicting soft ground attenuation. CMHC Table 3.5 values noticeably exceed theoretical attenuation over soft ground, and the discrepancy increases with distance to -7dB from theoretical soft ground attenuation at 180m.

CMHC includes effects of continuous sound barriers of various lengths, heights and geometries, providing calculation procedures to determine approximate attenuation. For multiple rows of long barriers with gaps in between, such as rows of detached buildings, simplified correction factors are used in combination with barrier length adjustments [14, pp. 20, 33] [15, p. 26]. The FHWA TNM has an independent barrier calculation. There is no consideration given for roof and eave shape effects on diffraction, vertical surface materials, building arrangement or layout, building size, roof heights and other factors salient in more complex urban environments.

The CMHC and FHWA models do not include meteorology effects which can be important in the outdoor propagation of traffic noise. Atmospheric absorption, wind, and refraction due to temperature gradients are complex phenomena influencing outdoor noise propagation, especially at distances over 60m [39]. If weather and wind conditions permit, stadiums and outdoor amphitheaters can be heard quite clearly many kilometers away even with absorptive grounds and attenuating hills between source and receiver. Ovenden et al.'s model show significant meteorological effects on traffic noise. Refraction by atmospheric stratification and wind shear can raise sound levels by 10-20dB at significant distances away from the traffic route (in this case a highway) and cause otherwise normally complying residential areas to violate FHWA criteria [40]. According to Ovenden et al., TNM without consideration for meteorological effects can render path-and-receiver noise control measures useless, but will not be a problem for source-controlled scenarios [ibid]. Regardless, Canadian and US standards neglect meteorological effects. In urban canyon models, meteorological effects are typically neglected, except where it is the focus of study [39].

2.1.2.1 Metric for traffic noise and sound propagation study

Traffic and steady environmental noises are often represented by LAeq, a time-averaged measure of acoustical energy in sound pressure level dBA at a specific point in space, and sometimes called the "community noise descriptor" [41]. The daily average noise level is LAeq(24), the 24 representing hours in a day. The A-weighted sound pressure level (SPL(A) or dBA) is most widely used as it is closest to the spectral sensitivity range of the human ear. CMHC and other standards use LAeq and dBA; this study uses LAeq and dBA for fair comparison.

2.1.2.2 Building effects in traffic noise modelling

ISO 9613-2, for the calculation of environmental noise propagation, takes into consideration obstacle reflections that create image sources and increase source levels [42, pp. 26-27]. However, these considerations are not found in the CMHC TNM. In CMHC, buildings are predominantly treated as obstacles that attenuate noise. This underestimates the fact that in the urban context, buildings can often be reflectors that amplify noise.

CMHC considers building reflections explicitly only in one specific procedure regarding application of the shielding correction factor. If a facade being modelled is shielded from the source by building orientation—for example on the "quiet" or "shadow" side of a building, -15dB is applied to the resulting noise level to account for attenuation by shielding. However, if this shielded facade faces another reflective building element (e.g. the wall of a neighboring building) that can reflect noises towards it despite it being in the shadow zone, then instead of -15dB, only -10dB is applied for shielding attenuation. In other words, CMHC acknowledges building reflection to contribute a +5dB magnifying effect on the noise level, although only under this specific situation [14, pp. 51-53]. CMHC does not explicitly consider building reflections anywhere else in its model. NRC briefly mentions that urban high-rises and suburban building reflections decrease barrier and ground attenuation but does not give clear instructions to address this phenomenon [15, p. 15].

J.D. Quirt suggests *adding* 3dB to the CMHC predicted sound level to account for building reflections, particularly when modelling urban and suburban environments [37, p. 3]. Whether or not +3dB is a good approximation, it is clear that users should anticipate an increase in noise level from building reflections in urban and suburban environments. Kang considers classic sound propagation models unsuitable for describing sound behavior in long spaces such as urban canyons and street channels, again indicating the need to specially address building reflections [43, p. 24].

2.1.3 Canyon effect: sound propagation between rows of buildings

Vancouver's laneways can be explored as a type of street canyon, particularly given the current development trend of increasing laneway houses and bigger garages. In comparison to regular residential streets, laneways are more prone to the canyon effect, depending on their form and dimensions. Urban streets are more often fully paved, and set between parallel and relatively close rows of tall, reflective building facades. These facades form a "street canyon" in which sound energy cannot fully dissipate by hemispherical spreading. Some percentage of sound energy remains reflecting between the building facades and the hard-paved road surface. See Figures 28 – 31 for sound energy diagrams exhibiting canyon effects. Depending on a canyon's characteristics, limited geometrical spreading and multiple reflections reduce attenuation and amplify sound relative to open terrain [44]. On a larger scale, areas with higher densities of urban canyons will experience higher levels of traffic noise, exacerbating the urban noise problem [45].

The street canyon effect is most evident when the noise source, such as heavy traffic, is inside a tall canyon, such as a busy downtown street during rush hour with large office towers closely lining both sides of the street. However, the canyon effect can also be seen in low-height streets that are narrower and when sources are outside the canyon. In fact, the sound source does not necessarily have to be inside the canyon for noise magnification [39]. “Receiver canyons,” such as smaller streets and lanes adjacent to or nearby noisy source streets, can also experience magnified noise [39].

In canyon literature, the height and width dimensional ratio is one indicator of how a street may behave [43] [46]. Laneways are immediately flanked by built structures such as garages and LWHs with shallow setbacks (minimum 0.9m or 3ft). This geometry exhibits a narrower “U” in cross section than does the front street, as the latter has sidewalk and lawn space that makes the canyon height-to-width ratio fairly small and closer to open field. To illustrate, a typical laneway may be about 4.6m (15ft) wide and 4.6m (15ft) tall (weighted average between LWH and garage heights), while a typical residential street may be approximately 30m (98ft) wide (including front yard, sidewalk and curb strip distances) and on average 8m (26ft) tall (see Figure 27). The height-to-width ratios are 1 and 0.27, respectively. In this way and others, laneways function more like urban canyons than do their residential front streets, giving the LWH a unique acoustical environment where noise can be sustained for longer and farther down the lane.

Figure 29 to 31 provide visualization of urban canyon effects.

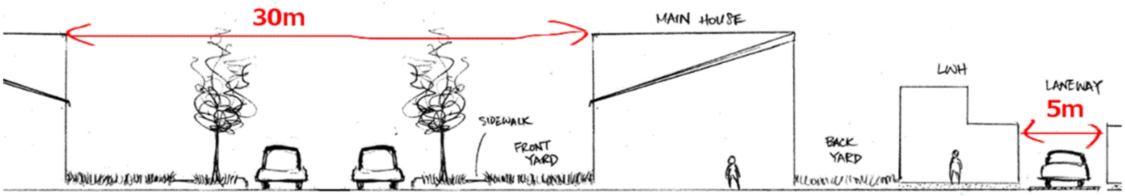


Figure 27: Block section comparing street canyon to lane canyon.
The lane canyon may function more like an "urban canyon" where sound is reflected between narrow vertical surfaces.

2.1.3.1 Canyon factors influencing sound propagation

Key characteristics affecting sound propagation between a row of buildings or within a street canyon are (1) surface material and textures, including degree of vegetation, (2) dimensions (width and height) and (3) form (open versus closed, or leaky versus continuous). In addition to these path-related factors, source geometry, which concerns the orientation of laneways in relation to streets, also influences receiver sound levels.

2.1.3.1.1 Surface

The *surface materiality* of a canyon on its three boundaries, the horizontal road surface and the two facades forming vertical boundary planes, affects sound wave interaction and propagation through the channel. Kang found canyons of the same dimensions exhibiting very different sound fields due to different surface conditions [47].

Material surfaces are rated on a scale of reflectivity [17, p. 250]. A reflectivity of 1 or 100% means all sound energy encountering a surface is reflected. A reflectivity of 0 or 0% means all sound energy encountering a surface is absorbed or transmitted. Reflectivity can be further differentiated as specular or diffuse. Diffuse reflectivity is also known as scattering. Specular reflection is “mirror-like” reflection, meaning that sound waves from a single incoming direction is reflected into a single outgoing direction with little energy loss. These sound reflections have enough energy to continue reflecting, and maintain amplitude and signal integrity for a longer time and greater distance. Specular reflections are also more likely to interfere with other signals in complex patterns of destructive or constructive interference. Diffuse reflections occur where sound wave from a single direction is reflected in a "scattered" manner into multiple outgoing directions. The original incident sound wave is scattered into many smaller vectors at many different angles; the amplitude instantly decreases, the signal dissipates and the scattered energy cannot travel very far for very long or directly disrupt other signals.

Specularly reflective materials are smooth and dense. The degree to which an incident sound wave is specularly reflected depends on the frequency wavelength. Examples of specular reflectors in the laneway are asphalt, concrete, large panels of metal and glass, flat surfaces like metal or painted wood garage doors, and some gates and fences with flat, continuous surfaces. For lower frequency sounds with longer wavelengths, even stucco walls and torch-on shingle roofs are smooth enough for specular reflections. Canyons with specularly reflective surfaces have higher amount of reflected energy and longer reverberation time which increases annoyance and interferes with speech and hearing [48].

Diffuse reflectors have uneven rough surfaces. Examples of diffuse reflectors in the laneway are vegetation (foliage, tree trunks and branches), rocks, randomly-shaped objects like fixtures and furniture, some fencing types such as the picket fence, irregular architectural surfaces, recesses and protrusions such as edge decorations, roof eaves, balconies and parapets.

Absorptivity is dictated by material elasticity, porosity and permeability. Examples of absorptive material in laneways include sand, gravel and dirt, garden soil, bark chips, discarded upholstered furniture with heavy fabric, exposed batt insulation, and thick, dense foliage. Thick overgrown lawns, layers of fallen leaves and snow are also highly absorptive. In architectural acoustics, material surfaces are generally assigned an absorption coefficient, expressed as a decimal or percentage, based on its capacity for sound absorption. Different frequency sound waves will interact differently with each type of surface material, and thus, in all noise-control scenarios, frequency bands are an important consideration.

Absorptiveness and diffusion/scattering are two major mechanisms that minimize high energy reflections in a canyon space. Van Renterghem et al. found that surface roughness has scattering-diffusing effects that reduce sound reflection energy buildup [44].

Asphalt pavement, gravel, and dirt road coverings each have a different effect on sound propagation; ground effects occurring at low grazing angle contribute to higher attenuation. Although gravel is more sound-absorptive than the typical asphalt pavement [49], in real laneways, it is observed by the author that rough gravel road covering generates unique noise by slower drive-through and non-uniform surface.

2.1.3.1.1.1 Noise Mitigation in Urban Canyons by Architectural Vegetation Systems

The degree of vegetation along laneways is considered an important surface materiality. Vegetation and porous soil are better acoustical absorbers (partially due to them containing more airspace) and diffusers than constructed surfaces like asphalt and concrete [50]. As laneways become more developed and inhabited, changes in vegetation will occur. LWHs will replace shrubs, trees[5], grass and otherwise acoustically soft grounds and vertical spaces. Live vegetation provides psychoacoustic relief, visual appeal, and more dynamic ways for sonic interaction [51] [52]. Presence of vegetation can result in more natural sounds and animal life

[5] Trees are generally protected; a permit is required to remove a tree [18].

to help make the laneway soundscape healthier [45] [53]. Though landscaping is recommended in CoV's LWH Design Guide, the constrictive space greatly limits ground-oriented planting. Meanwhile, substantial vegetation is required to achieve meaningful noise abatement [54].

Architectural vegetation systems (AVS) or architectural greenery systems (AGS) such as green walls, living fences and green roofs can be advantageous alternatives in urban residential settings to provide lush foliage and substrate that contribute to noise reduction. AVS are relatively space-efficient and pleasant to view, imparting many ecological, leisure and community benefits in comparison to conventional noise barriers and insulation. AVS may be superior noise reducers than conventional shrubs, tree-fences and ground-oriented vegetation within the lanescape due to the vertical substrate layers that can block, diffuse, and/or absorb noise.

Researchers are exploring the noise-absorption and diffusion capacity of architectural vegetation systems (AVS) in urban areas. Several HOSANNA studies sought the optimal configuration of vegetated facades along street canyons for acoustical improvement [50] [55] [56]. Connelly found through field and laboratory experiments that green roofs increase sound transmission loss and surface absorption [10]. Wong et al. by field experiments found insertion loss of green walls to be as high as 9.9dB (at 800Hz 1/3 octave band frequency) depending on thickness of substrate and angle of incident sound waves [57]. For reference, 10dB is an approximate doubling in loudness, and 800Hz is just above the midpoint of the architecturally relevant sound spectrum. The primary mechanism of attenuation in the higher frequencies is the scattering effect before transmission [ibid]. For low to middle frequencies, the absorbing effect of the substrate can account for substantial attenuation [ibid]. Wong et al. then found that vertical greenery systems (VGS) “reduce the reverberation time tremendously, especially within the frequency range of 200Hz to 1kHz [ibid].”

Experimental results for sound absorption coefficients of the VGS distribute evenly around 0.5 from the middle frequency band [57]. A 0.5 absorption coefficient means absorption of half the incident sound energy, which is significant depending on source level. Wong et al. found that vertical greenery systems an achieve acoustical attenuation (insertion loss) of up to 9.9dB in the frequency range 125-1250Hz and 8.8dB in the high frequency range 4-10 kHz [57] [58].”

Van Renterghem et al. found that green walls can achieve good sound attenuation (“insertion loss”) if placed over acoustically hard facades— fully vegetated source canyon facades achieved a maximum sound reduction of 4.4dBA in empirical experiments [50]. The greenery works by scattering noise before it can hit highly reflective and acoustically hard (non-transmitting) backing, in this case brickwork. If the backing is highly transmitting to sound or of low impedance and non-reflective, then the green wall covering cannot help much with attenuation. In other words, scattering works best in conjunction with some high-impedance material behind it to stop the sound waves from transmitting through. They also found that, for the source canyon, green walls are more effective when placed higher up on the facade because “direct sound propagation from the source to a building roof edge is an important contribution to the sound pressure levels in the receiver courtyard [50].” Placing the green wall as an absorber-diffuser strategically at the diffraction edge helps attenuate the highest amount of sound energy. In the receiver courtyard, full coverage of all walls with greenery is more efficient for sound reduction than full coverage of the source canyon walls— it is important to keep the receiver reverberation time (RT) low [ibid]. This is relevant to lanes acting as receiver canyons. Installing green walls and living fences along lanes and over LWH facades that have a high impedance surface such as fiber cement boards or stucco may help lower noise levels within the laneway habitat. The study also shows that *green roofs* between the source and receiver work best to reduce noise in the receiving courtyard space, depending on roof edge geometry and installation configurations [ibid]. The most effective combinations are green wall or green roof combined with roof edge screen [ibid]. Courtyard spaces are relevant as the outdoor living spaces around LWHs.

In a modelling study done for HOSANNA by Guillaume et al. using the "transmission line matrix method" involving only a single canyon, where source and receiver are within the same canyon, the researchers modelled all combinations of green roof and green facade arranged at different heights and positions in an urban canyon. They found good evidence of attenuation by the vegetated facades and roofs, more noticeably for the higher floors.

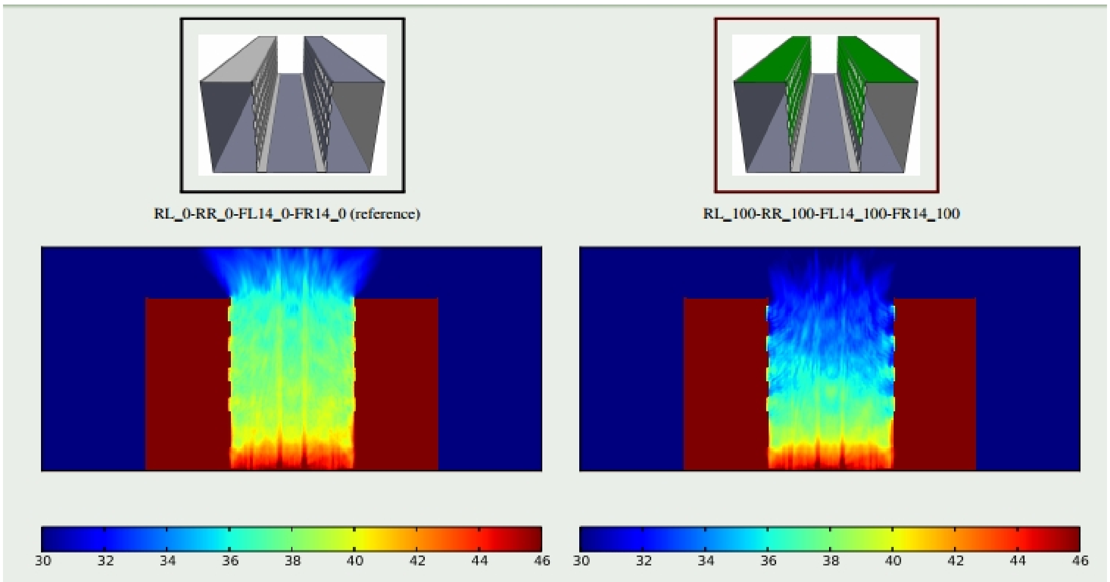


Figure 28: Green walls and green roofs effects on canyon sound levels (modelled). Comparison of modelled Leq at 100Hz, for a fully reflective canyon (left) versus a fully vegetated canyon (right). Sound levels are higher in the reference canyon at heights above the ground level [55].

In this model, researchers noticed that there are strategic positions on the facade and roof where vegetated systems can make a meaningful difference. The green facades work better on higher floors closer to the diffraction edges, achieving more SPL attenuation, which agrees with the Van Renterghem et al. field study [55].

HOSANNA published green wall test results by CSTB (Scientific and Technical Center for Building, France) of 18-32dB of absorption and insulation [56]. These results from experiments and models show that green walls are promising acoustical devices for noise reduction, provided that they are installed in the strategic configurations found to be most effective in research.

Regardless of actual noise reduction performance, the public prefers green walls over conventional non-living berms, concrete or steel noise barriers with proven performance [51]. In a Hong Kong survey, people voted consistently in favor of green wall installations over concrete berms as noise barriers for public roadways, to the extent of overlooking the higher sound-reduction efficiency of conventional, less-visually appealing systems [ibid].

The details and resources necessary for exploring acoustical benefits of real green walls and living fences in laneways exceed the scope of this study. However, the effect of general vegetation in laneways as a canyon surface materiality is to be observed in empirical measurements and models of this study.

2.1.3.1.2 Dimensions

Sound propagation in the canyon can be a function of its *dimensions*, particularly the separation distance (canyon width) and height of flanking buildings. In some studies the length is assumed to be infinite (or much longer than the width and height), while other studies treat length as an important factor. In Vancouver, most RS zone laneways are quite narrow, roughly 3.6-5.2m (12-

17’) in width which is just enough room for one line of traffic. The practical lengths for Vancouver laneways examined in this study range from 80m to 190m.

Researchers agree through independent work that width and height relationship of street canyons affect sound levels. Narrower canyon width (facade separation across a street) and taller canyon height (building height) result in higher sound energy by sustaining higher-order reflections within the street canyon [44] [45] [46] [59] [60]. This can lead to higher overall noise levels, longer reverberation time, communication interference and signal degradation for humans and animals, and the phenomena of source-dependent flutter echoes [45] [59] [61]. In particular, Iu and Li find that where facade separation is less than 4m, 8^{th}-and-higher order reflected rays make up a significant portion of the energy in the sound field [59]. The proportion of high-order reflections becomes insignificant when the separation is greater than 10m [59]. Although their model of infinite height and perfectly reflective and continuous boundaries is different from real laneways, the width examined is highly relevant to laneways, suggesting that significantly more late reflections will remain within a 4 – 6m wide laneway than in a 20 – 30m wide residential street.

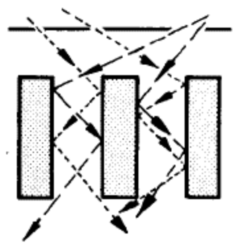


Figure 29: Urban canyon plan view.
Urban canyons perpendicular to a line source creates sound reflections and energy buildup. [14]

Figure 30: Urban canyon section view.
Wave fronts bouncing in a street canyon from a short acoustic pulse at center of the canyon [48].

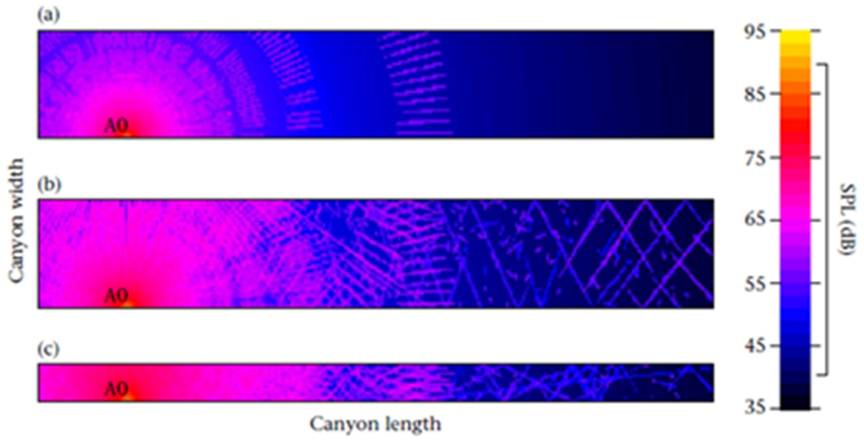


Figure 31: Urban canyon energy distribution by canyon width.
2000Hz wave reflection visualization showing different sound fields for (a) an open field, (b) a large canyon, and (c) a small canyon. [45]

Pieter Thomas and Van Renterghem et al., using a width-to-height ratio instead of assuming infinite height, found that streets with larger width-to-height ratios—being wider or flatter—have lower reflected sound energy [44]. Sound pressure levels (SPL) are inversely proportional to the street width; increasing the width or lowering average height will reduce SPL by allowing sound energy to escape into the atmosphere [44]. An increase in average height increases SPL, especially for traffic noise from highways and farther streets [ibid]. Heutschi uses a different parameter, the ratio “facade height/gorge width” (h_f/w) [46]. In combination with other parameters, the higher the ratio h_f/w, the larger the “building correction” (BC), which is a decibel factor to add to the traffic noise level inside the canyon [46]. In other words, taller facades along a street contribute to higher traffic noise.

Vancouver residential laneways are much lower in height than most canyons examined in literature. However, it follows that a laneway lined with 1.5-storey LWHs will theoretically contain more reflections than a one lined with small garages.

2.1.3.1.3 Form

In addition to surface, width and height, the form of a canyon also affects sound propagation. It can be “open” or “closed.” “Open” means that there are significant open spaces and gaps along the canyon, such as open yards and uncovered parking spaces, or wide separation between neighboring buildings. Depending on the degree of openness, canyons with gaps and openings are modelled as “leaky” waveguides. These better represent real laneways. With less buildings present, the sound field behaves more like the open field and less like a canyon. “Closed” indicates that a canyon is fully built-up, continuously flanked by building facades, and with negligible vertical gaps for sound energy to dissipate through.

2.1.3.1.4 Source Geometry

Urban streets are among the major noise sources for laneways. Thus, the siting of laneway relative to street affects resulting sound levels in the laneway. Kang investigated the effects of intersection geometry on sound levels inside the street canyon and observed major factors to be dimensionality (canyon width and height) and the principles of acoustical shielding and directivity [61]. Many researchers have investigated multi-street sound propagation in complex urban geometries [39] [61] [62] [63] [64] [65]. However, the results are not applicable to the perpendicular street-to-laneway block geometry typical in Vancouver RS zones. Vancouver RS zone laneways have unique surfaces, dimensions, forms and street-to-laneway geometry different from urban canyons in literature.

2.1.3.2 Methods for canyon research in literature

The challenge to develop appropriate models for acoustical canyons resulted in a significant proportion of literature being dedicated to methodology. Unique sets of tools and research methodologies have been developed for different types of acoustical canyons.

Basic studies examine only one canyon with the simplest geometry (narrow long horizontal path bound by two parallel vertical surfaces) and homogeneous surface characteristic. Even the simplest case invokes complex mathematics and a variety of modelling methods [46] [59] [60]. More complex cases involve gaps between buildings (leaks and openings in the vertical surfaces of the waveguide), propagation between multiple streets, varying surface conditions, and edge effects affecting diffraction over the building tops [60] [62]. Edge effect-influencing factors include building heights, roof shapes, and materiality at strategic positions on a building facade [63] [66] [67]. Study methods include ray-tracing, variations on image-source modelling of reflection energy, radiosity models, reverberation-based models, physical scale models, and in-situ field measurements [43] [56] [68] [69] [70]. Quantifiers used to describe or assess canyon sound fields include reflection ratio, reverberation, and SPL attenuation over distance [45] [43].

There are advantages and disadvantages to using each method. The common disadvantage is mathematical and physical complexity unsuitable for lay-application.

2.2 Methods

The three methods used in this chapter are field measurement, CMHC modelling, and software modelling using Odeon [71]. Results from different methods are compared and the modelling tools are tested for validity in predicting the sound field in Vancouver residential laneways.

The common metric for comparison and analysis is *sound level attenuation over distance* (ΔSPL), the difference between source and receiver level at a distance *x* from a reference point close to the source. A single-number *decay rate* ("fall off rate"), or *SPL attenuation per doubling of distance* (ΔdB/dd) is calculated from ΔSPL data trend-lines to approximate the behavior of each laneway. This will enable comparison to theoretical propagation falloff rates shown in Table 8.

Real traffic noise source types and levels vary between the case studies. It is necessary to have controlled sound sources to properly compare the different case studies. Two types of sound sources are used: (1) the point source as a model for unique sound events and (2) the line source as a model for road traffic noise, specifically the perpendicular line source to which a typical laneway is directly connected and exposed to. Receiver noise levels through the center of the laneway or at the lane-side facade down a laneway will be compared and analyzed.

In addition to the four case study laneways, an ideal waveguide and an ideal street block are also modelled using the computer software, Odeon, to explore effects of surface materiality and dimensions under controlled conditions. In the following section, details are provided for each investigative method.

2.2.1 Field measurement

Empirical data are collected by field measurements of point source sound propagation. ISO 9613-2:1996 and ANSI S12.18-1994 (R2009) are used as reference guides for outdoor field measurement procedures [42] [72]. Receiver points were set up every 10 meters down the center of a laneway. Close to each end of the laneway in the approximate near field of the source locations, receiver points were set up at 1m and 5m apart to capture any erratic near field behavior. A Larson Davis real-time analyzer (RTA Model 831) with a 13mm omnidirectional microphone is the measurement instrument, moved progressively through the laneway to capture signal level at each receiver point. Calibration of the measurement instrument was performed before the first measurement and after the last measurement at each laneway tested. Calibration of the microphone was done using a 1000Hz sine wave at 114dB. The receiver height was 1.57m, though ground surface conditions and gradients may contribute to slight variations. Each measurement duration was at least 15s and at most 30s, depending on field conditions. The test signal was 88 – 113dB(A) of pink noise emitted from a JBL EON10 G2 directional stage speaker raised to a height of 48 – 65cm, located at one end of the laneway and pointed towards the other end of the laneway. The signal had to be 10dB above ambient level at the furthest receiver point (up to 190m away from source) to eliminate the effect of most environmental disturbances. Each laneway was measured twice, once in each direction.

Due to equipment sensitivity and a need for reasonably controlled meteorology, measurements were performed on non-raining days with dry ground surface in the months of September and October 2013. Wind speeds were less than 5m/s; air temperatures were 20-25°C for all laneways except W34th tests at around 13°C; RH was 50 – 60% for all laneways except W34th at 72%.

Given the complexities existing in field conditions, including effects of surrounding buildings, landscape, meteorology, ambient levels, and uncontrollable surrounding activities, field measurements are a product of synergy by many variables. Control studies to isolate effects of discrete variables are more practically done through modelling.

Figure 32: Photographs of field tests at E. Hastings (left) and Charles (right) laneways.

There is no field data for line source sound propagation. To measure line source sound propagation in a Vancouver laneway, a single dominant, consistent line of traffic with continuously high sound level (above 80dB) is required. This is because the signal level needs to be dominant over all other sources and at least 10dB higher than ambient noise level within a 180m range (or the length of laneway) from the source. The source requirement is beyond resource and scope limits for this study. Line source propagation is explored through modelling by using CMHC and Odeon.

2.2.2 The CMHC traffic noise model

In Metro Vancouver, the CMHC TNM is the standard tool used for predicting sound levels at any residential site. CMHC is based on line source propagation over unobstructed open field combined with other important factors. Source level is determined from traffic volume, posted speeds, flow pattern and intersections, road gradient, and % heavy vehicles. Average daily traffic volumes at each source street are estimated using City of Vancouver's Vanmap application [73]. Gradients are assumed zero, and % heavy vehicles estimated from obse4rvation. Other factors calculated in CMHC are:

- distance between source and receiver
- source and receiver heights to determine magnitude of ground effects
- ground effects (hard vs soft grounds)
- barriers and obstacles (type, continuity, height, width, length and asymmetry)
- shielding effects (facade orientation in relation to whole building and sound direction)

With the right information, CMHC TNM Part 3 predicts traffic noise levels at any residential facade [14]. The lane side of each lot down a lane, from corner to midblock (except Charles which is a short block and modelled for the full length), are modelled consecutively to predict sound pressure level every 10-15m, depending on lot size.

In CMHC, any number of roads may be included as a source so long as traffic data is available for source noise level estimation. The laneway is not included due to insufficient traffic volume data. Sources modelled in CMHC are the four roads bounding a case study residential block, and any additional high-traffic arterials in the vicinity that contribute to noises at the facades.

Noise traffic data is obtained from Vanmap [73]. For streets without traffic volume data, data for the nearest and most similar street is used. For traffic volumes below 1000, the 45km/hr level 45LAeq is used. There is no percentage heavy vehicles data available and this value is estimated by observation during measurement period. Percentage of heavy vehicles includes public transit (e.g. buses) that make frequent stops. Locations close to a bus stop will see increased noise due to activities similar to those at intersections; however, CMHC does not include the effects of being near transit nodes such as bus stops. For detailed CMHC TNM procedures please see the original publication, "Road and Rail Noise: Effects on Housing." For more information on detailed application of the CMHC TNM in this thesis and for LWH, please see Appendix 5 and 6.

2.2.3 Modelling by Odeon

Outdoor acoustic modelling software *CadnaA* and *SoundPLAN* are generally used for modelling much larger land areas and excessive for the application of this study. Odeon is a room acoustics software that uses a hybrid reflection method which combines the image-source method, ray-tracing, and ray-radiosity [71] [74]. It has few precedents for use in outdoor scenarios. The company is exploring environmental noise simulations and has published work comparing traffic noise model results on a city and highways scale with CadnaA [75]. Odeon is selected because it is more appropriate for the scale of laneways. This thesis project tests Odeon's capabilities for outdoor traffic noise modelling and evaluates its accuracy in predicting sound levels in RS zone laneways.

To model in Odeon, 3D architectural models of each laneway case study residential block are created according to real dimensions in Sketchup, then imported to Odeon for acoustical modelling. Each laneway is modelled for point source and line source propagation. Point sources are placed at either end of a laneway; line sources are at one end and perpendicular to the laneway. Receivers are placed through the center of a laneway at 10m intervals. The line sources are modelled as a linear series of point sources [71]. Points in the line source are set to 5m apart to approximate the space occupied by one car in a line of traffic. See Figure 6, Figure 10, Figure 14 and Figure 18 in Chapter 1 for Odeon model view of the case study laneways.

A 100% absorptive box is placed around each block model to represent the sky or atmosphere thereby simulating an outdoor environment. Aside from static air conditions, no meteorological effects may be modelled in Odeon and is beyond scope. Room air conditions were disabled in this outdoor application. Transmission through partition is beyond scope. Surfaces are simplified, have no internal layers, and are assigned absorptivity and scattering coefficients to best reflect reality within computing capacity. Surface absorptivity coefficients are frequency dependent and vary from 63Hz to 8000Hz octave bands. Scattering coefficients are assigned to simplified model surfaces to represent the roughness of outdoor surfaces and building irregularities [71, pp. 6-78]. The scattering coefficient input at 707Hz is expanded by Odeon into “interpolated or extrapolated values” for the entire 63Hz – 8000Hz octave band frequency spectrum [ibid]. Outdoor material surface absorptions and scattering coefficients are assigned by literature and closest approximation [49] [76]. Odeon’s computing resource requirements are considerable and can be challenging to troubleshoot.

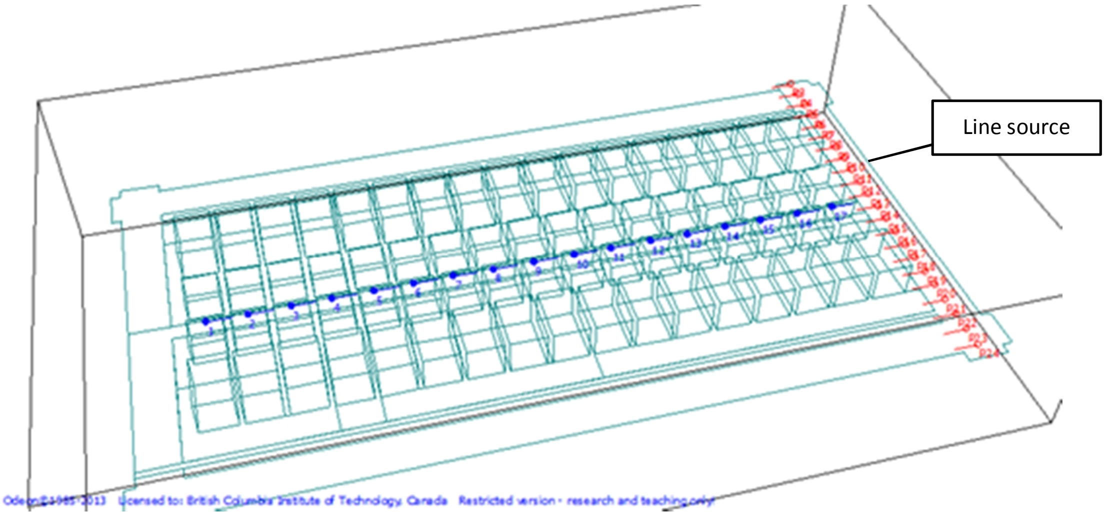


Figure 33: Standard block model in Odeon.
Receivers are placed along the center of the laneway and the line source is perpendicular to the laneway at one end.

In addition to the case studies, waveguides are modelled in Odeon. Waveguides are straight, homogeneous and continuous U-section channels with dimensions and absorption coefficients relevant to the study of Vancouver laneways.

2.3 Results

The metrics used for analyzing findings are LAeq, SPL attenuation over distance (also denoted ΔSPL/m), and the decay rate (denoted ΔdB/dd or ΔSPL/dd).

2.3.1 Field results for point source

2.3.1.1 Field results

Figure 34 shows decay patterns of the four case study laneways as measured in the field. Point source sound level attenuation over distance increases in magnitude with increasing degree of acoustical absorptivity. Field results reflect that sound level drop over distance (ΔSPL) is least through Charles, a 90% reflective laneway, and greatest through W34th, a 35% reflective laneway. All laneways decay less than Eq.(3) (hard open field) until around 90 – 100m where the absorptive laneway W34th approaches and exceeds hard open field decay, then moves towards soft open field decay. William approaches open field ΔSPL after 130m and exceeds it beyond 135m. In E. Hastings, which has taller buildings on one side and residential garages and carports, acoustic energy remains well above -30dB and does not attenuate much through to the end at 170m. All laneways attenuate notably less than open field phenomenon within 100m, which agrees with the idea that vertical buildings and other objects through the laneways keep the acoustic energy reflecting within the sound field, thereby resulting in a higher overall SPL level in laneways.

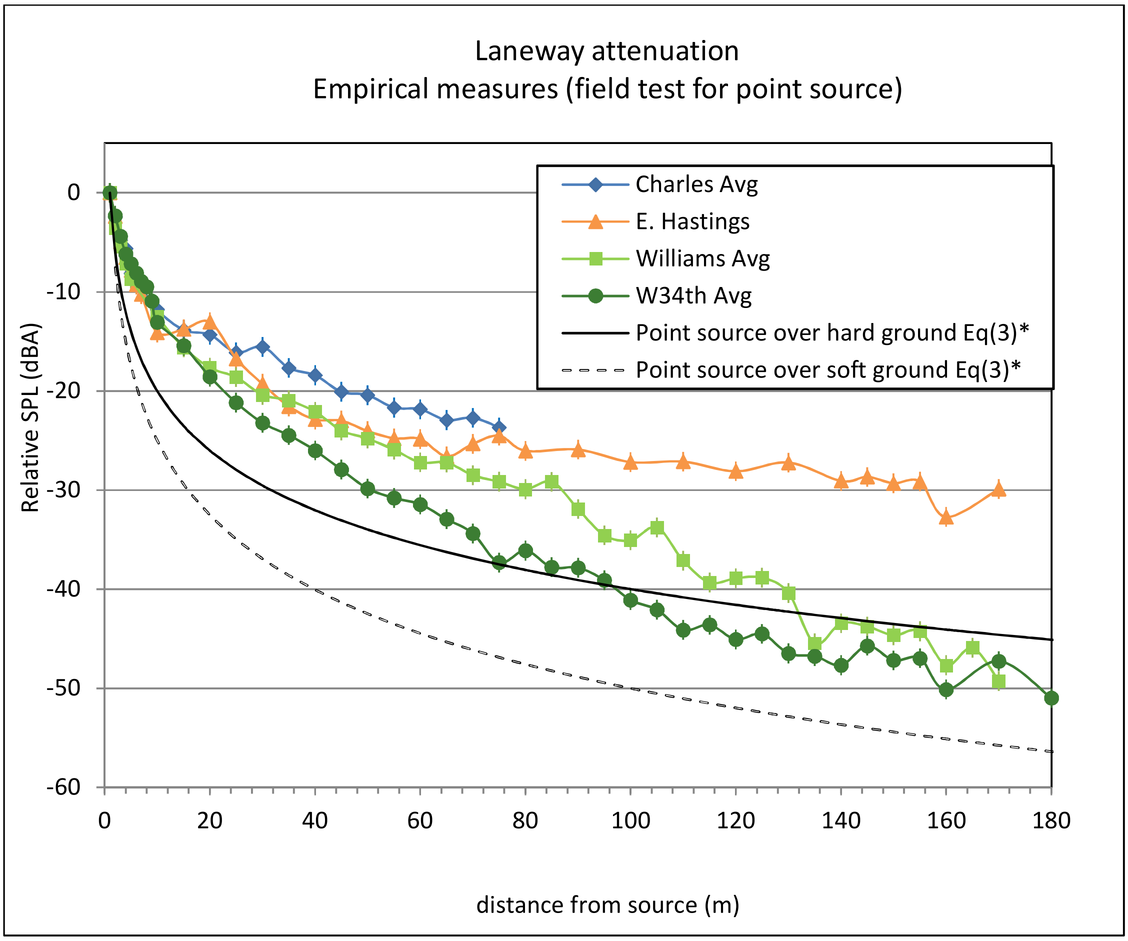


Figure 34: Field results of point source SPL attenuation.
***Eq.(3) curves are calibrated to a reference distance of 1m to match the reference distance of 1m for empirical measurements.**

Decay trends are similar for tests in either direction, except for E. Hastings where half of the data was invalid for the westward direction and results represent only one direction (eastward). The valid half of westward E. Hastings data agreed with the eastward data.

Assuming the same point source level from one end of each laneway, at 60m down the lane, Charles is 14dB higher in SPL than a hard open field, E. Hastings is 11dB higher, William is 9dB higher and W34th is 5dB higher. 60m is about five to seven lots down the block from the street corner depending on lot size of a block.

Table 9: Comparison of SPL drop at 60m and 160 from source (ref. point) for all case studies.

SPL attenuation (dBA, ±1)	60m	160m	**SPL relative to hard open field**	
Open field (hard ground)	-36	-44	Difference at 60m	Difference at 160m
Open field (soft ground)	-45	-55		
Charles	-22	N/A	14	N/A
E. Hastings	-25	-33	11	11
William	-27	-48	9	-4
W34th	-31	-50	5	-5

Based on Heutschi's method for determining building correctors for sound levels through laneways, SPL in Charles lane should be 1 – 5dB higher than that predicted by standard point source propagation theory, E. Hastings should be 1 – 5.5dB higher, and William and W34th should be 1 – 4.7dB higher.

According to results in Table 9, the CMHC +5dB and Heutschi +4.7 – 5.5dB adjusters for building reflection are severely inadequate to predict SPL in laneways like Charles and E. Hastings, and William within 90m, sufficient for cases like W34th within 60m, and not applicable for William beyond 135m and W34th beyond 100m.

When comparing the laneways to one another, the difference in sound level drop between Charles Lane (most reflective) and W34th Lane (most absorbent) is about 9dB at 60m. This means Charles Lane is almost twice as loud as W34th Lane (every 10dB translates to a doubling in perceived loudness) at about the 6th house down the block. For houses closer to the end of the block, approximately 160m away from the street noise, there is a 17dB difference in sound level between E. Hastings and W34th, with E. Hastings being close to four times louder than W34th.

2.3.2 Model results for point source (Odeon)

Prior to modelling the case studies, a series of waveguide experiments were used to validate Odeon for this project, primarily to explore Odeon's capacity in calculating height and absorptivity variance.

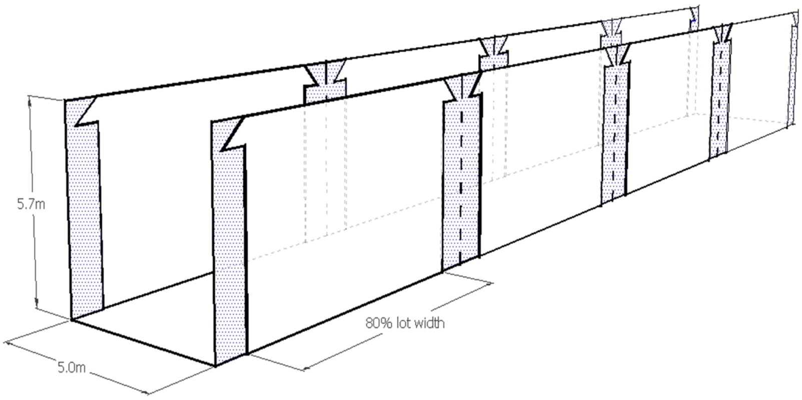
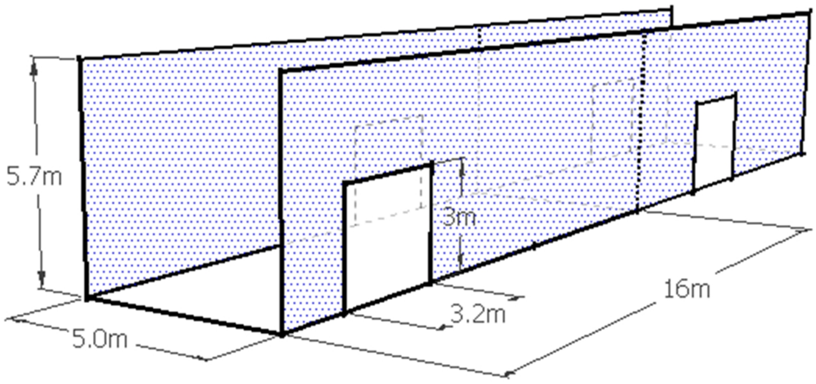
2.3.2.1 Waveguide: absorptivity and height comparison

The waveguide is a straight U-section channel bound by three continuous surfaces through which sound propagates from a point source at one end towards the other. It is the archetypal form of urban street canyons. Receivers are placed at 10m intervals along the centerline.

In one waveguide experiment, the variables are absorptivity of the vertical (walls) and horizontal (road surface) boundaries. The waveguide models are assigned a constant height of 5.7m, which is the maximum effective height (maximum allowable roof peak height is 6.1m) calculated from RS zone laneway building dimension specifications from Vancouver Zoning and Development By-law RS District Schedules [77]. The horizontal (road) surface is assigned a constant width of 5m. Percentage of vertical coverage by buildings along the laneway, geometry such as actual building height, building width, and amount of open space between buildings, are evaluated in terms of *absorptivity*.

Two extreme cases are compared. One is where every lot is built to the maximum allowable dimensions at the rear property line, which translates to the laneway being 80% reflective, assuming building materials are all reflective. The other is a laneway that has only very small garages set far apart from each other, which translates to it being 10% reflective or 90% absorptive. Table 10 below depicts the attributes of the two models.

Table 10: Odeon waveguide models by surface absorption variation

Laneway form and surface materiality translated to waveguide surface absorptivity		
Built-up or closed laneway approximation	Laneway geometry	Model surface
	Vertical building coverage: 100% of 5.7m Building width: 80% of lot width (10m lots) E.g.: 1.5 storey LWH on 10m wide lots.	Vertical surface absorption: α=20% Ground condition: α=0.01 (smooth paved asphalt) Scattering =0
Open laneway approximation	Laneway geometry	Model surface
 **Note**: Model surface description is based on RS zone lane side building specifications. Figures are not to scale.	Vertical building coverage: 53% of 5.7m Building width: 20% of lot width (16m lots) E.g. minimal buildings (small older single-garages) on 16m wide lots.	Vertical surface absorption: α=90% Ground condition: α=0.3 (broken asphalt and gravel [49]) Scattering =0.3

In Figure 35, Odeon results agree with expected trend: the less absorptive (α=0.2) waveguide demonstrates less sound attenuation than the more absorptive (α=0.9) waveguide; the two curves are at least 2.5dB apart and at most 6.5dB. However, the magnitude of differences between the two extreme cases for laneway buildup appear lower than expected.

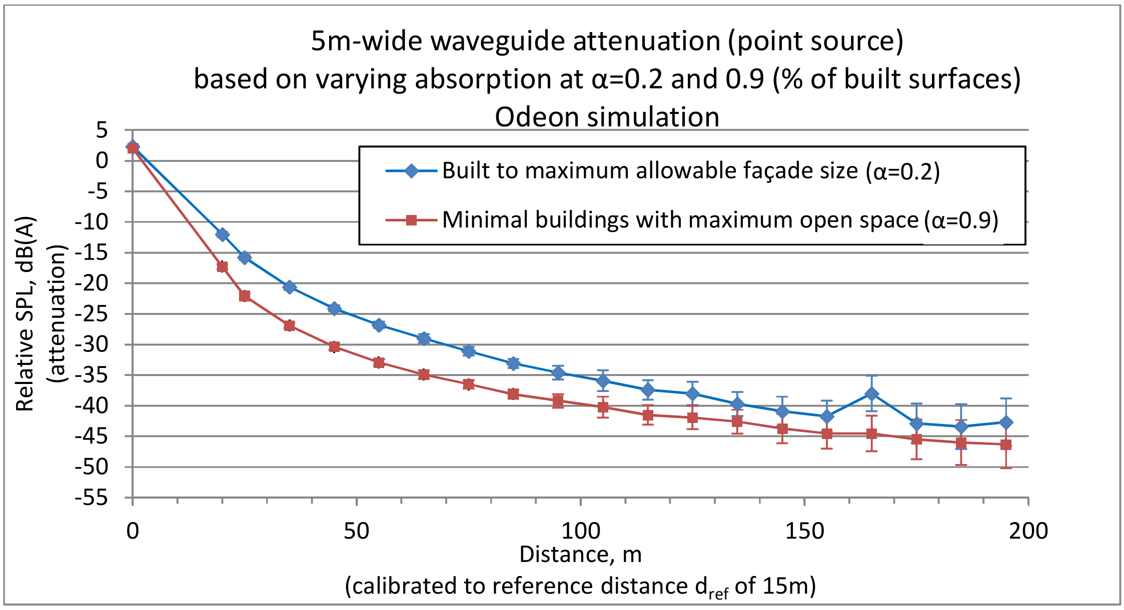


Figure 35: Odeon waveguide point source decay results for varying surface absorption coefficients

In the next waveguide experiment, the variable is height, set to 3m, 5m, and 10m, roughly representing one storey, 1.5-storey and three-storeys building height which would be applicable to Vancouver residential laneways. The width is set to 6m, an average for all case study laneways, and the length is 180m to approximate the typical residential block length in Vancouver. All surfaces have 100% reflectivity and default scattering at 0.05.

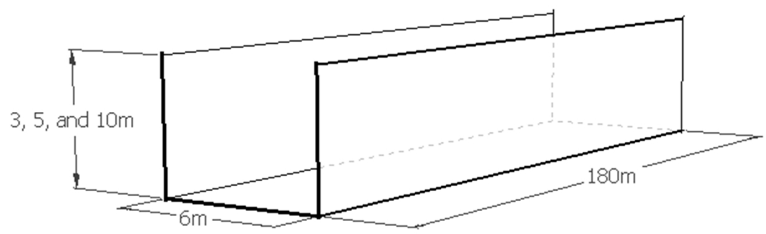


Figure 36: Odeon waveguide with height variation
This model examines effects of height variation based on heights of Vancouver's residential zone laneways. Figure is not to scale.

The taller the waveguide walls, the less attenuation or higher the sound energy through the space. The difference is greatest between the 3m-tall and the 5m-tall waveguides, with as much as 10dB difference in relative SPL. Less difference is noted between the 5m-tall and the 10m-tall waveguides, with a maximum difference of 3dB in SPL.

It should be noted that there is lower attenuation within the 100m range; SPL attenuation increases at farther distances beyond 100m, exhibiting a higher decay rate.

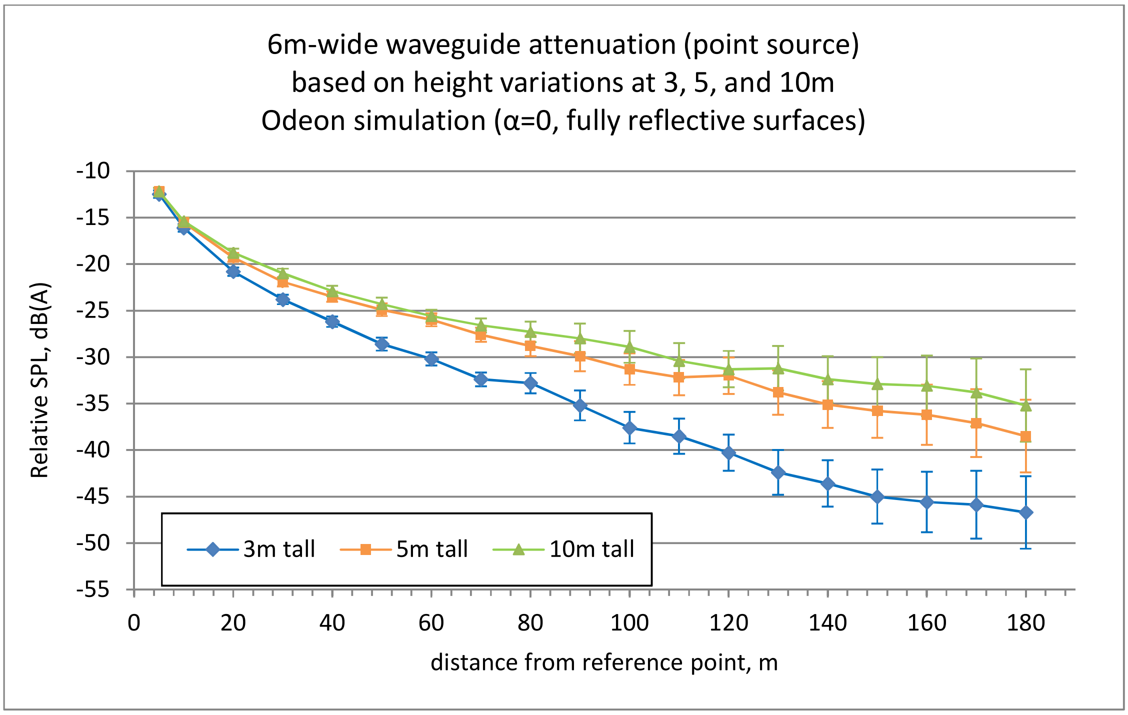


Figure 37: Odeon waveguide point source decay results for height variations

By comparing the two sets of exercises in Figure 36 and Figure 37, the resulting difference by modelling actual geometry is more significant than the resulting difference by adjusting the surface absorption coefficients alone.

In all waveguides, errors are attributed to distance over 100m, air absorption and scattering coefficient allotment (see "Errors and sensitivity analysis" section at the end of this chapter). The farther the distance, the larger the uncertainty. Without air or scattering effects, decay values would be lower and behave closer to the canyons in literature.

2.3.2.2 Case studies: Odeon vs. empirical data

Images of the case study laneway Odeon models are found in Chapter 1: Figure 6, Figure 10, Figure 14 and Figure 18, with more detailed geometry and surface materiality assignments. The field results are compared to Odeon model results for each case study laneway and presented in Figure 38 to Figure 41.

Each laneway is compared to examine the difference between empirical and modelled data. Odeon data is calibrated to a reference distance of 15m per FHWA standard practice, to account for unpredictable behavior in the acoustical nearfield. 15m conveniently aligns with the empirical graphs and is approximately the lane side width of one lot to one and a half lots.

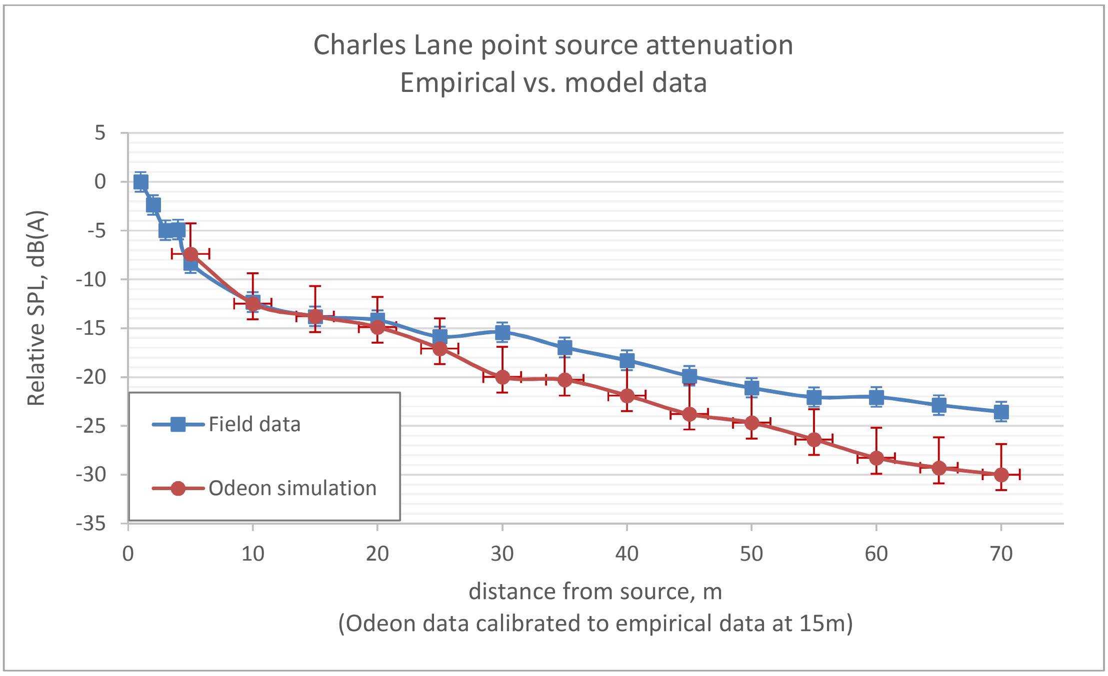


Figure 38: Charles lane point source attenuation; empirical versus model data

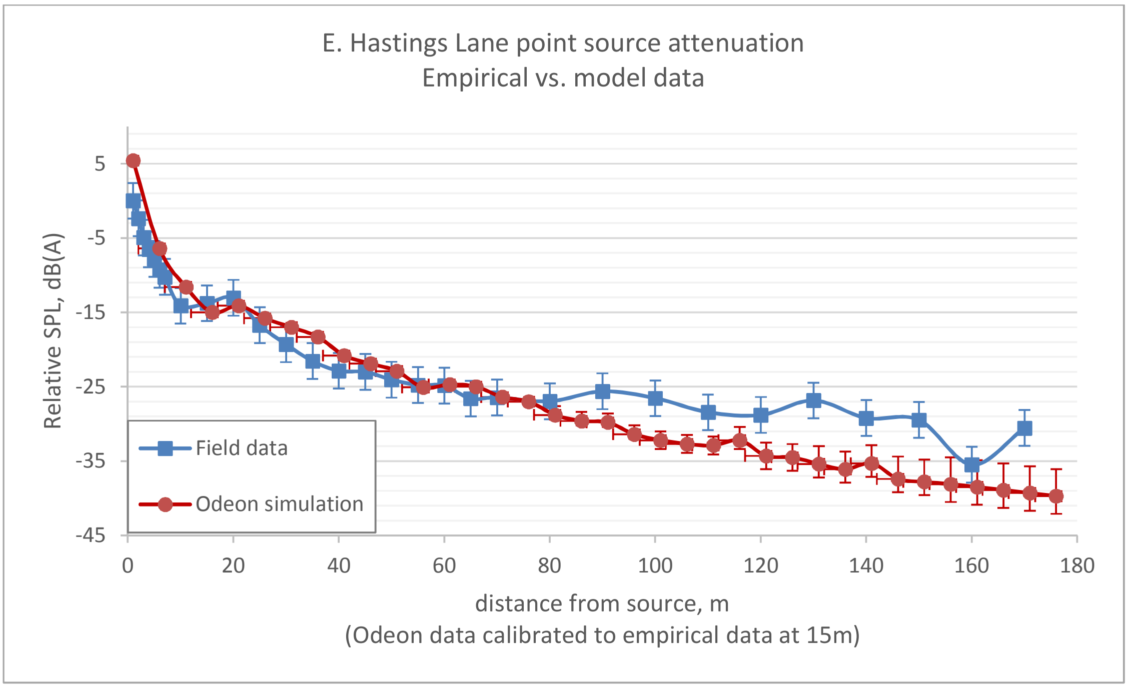


Figure 39: E. Hastings lane point source attenuation; empirical versus model data

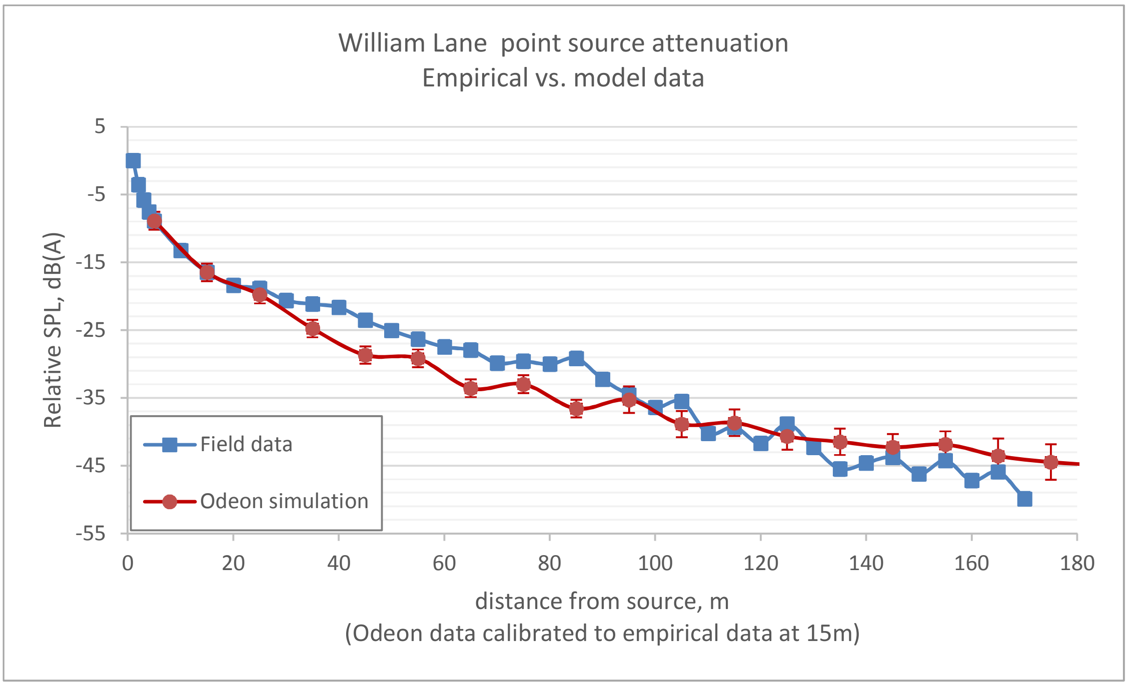


Figure 40: William lane point source attenuation; empirical versus model data

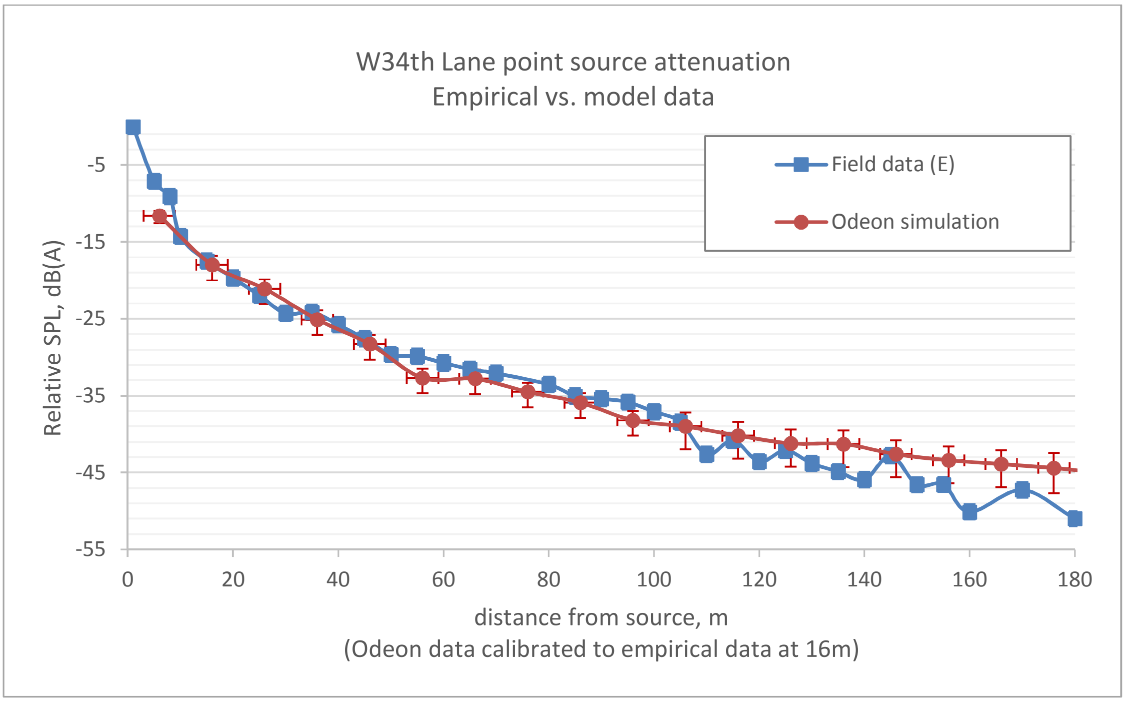


Figure 41: W34th lane point source attenuation; empirical versus model data

When properly calibrated for reference distance, Odeon results reasonably reflect point source sound propagation trends through the case study laneways, with some deviation in magnitude under very reflective conditions, very absorptive conditions, and at long distances from the source. In the reflective Charles and E. Hastings laneways, Odeon progressively overestimates attenuation, or underestimates SPL levels, beyond 25m and 80m, respectively. In Charles lane at the 70m mark, Odeon underrates possible noise exposure by 6.5dB. In William lane near the source, before the 85m mark, Odeon underrates possible noise exposure by as much as 7dB. Odeon is fair in its prediction of sound behavior in the two more absorptive laneways, though beyond 130m, underestimates attenuation and overestimates SPL levels. In W34th this is possibly due to heavy foliage being difficult to model accurately [66].

Figure 42 below displays point source attenuation by distance results from Odeon for the four case study laneways. It is clear that the difference between Charles (hardest) and W34th (softest) is far less dramatic than what is shown by field measurements in Figure 34.

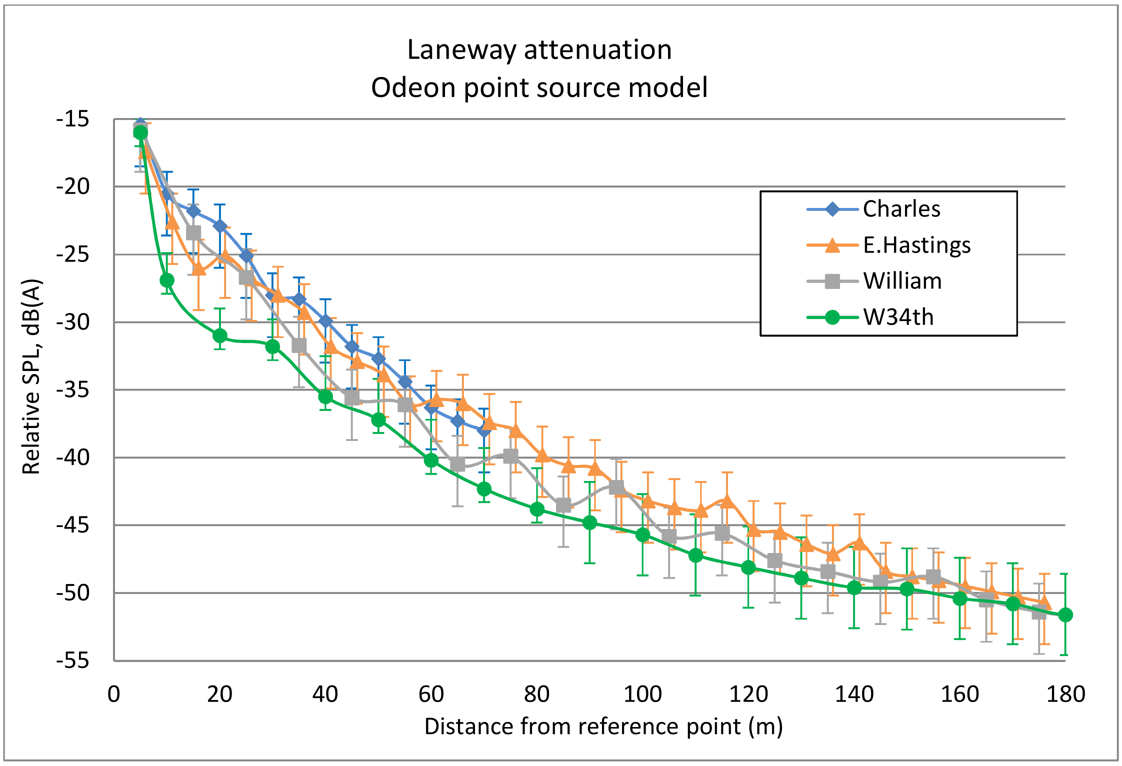


Figure 42: All laneways, point source model results by Odeon

2.3.2.3 Standard block model

To estimate the effect of installing absorptive and diffusive material such as AVS (architectural vegetation systems including living walls, green facades and green roofs) on laneway building surfaces, a standard block model is tested in Odeon. Vegetated systems are modelled by using absorption and scattering coefficients found in literature for thick vegetation, which is more conservative than the actual absorption achievable with green walls [57] [76] [78] [79]. The configurations are illustrated in the figures below. First, a fully reflective block (all hard built surfaces except for lawn and curb grass) is modelled (Figure 44), then all the lane side facades are fully vegetated (Figure 45) and finally the lane side facade is left reflective to mimic garage and access doors, but the remaining LWH facades, including the rooftop, are fully vegetated (Figure 46).

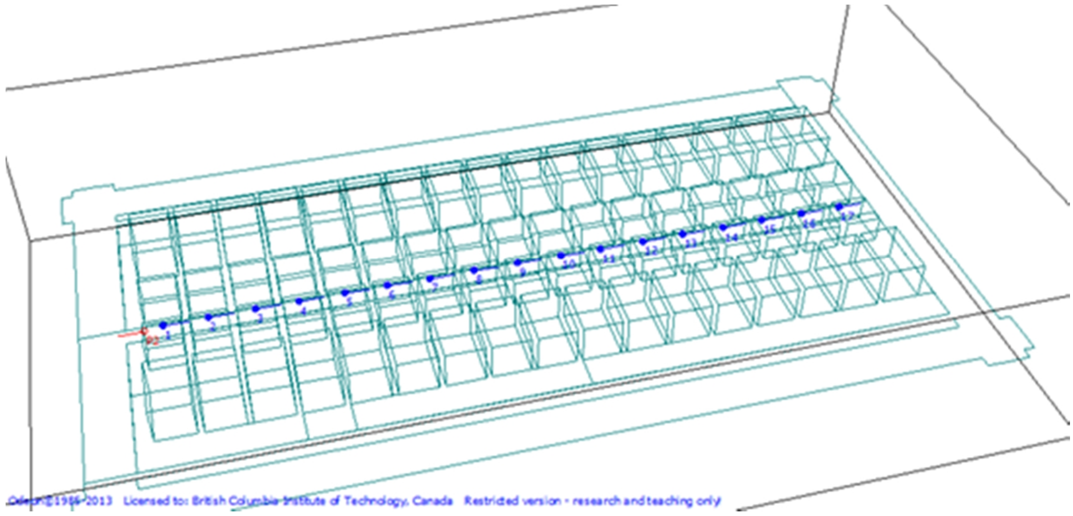


Figure 43: Standard block model in Odeon.
Receiver points in blue dots, point source in small baton marker on left.

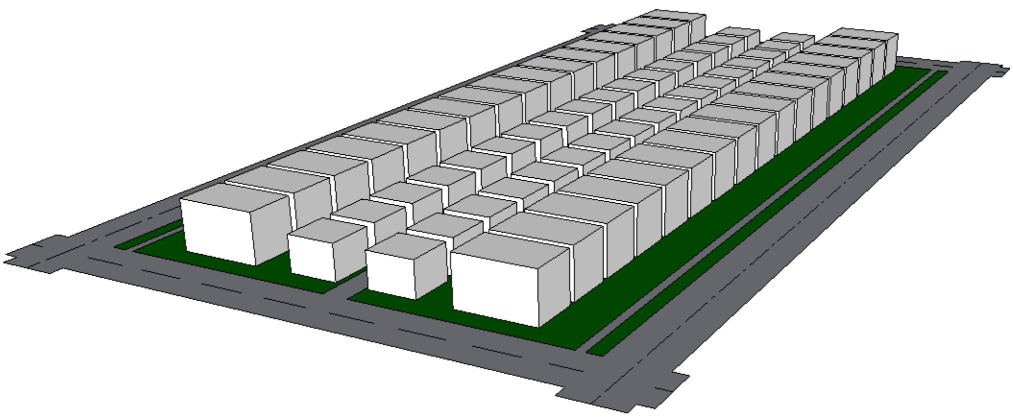


Figure 44: Standard block model, fully reflective.

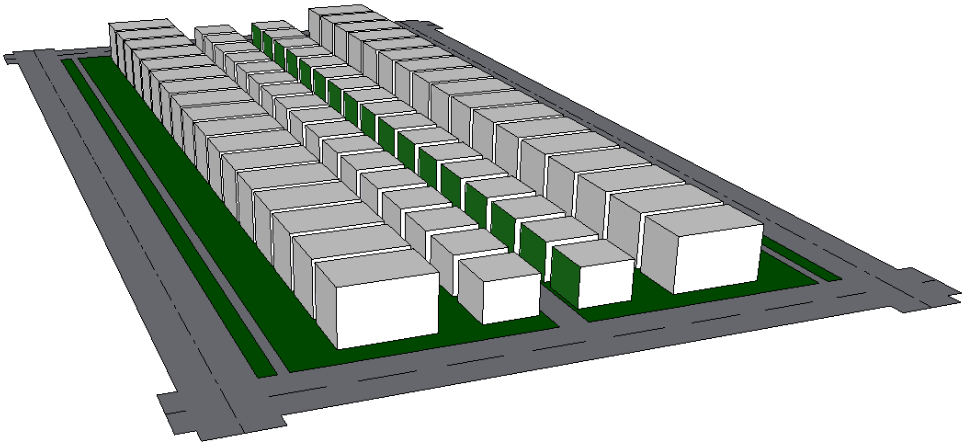


Figure 45: Standard block model, soft lane side facade.

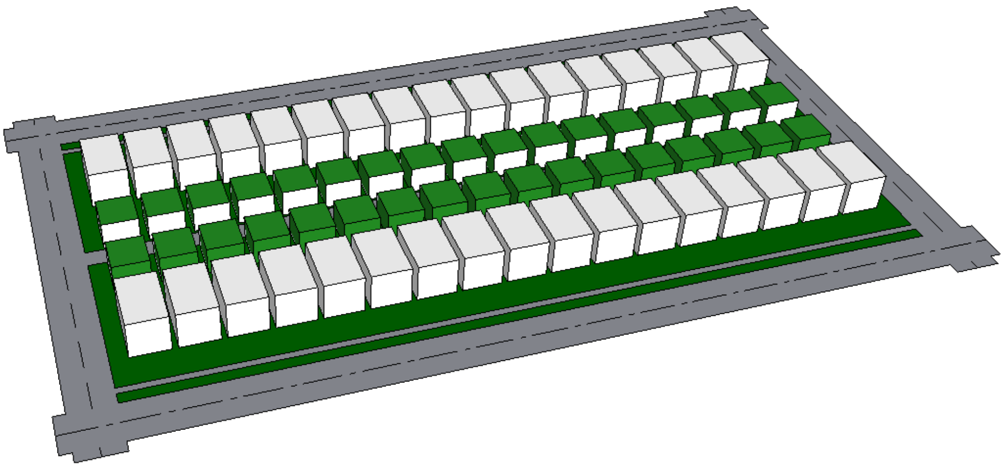


Figure 46: Standard block model, soft LWH fully vegetated on all sides except lane side. All LWH sides are covered in architectural greenery systems, including rooftops with green roofs, except one facade on the lane side for garage door and access which remains reflective.

Figure 47 below shows 3dB to 9dB decrease in SPL by vegetating the lane side facade, which increases diffusion and reduces reflectivity. Vegetating the surfaces not on the lane side is less effective for attenuating laneway noise from a point source close to the road.

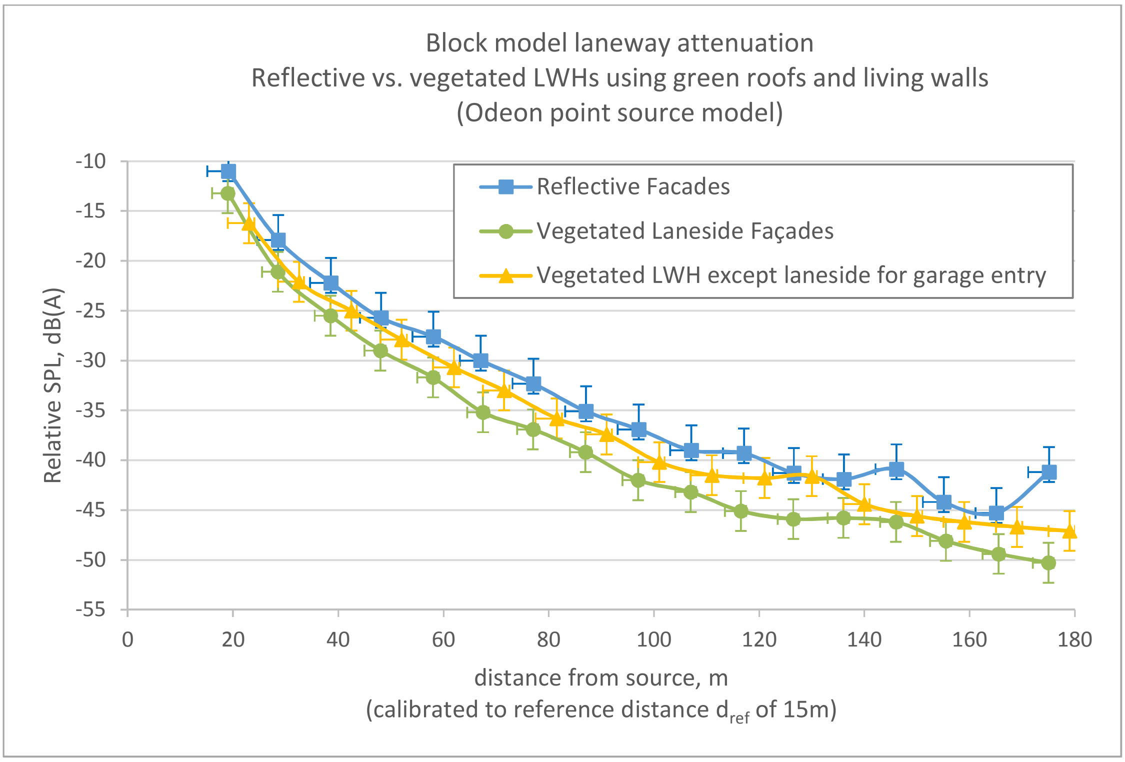


Figure 47: Odeon standard block model point source attenuation results for varying vegetated facade configurations

Figure 48 below shows the difference between modelling a gapless waveguide and a full block with gaps between buildings along the laneway. Again it is clear that in Odeon, geometry has more impact than surface absorptivity alone; the standard block at 0.4 absorption is more attenuating than waveguide at 0.9 absorption.

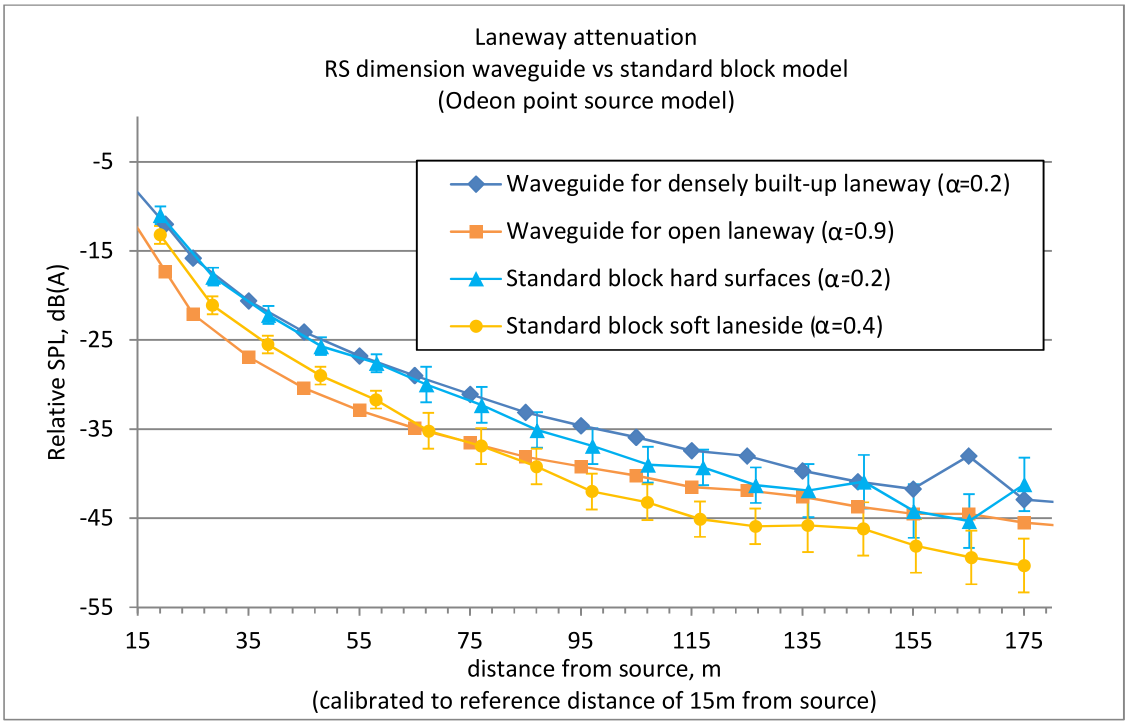


Figure 48: Comparison of waveguides to standard block model for point source attenuation in Odeon

2.3.2.4 Findings for point source sound propagation

Empirical data by point source tests agree with the understanding of open field sound propagation combined with urban canyon effects, demonstrating that laneways with more building area on both sides maintain higher sound levels within the lane space. The canyon effect is so significant in highly reflective laneways that the building reflection correction factors and SPL adjustments literature recommends for urban areas are insufficient. On the other hand, laneways with less built surfaces and lots of vegetation attenuate sounds well and can be two to four times lower in noise level than laneways with more building coverage. An interesting general observation is that even in low-height laneways, source-dependent flutter echoes are notable through Vancouver’s narrower paved residential laneways between reflective buildings.

2.3.3 Model results for line source

Line source attenuation is theoretically lower than point source attenuation; which means sound levels remain higher at farther distances from a line source than from a point source. Refer to Figure 26 (Chapter 1) to see SPL attenuation trends predicted by standard TNMs and by Odeon in an open field, for comparison to the results presented in this section.

2.3.3.1 CMHC

The laneways were modelled in CMHC from corner to midblock, assuming that the midblock will have the least sound level due to it being furthest away from side streets. Sound levels at the lane facade on the ground floor at a height of 1.6m are predicted. CMHC is applied in two different ways. One isolates the laneway decay effect by using only one perpendicular source, and the other predicts sound level resulting from all sources.

2.3.3.1.1 One perpendicular line source

One dominant perpendicular line source is modelled to observe sound attenuation through a laneway by line source (Figure 49).

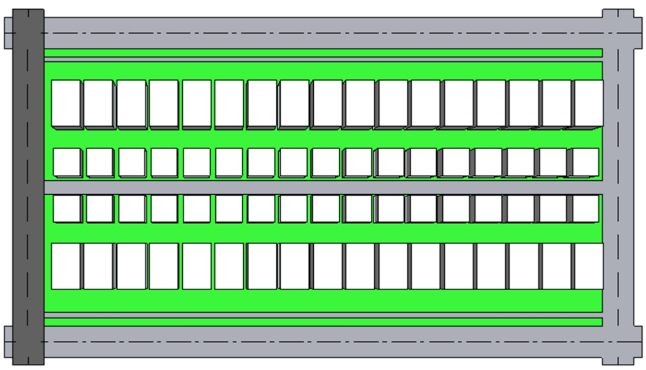


Figure 49: CMHC: one source only—perpendicular line source to a laneway.

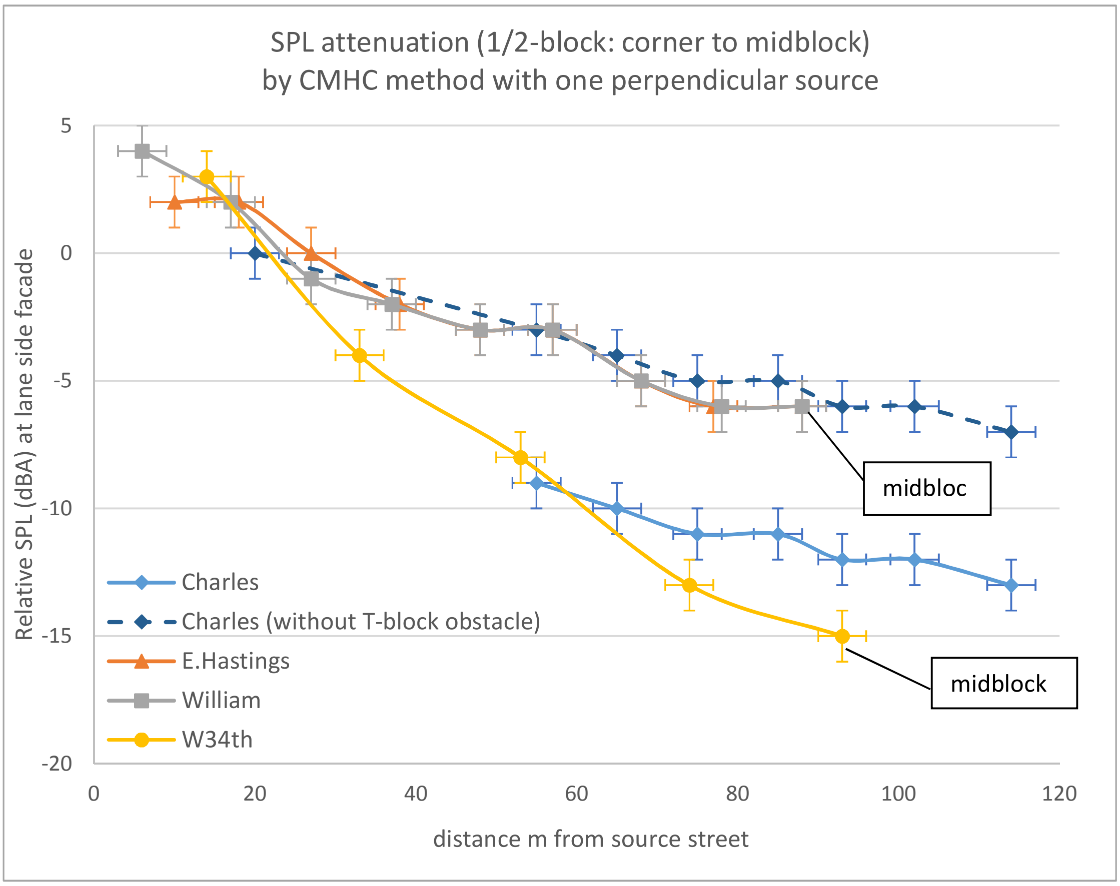


Figure 50: CMHC laneway attenuation by one perpendicular road source.

Results show the three laneways, Charles, E. Hastings and William, all with hard paved ground surfaces, behaving quite similarly. W34th, due to its partially paved (gravel-, dirt- and grass-covered) drive path, exhibits soft ground effects and more decay more than the other laneways. Charles due to rows of buildings experiences barrier attenuation of 6dB. However, W34th decays more than Charles even without shielding.

CMHC only accounts for the horizontal sound path (soft ground effects); attenuation or magnification by non-obstructing vertical surfaces is ignored. Results may be questionable for paved laneways that classify as hard ground, but have more vertical foliage and air absorption, such as William.

2.3.3.1.2 All road traffic line sources

The standard CMHC Part 3 method is applied to simulate *all* road traffic sources that influence the receiver(s). Figure 51 shows the most pertinent four sources for a regular laneway.

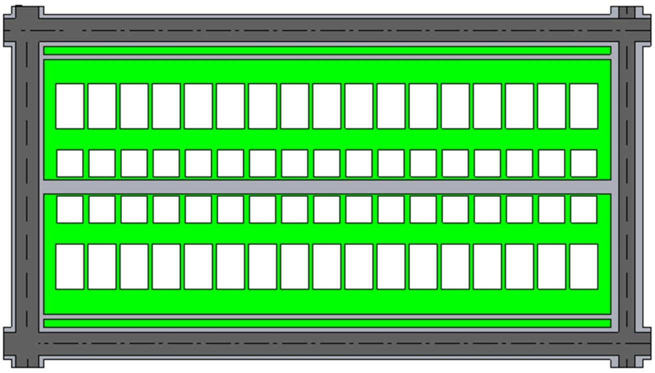


Figure 51: CMHC, four line sources affecting a standard block.

In Figure 52, E. Hastings lane has the highest SPL and does not attenuate through at least five lots down from the corner. At least 5 of 9 LWH facades modelled at E. Hastings lane exceed outdoor residential noise criteria (55dB) by 10-11dB, starting with the corner lot and continuing towards midblock. The dominant road source, E. Hastings Street, runs parallel to the lane and thus the laneway exhibits little effects from attenuation by distance from source. The significant attenuation closer to midblock in E. Hastings Method 2 is the result of barrier attenuation coming into “full effect.” In E. Hastings Method 1, no correction for actual barrier length was applied. In E. Hastings Method 2, correction for actual barrier length is applied where the effective barrier length ratio (w) is greater than 10, which is when the barrier is more effective in blocking noise from the receiver [14, p. 21].

The first two LWH facades on Charles closest to Nanaimo exceed criteria, and SPL drops very slightly by 2.3dB over the short 75m block to just under criteria. William and W34th are much quieter than the other two lanes. William drops by about 5dB from corner to midblock. W34th lane has the highest attenuation, about 11dB, resulting in the lowest SPL at midblock despite having a relatively high source (Crown Street) at the west end. The LWH facades at the corner of W34th Avenue and Crown Street can easily exceed criteria level if other noise sources in addition to road traffic are present.

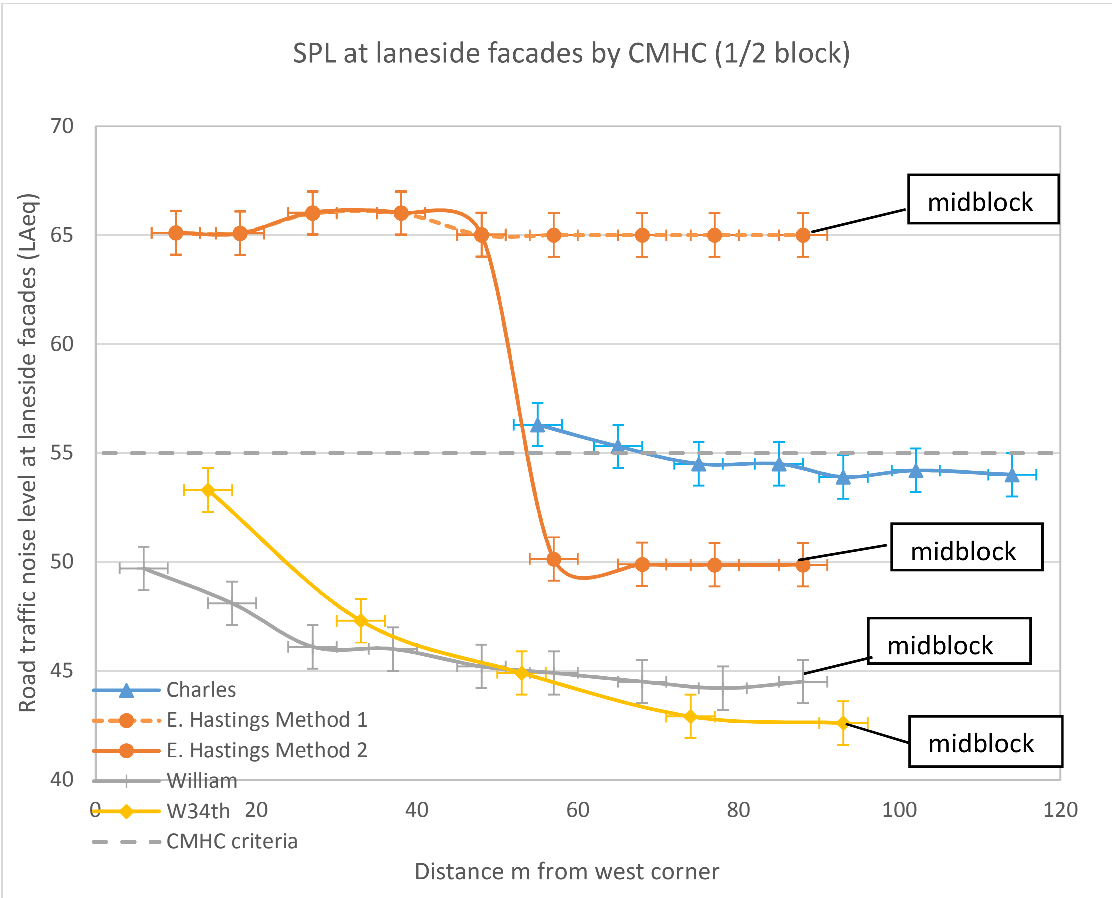


Figure 52: CMHC TNM results for laneways

Up to this point, discussion has focused on the lane-side facade. In the graphs below, all the facade levels predicted by CMHC are presented. Lengthwise decay trends here have muted in E. Hastings and in Charles: E. Hastings shows a flat line until barrier attenuation takes effect, and

Charles shows minor SPL difference between one end and the other.

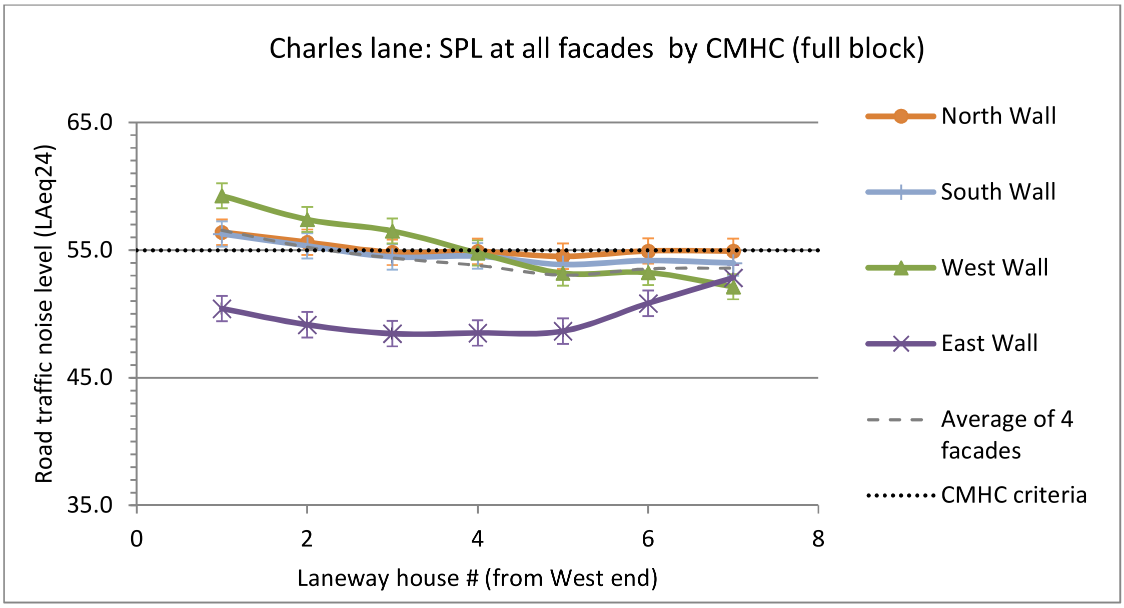


Figure 53: CMHC results through Charles lane, all facades

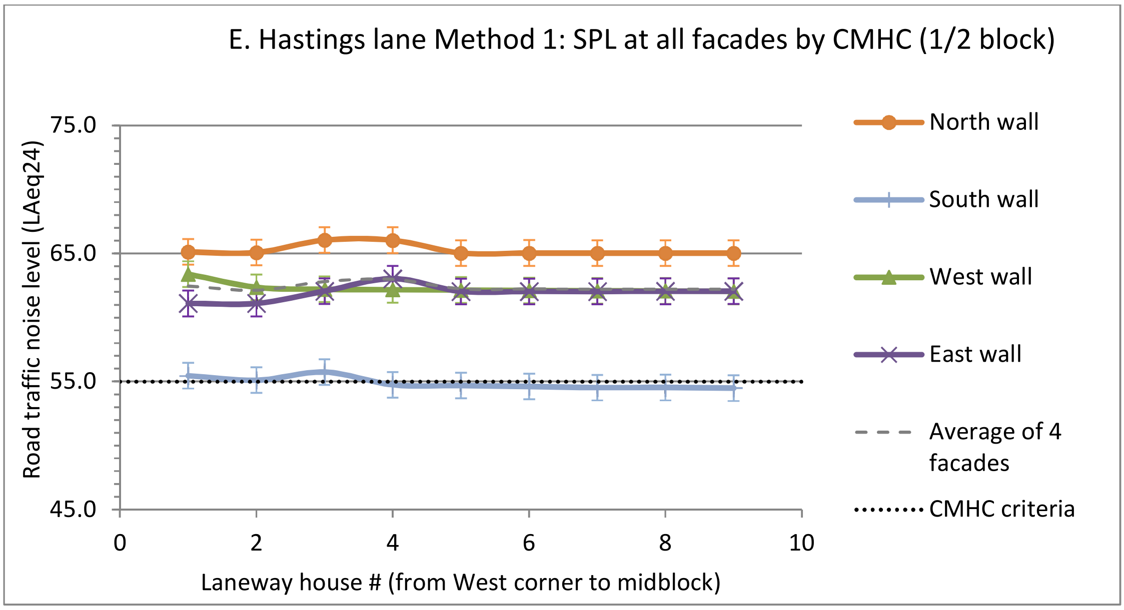


Figure 54: CMHC results through E. Hastings lane by Method 1 (no barrier length correction)

not including CMHC's correction for barrier length

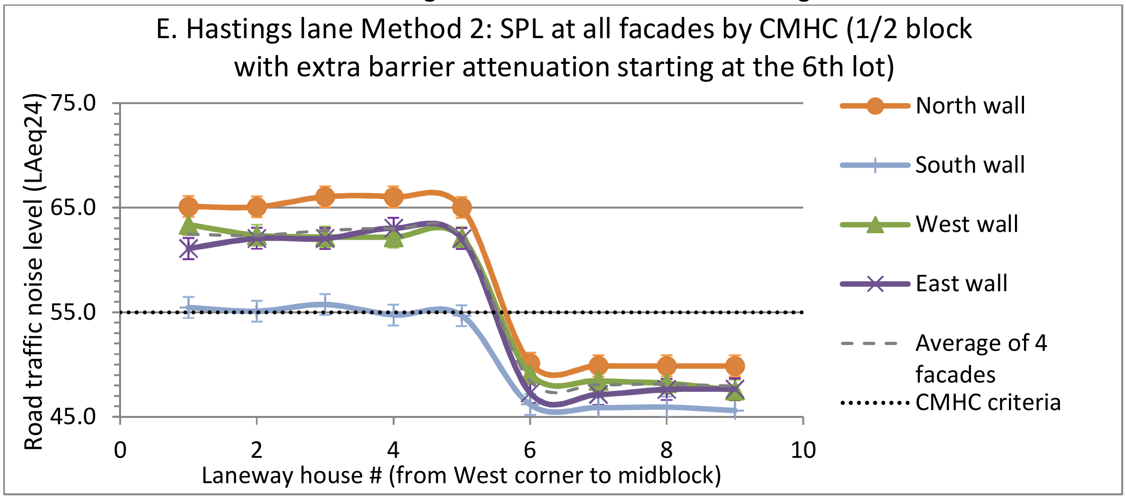


Figure 55: CMHC results through E. Hastings lane by Method 2 which includes CMHC's correction for barrier length for locations where effective path length ratio is greater than 10

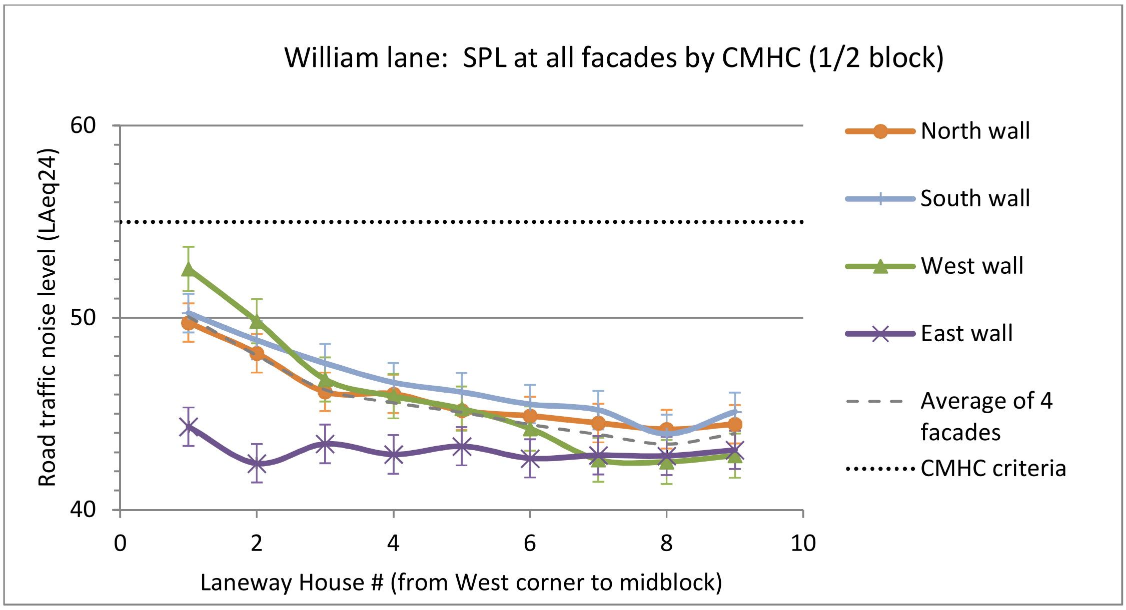


Figure 56: CMHC results through William lane, all facades

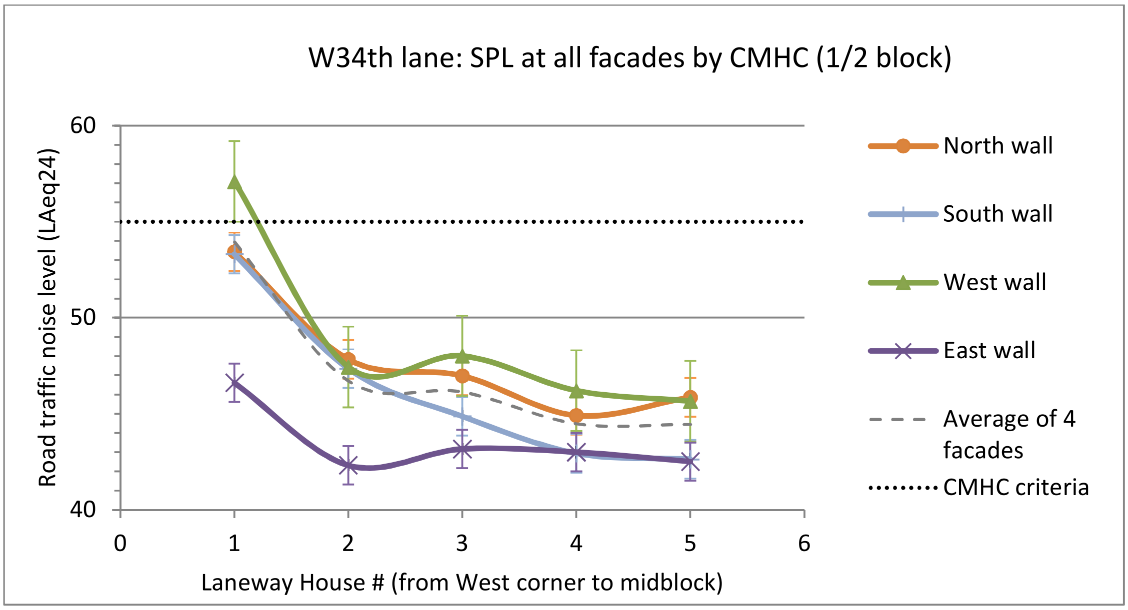


Figure 57: CMHC results through W34th lane, all facades

CMHC appears to adequately predict ambient road traffic levels in a regular Vancouver laneway like William and W34th, though results are still questionable for E. Hastings and Charles where building effects—both attenuation by barriers/obstacles and magnification by reflectors—are more complex. Barrier attenuation by T-block buildings at Charles invites further investigation. As for E. Hastings, taking into consideration that it is a half-commercial block with much higher levels of activity, possibly in the form of point source vehicles through the laneway, CMHC predicted levels appear to be reasonable for E. Hastings.

2.3.3.2 Odeon

Field measurements of line source propagation are beyond the resource limits of this study. However, Odeon is used to simulate line source results for comparison to CMHC results. As seen in Figure 26, Odeon results agree with TNM Eq.(4) at 4.5dB/dd, which Long indicates is more appropriate for application than 3dB/dd in most real life line source cases [17, p. 185].

Figure 58 presents Odeon-modelled SPL attenuation through all case study laneways. Results follow the trend of SPL decay increasing as laneway reflectivity ranking decreases. Charles exhibits shielding attenuation by the rows of buildings between the laneway and the Nanaimo line source. The point source (Odeon model in previous section) was located at one end of Charles laneway and not affected by this obstacle shielding attenuation.

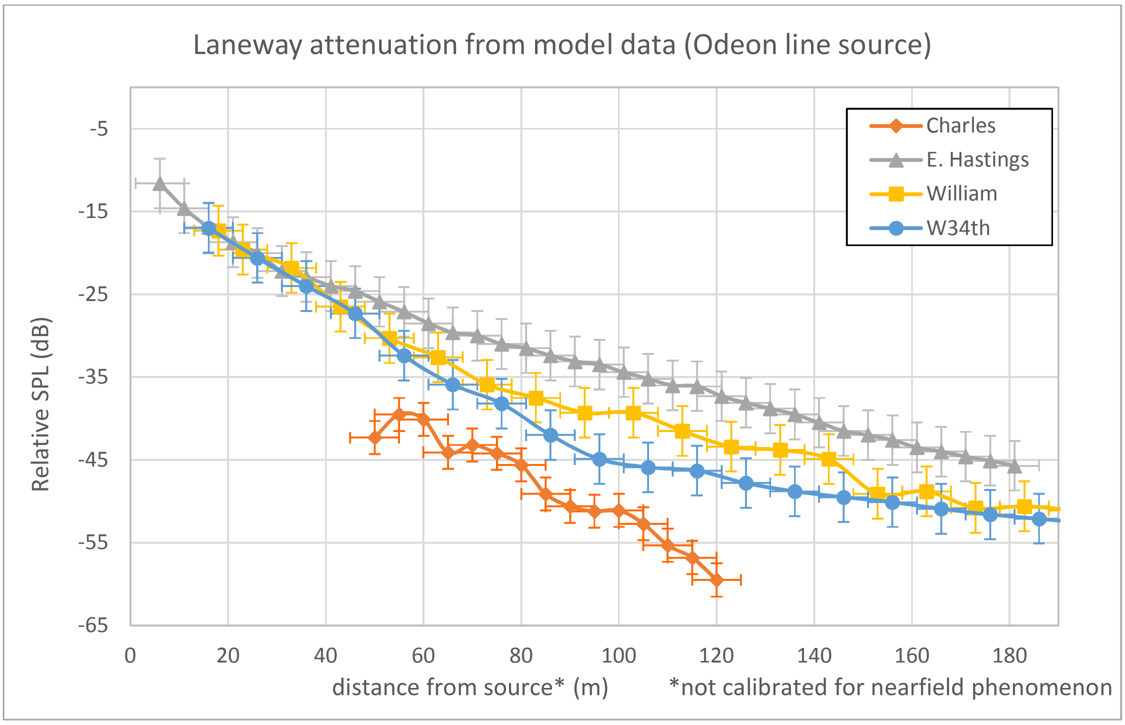


Figure 58: Odeon line source results for laneway attenuation

2.3.3.3 Odeon versus CMHC

Results from Odeon are compared to CMHC (model with only one perpendicular road source). Odeon results require significant data-alignment for fair comparison to CMHC curves. Point source field data was also calibrated and plotted for reference.

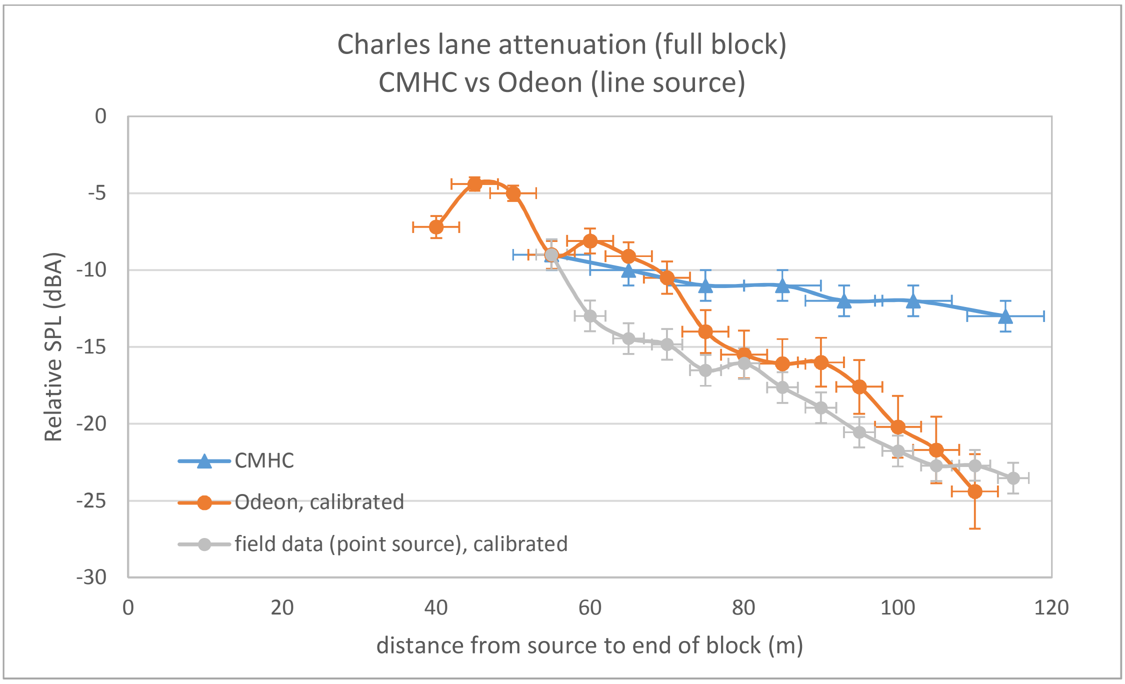


Figure 59: CMHC and Odeon line source propagation results for Charles lane

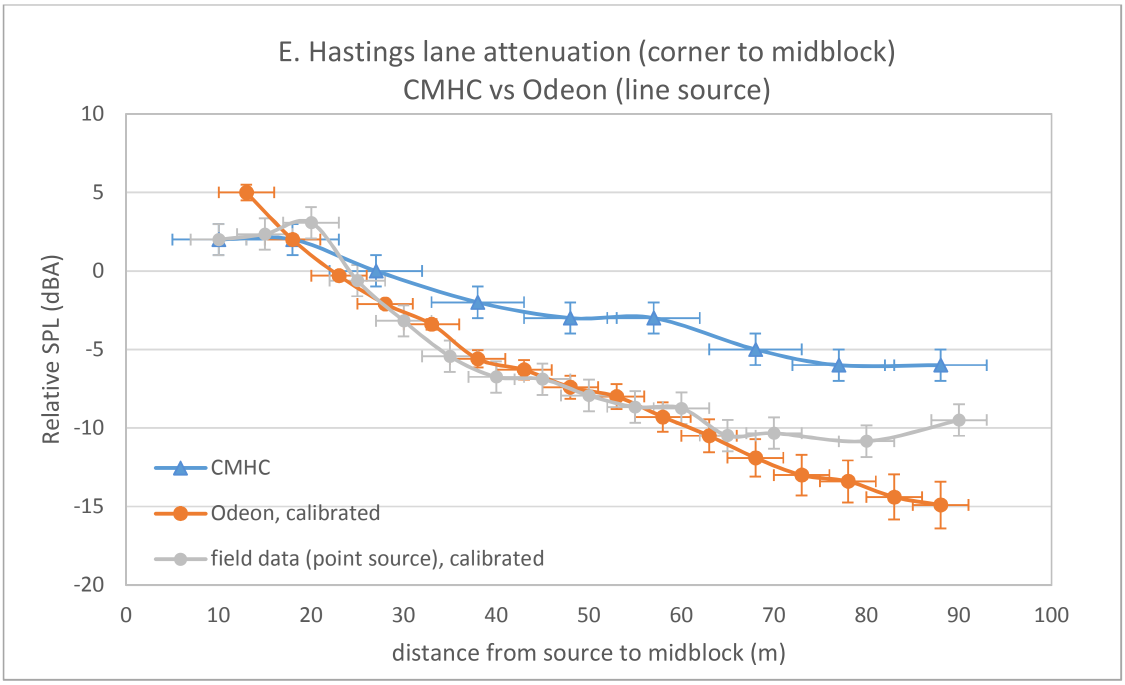


Figure 60: CMHC and Odeon line source propagation results for E. Hastings lane

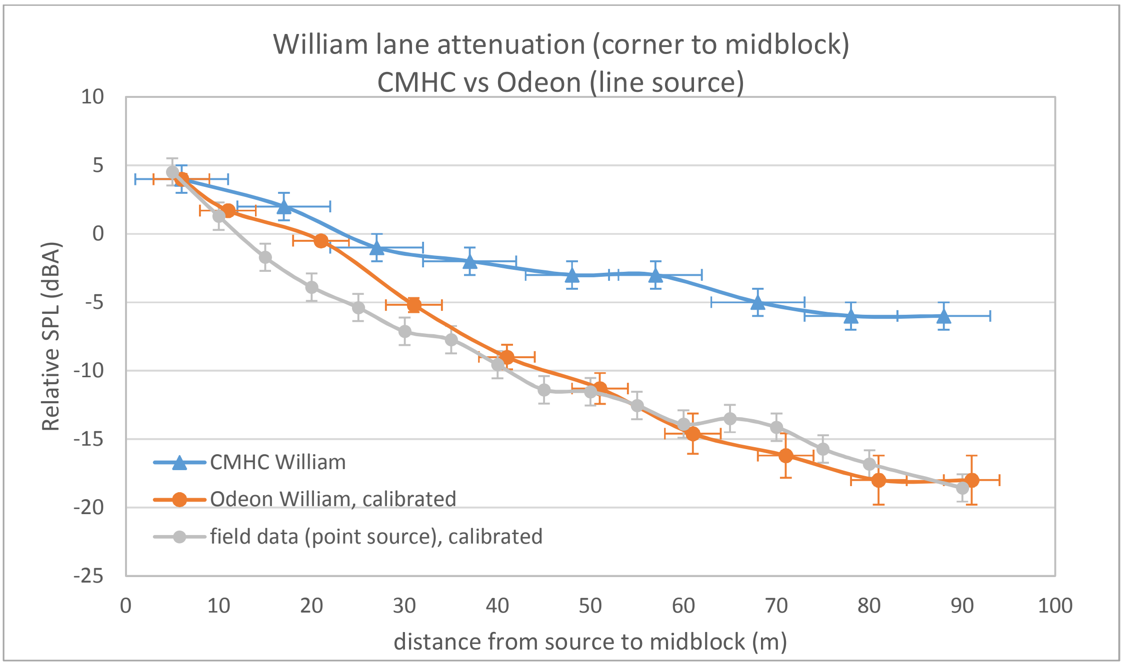


Figure 61: CMHC and Odeon line source propagation results for William lane

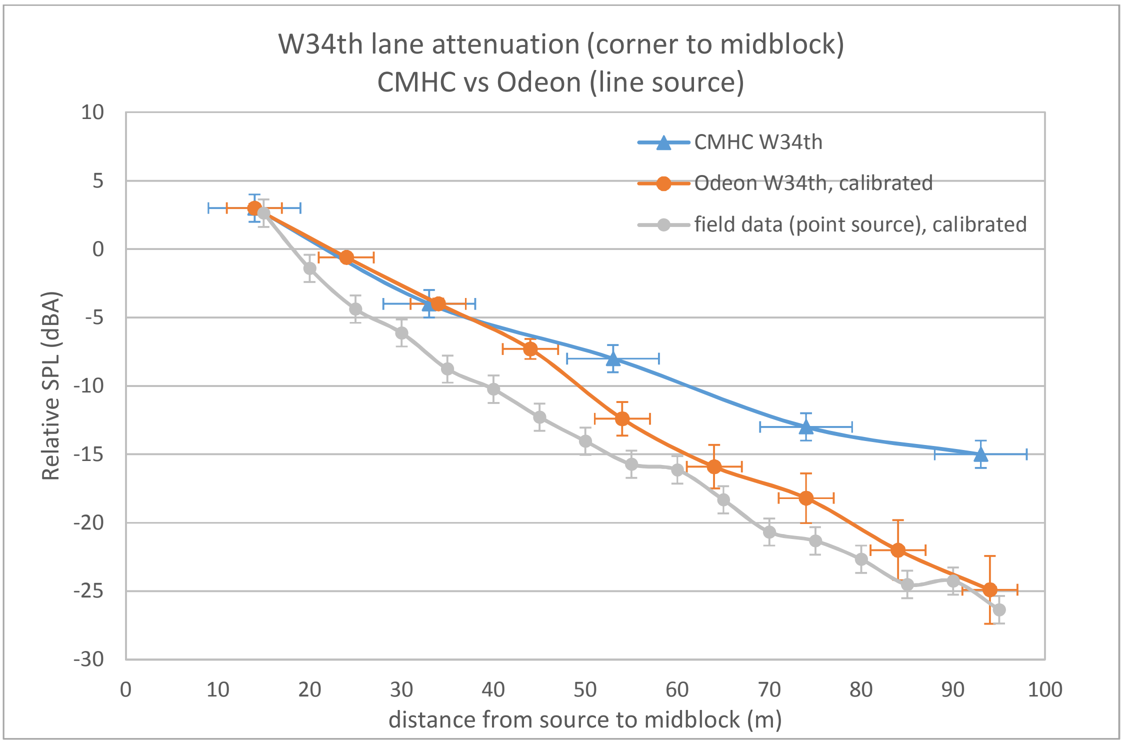


Figure 62: CMHC and Odeon line source propagation results for W34th lane

The Odeon results do not match well with CMHC. Odeon line source results match better with point source patterns, with decay rates far greater than the 4.5dB/dd of Eq.(4), ranging from 7.5dB/dd to 15dB/dd (summary found in Table 11). Odeon seems to underestimate sound levels by over accounting for barriers and shielding effects. The buildings on either side of the lane truncate the line source, making it more similar to a point source from the mouth of the lane, as illustrated in Figure 63. This shielding effect also greatly outweighs any in-canyon reflectivity.

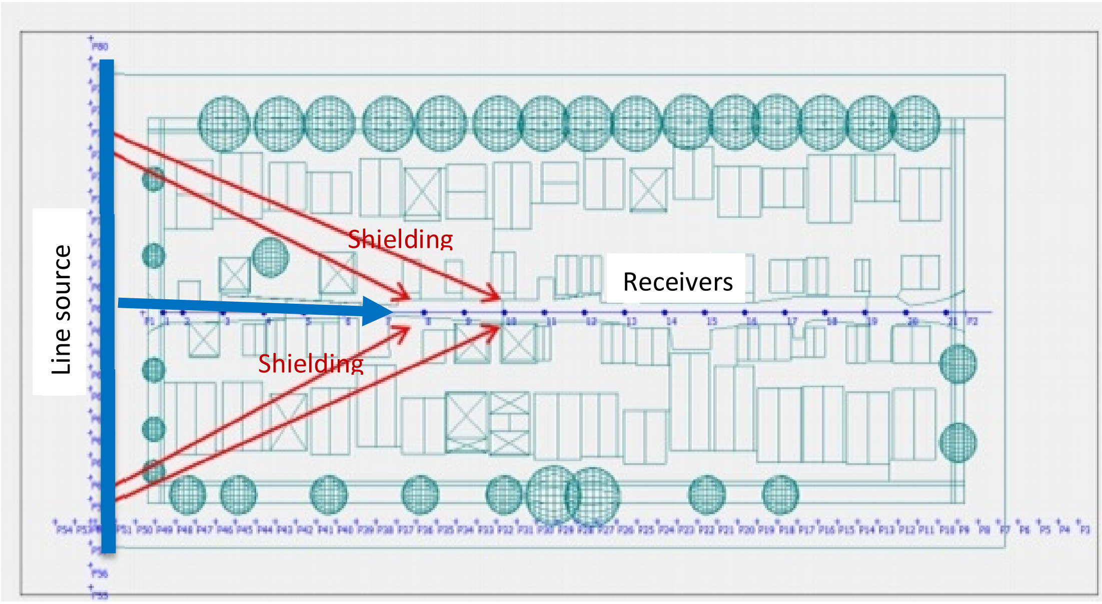


Figure 63: Pronounced obstacle shielding effect in Odeon [80].

An experiment is run in Odeon to compare line source and point source propagation through waveguides and results indicate that point and line source behave almost the same (Figure 64 below). The vertical walls of the waveguide renders a line source virtually the same as a point source.

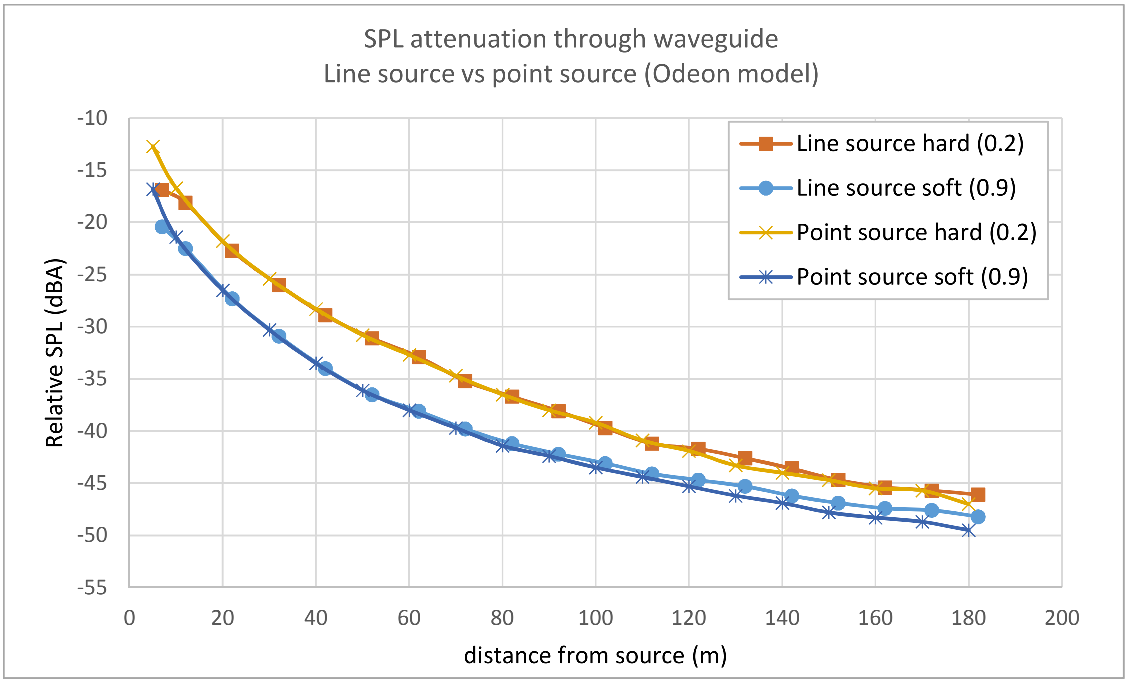


Figure 64: Point source and line source sound propagation through waveguide in Odeon

CMHC bases propagation on a very conservative 2.7dB/dd decay rate, much lower than Long's suggested 4.5dB/dd for common residential application, and predicts much higher receiver sound levels than Odeon in a line source scenario.

2.4 Discussion and chapter conclusion

General trends for laneway sound propagation found by all three investigation methods (empirical, CMHC and Odeon) follow predicted trends. Noise from both line and point sources attenuate at higher rates and magnitudes through an absorptive laneway and less so through a reflective laneway. Charles and E. Hastings laneways being highly reflective consistently see lower attenuation and William and W34th laneways, particularly the latter, see higher attenuation. The lower SPL attenuation at Charles and E. Hastings, as well as William within closer ranges to the source, fit with the urban canyon effect documented in literature. Given a controlled noise event at one end of the block, the reflective laneways (Charles and E. Hastings) are twice to four times louder than an absorptive laneway (W34th).

Adjustors and building reflection correction factors proposed in literature are insufficient to account for the sound-magnifying contribution of urban canyon building reflections in the 3 harder laneways for point sources, by 4 to 11dB.

2.4.1 Validation of modelling methods

Odeon, while able to predict the larger trend, requires considerable data-alignment due to different treatment of the near field phenomenon. Odeon explains that in its understanding of the "real world," there is no exact point of transition between near and far field and that "this is a smooth transition [81]." Although this statement is acceptable by looking only at *field data*, Odeon results require reference distance calibration. When calibrated properly for near field, and corrected for air absorption and scattering details, Odeon shows promise in predicting point-source sound attenuation trends through case study laneways, generally agreeing with empirical data. Sound behavior modelling in highly reflective outdoor environments requires improvement. Predicting attenuation by complex types of absorptive material such as vegetated facades also needs improvement. Line source modelling in Odeon yields reasonable results in a soft open field, but becomes questionable when buildings are introduced, particularly for a residential block laneway configuration.

CMHC conservatively underestimates sound attenuation over distance, the margin possibly covering for items it does not explicitly consider, including building reflections and/or canyon effects at source and at receiver, unique traffic noise sources like bus stops, and roads without traffic data, such as the laneway. CMHC's barrier attenuation and correction values for actual barrier length require further investigation. The +3dB suggested by J.D. Quirt (for line source sound levels) appears to be unnecessary for the case studies, although there are no empirical line source data to truly confirm this within project scope. CMHC takes into account many important factors along the sound path, giving final results that do not contradict instantaneous ambient SPL checks. To discover whether a true LAeq24 will match CMHC results requires further research extending beyond the scope and resources of this study. Within the practical limits of this project, final results by CMHC are fair to adopt for real situations and it is a sufficient modelling tool.

Odeon requires considerable skill, experience, resources and time to setup, learn, run, debug and troubleshoot, and is inaccessible to the average homeowner looking to build a laneway house. CMHC is more accessible to the lay person, but is time-consuming and demands significant focus and dedication to complete with reliable accuracy.

2.4.2 Single number decay rate

A single-number rating tool used to approximate the SPL attenuation trend for a laneway is its decay rate, or *decay per doubling of distance* (ΔdB/dd). The decay rate is obtained by the following set of equations:

$$Decay\,rate = \; y_2 - y_1, \; if\; x_2 = 2x_1 \quad \text{and} \qquad \textbf{Eq.(7)}$$

$$y = Alogx + B$$

where equation *y* is the best-fitting logarithmic trend-line for the SPL attenuation data plotted against propagation distance. Table 11 below summarizes SPL attenuation trend results for all cases explored in this chapter.

Table 11: Summary of all cases by decay rate

	Decay rate (ΔdB/dd)		
	Point source	**Line Source**	
Theory	Eq.(3)	Eq.(4)	CMHC Table 3.5
Open field hard ground	6.0	3.0	2.7
Open field soft ground	7.5	4.5	5.1
Case Studies	Empirical measurements	Odeon model	CMHC model
Charles	3.8	14.8	3.6
E. Hastings	4.5	7.5	2.9
William	6.6	10.6	2.7
W34th	7.7	10.9	6.6
Other Odeon models			
Waveguides/canyon model			
3m tall waveguide	5.8	-	-
5m tall waveguide	4.5	-	-
10m tall waveguide	4.3	-	-
5x5.7m waveguide @ a=0.2	7.5	7	-
5x5.7m waveguide @ a=0.9	7	6	-
Composite model			
Reflective buildings	6.8	9	
Soft lane side facade on LWH	7.5	9	

Although the decay rate is an easy number to use for quick comparisons between different lanes, it varies by laneway length and masks important details, such as the common trend of lower decay rates at closer range and higher decay rates at farther range. The trend lines these are calculated from may not exactly represent the decay curve. Odeon generates a decay rate (DL2) which only accounts for the 250-4000Hz frequency range and does not include lower frequency bands. Because of the uncertainties and possible errors in the single number decay rate, it is necessary to review the SPL attenuation graphs and to avoid making decisions based only on decay rate.

2.4.3 Canyon effect mitigation strategies

To mitigate urban canyon effects through laneways, decreasing height, increasing building separation, and increasing surface absorption and scattering will help reduce noise level buildup inside the laneway. However, decreasing building sizes along the laneway may conflict with high density and space-efficiency goals. Alternatives to consider are adding vegetation absorption through the laneways with AVS (architectural vegetation systems) on LWH facades and roofs, using absorbers and diffusers on garage doors and building surfaces, using underground space like basements, and paving laneways with grasscrete or other permeable surface materials.

In terms of building height, the trade-off between the benefit of traffic noise shielding and disadvantage of laneway amplification depends on the specific laneway, the noise source, and its environment. CMHC results and literature review indicate that shielding may not be as effective as increasing laneway building surface absorption to lower overall noise level inside the laneway, particularly placing vegetated facades at strategic positions, such as along roof eaves [50].

One last interesting point is that low frequency energy decays less than higher frequency energy. If there is low frequency noises and vibration from trucks, larger vehicles, mechanical equipment, motors, machines and aircraft, these low frequency noise levels will remain higher, for longer, and extend farther down the laneway. Although theoretically, humans are less sensitive to such low frequency sounds, they can still be disruptive and unhealthy, and should not be neglected [11]. Figure 65 below is an image of waveguide decay modelled in Odeon, with SPL breakdown by frequency band showing that SPL drops much faster in the frequency band 6000Hz than in the 63Hz band.

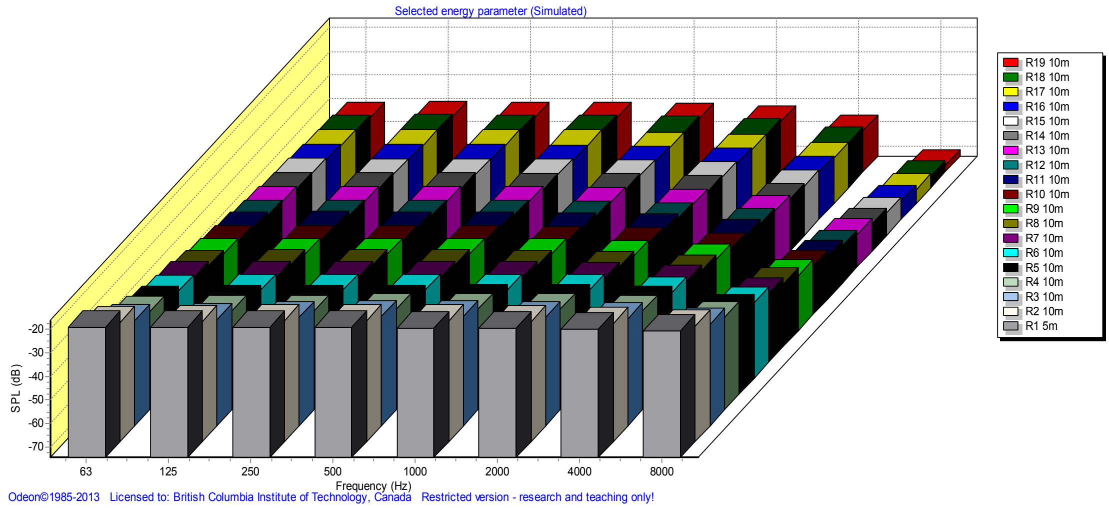


Figure 65: Low frequency SPL attenuation in Odeon

2.4.4 Errors and sensitivity analysis

In field measurements, sources of possible errors include meteorology (air temperature variance, wind, etc.) and unsteady background noise levels. During field tests while hearing protection is worn, extra environmental noise not a part of the test signal may not have been noticed and thus may affect the measurements; this also applies to inconsistencies in the signal such as power source, connectors, and temporary equipment malfunction. There was also frequent disruptions by through traffic during field measurements; each time a vehicle or pedestrian needed to pass through, the signal must be turned off and equipment moved out of the way. This may cause inconsistencies in signal levels before and after each interruption.

When taking multiple measurements within minutes under the same environmental conditions, the uncertainty is less than ±1dB. With environmental interference and randomly intrusive noise events, the uncertainty increases to as high as 8dB.

Meteorology and meteorology-related outdoor effects are beyond the scope of this study and not considered by the two modelling tools, but were given best-attempt efforts to reasonably control in outdoor field experiments. The weather was identical or similar for all field tests; data for W34th contains effects of a moderately lower air temperature and higher humidity.

Procedure-related uncertainties, traffic volume and percentage heavy vehicles approximation, and distance variance between multiple geographical mapping software and site measurements in using the CMHC model may account for ±1.5 – 2dB and 10m of uncertainty.

In Odeon, air absorption is excessive for outdoor application [17, p. 174]. Scattering effects can become significant over distance. Figure 66 below shows that air condition can contribute to around 3dB difference in results and scattering assignment of 0.05 can make a 5dB difference. These effects are magnified over propagation distance and can be significant; in Figure 66 it is 8dB at 180m. In un-calibrated data sets, the reference distance of the acoustical near field is an important error source.

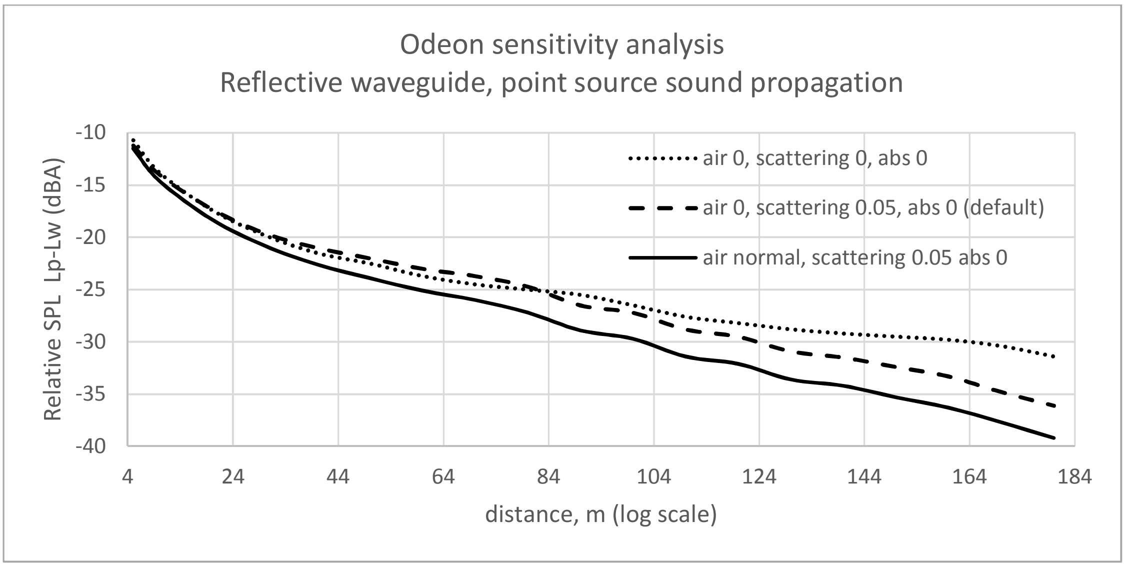


Figure 66: Sensitivity analysis of uncertainties due to air absorption and scattering coefficients in Odeon.
"Air normal" indicates air conditions of 20°C and 50% relative humidity. "Default" indicates the mode used by final models.

Table 12 shows the difference in result levels between a case with normal air condition (20°C, 50%RH) and default scattering coefficient (0.05), indicated by the solid line in Figure 65, versus a case without assigning air condition and scattering, indicated by the dotted line in Figure 65. The final Odeon models use the "default" mode where air conditions are disabled for outdoor application, but the appropriate surface scattering and absorption coefficients are assigned to all surfaces.

Table 12: Difference in result levels by modelling detail

distance (m)	60	120	180	Δ decay rate
ΔdB(A)	-1.4	-3.9	-7.8	-1.2

The above-discussed margins of error are included in error bars for all graphic data in this chapter.

CHAPTER 3: Sounds in Vancouver's laneways

Chapter 2 gave quantitative information such as road traffic noise levels and propagation patterns for point source and line source sounds. This chapter identifies, inventories and categorizes the point and line source sounds which can behave in the quantitative patterns discovered in Chapter 2. The taxonomy of sound content provides qualitative information about the laneway sonic environment.

The function of laneways or back alleys of single family residential (RS) zones is to provide vehicle access to garages and servicing to single-family houses. Common service activities occurring near the LWH site at the back edge of the lot include garbage disposal and collection[6], recycling, and utilities access such as electricity, water, and communications. HVAC and mechanical equipment such as outdoor heat pumps, handiwork projects, storage, recreation, gardening and yard work are commonly allotted to the rear yard, each having a range of noise effects on LWH.

Figure 67: Garbage truck approaching laneway house

[6] Proximity of garbage also implicates air quality and sanitation.

3.1 Literature review

3.1.1 Laneway noise exposure

Residential noise complaints reveal the typical noise sources affecting Vancouver neighborhoods. The charts below summarize findings by the Urban Noise Taskforce in 1997 based on the number of complaint letters received by type [12].

In Figure 69, the most significant city-wide noise source by a large margin is *traffic*, which was investigated quantitatively in Chapter 2. The next three most significant noise sources listed city-wide are *sirens*, *parties*, and *construction*. Figure 68 ranks noise sources by percentage of associated complaint letters back in 1997. *House/garden* is the most bothersome noise source, instigating 30% of complaint letters. Note that in Figure 69, *dumpsters* also made the top nine list of most significant noise sources and actually matches *gardening* (see lighter shade bar in Figure 69) in terms of city-wide effects. The next most bothersome noise source to Vancouverites is *vehicles* in Figure 68. Noise types and categories are discussed in detail in the COV 1997 Urban Noise Task Force Report; disruptive noise categories are addressed mostly by proposing social (including behavioral and planning) and legal solutions for source-control [12].

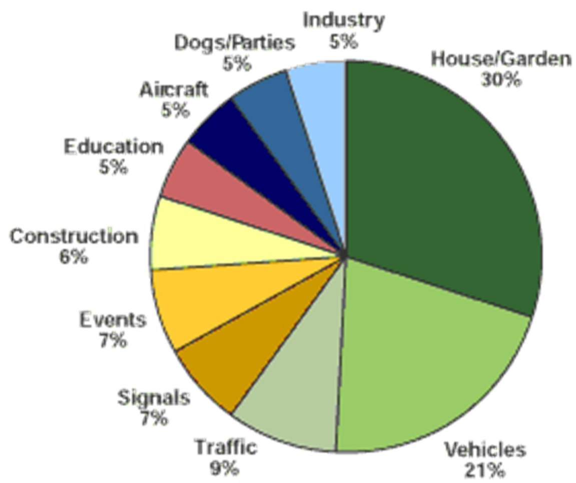


Figure 68: Noise complaint letters received by type [12]

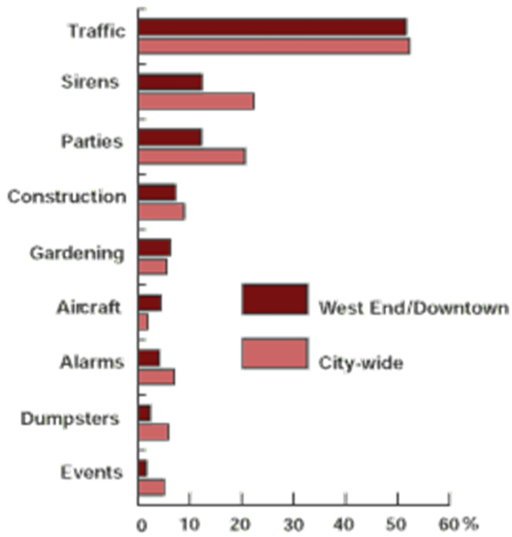


Figure 69: Most significant noise sources around Vancouver [12]

3.1.2 Semantic and qualitative consideration for environmental sound

Acoustical studies extend beyond quantitative physical analysis, requiring semantic and qualitative information of the perceived sounds to more accurately assess human experience. Regional airport authorities and ASHRAE provide rating systems that account for the variability of human responses to noise, including using tonal and quality labels like “hisses,” “whistle” and “hums” [9] [82].

In fact, the most basic terms “loudness” and “volume” already extend beyond physics into the realm of psychoacoustics, being a human perception rather than a pure measure of sound energy [83]. Experts often stress that loudness, as a psychological correlation of physical strength (amplitude), is affected by parameters other than just sound pressure [84]. Booteldooren et al. in their soundscape studies find that “annoyance depends on the difference over background levels, spectral composition, temporal and semantic content [48].” Connelly explains that sound levels and even loudness levels "are not sufficient to predict the level of annoyance and potential harm since different sources are perceived quite differently [10, p. 110]."

In additional to amplitude (SPL), sounds have many important characteristics containing a lot of information. Source identification is the most important information for human perception and response. Other important sound characteristics include source type, semantic content, context, relationship to other sounds, concurrent sounds, amplitude difference above background level, spectral composition (frequency), timbre and coloration, and temporal characteristics. Temporal characteristics are also complex, including tempo, beat, time of day, frequency of occurrence, and the duration of exposure to the sound signal [48] [84].

3.1.3 Soundscape and soundscape study methods

Researchers use *soundscape analysis* to study a sonic environment qualitatively in a scientific manner beyond using only SPL descriptors. Since its debut by R.M. Schafer of Simon Fraser University, the concept of "soundscape" has become very popular across multiple disciplines working with sound, including planners, environmental and urban acoustic engineers, and health researchers. Kang cites ISO (International Organization for Standardization) in his definition of soundscape: "the perceived sound environment in context by an individual or by society [85]."

The concept of soundscape allows for a comprehensive assessment of the acoustic environment or sound event by providing *quality, spatial and temporal* indicators and by including *human response* and *listener-environment interaction* [86]. Truax, a colleague of Schafer, argues that sounds should not be signals to be processed but information to be understood, and that one sound should not be treated similarly to any other sound [87]. Davies et al. found that soundscape recordings equalized for LAeq produced significantly different cognitive responses depending on their content [88]. Kang lectures on the benefits and methods of soundscape studies, calling it “more powerful than the classic level-based approach which is only suitable for providing primary needs such as sleep and hearing protection” [85].

Soundscape study methods are manifold and interdisciplinary, with many aspects extending beyond the scope of this project. Botteldooren et. al., Brown, Davies, Raimbault and Dubois, and Smith are among researchers who have proposed various scientific methods for analyzing sounds, some involving psychoacoustics [88] [89] [90] [91]. ASTM also provides its own version of standardized procedures and criteria for soundscape evaluation [92]. The sonic environment receives spatial analysis along with some visual source identification [10]. Sound data collected by structured soundwalks through the sonic environment undergo various listening and interpretive methods. Sound data is inventoried, categorized, measured and rated for amplitude, frequency and temporal characteristics. Cognitive appraisal and subjective evaluation, holistic and analytic verbal descriptors are applied, with narrative summary [88]. Sometimes auralization and other processes are done via audio-visual tools and computational models. The resulting soundscape is the human perception or impression of environmental sounds, possibly presented in the form of “soundscape quality maps” with “positive/ negative” labels in addition to SPL indicators, supplementing existing quantitative noise maps [88].

Because of the psychological and social aspects of the soundscape and the complexities inherent in current soundscape studies, researchers are working on simplifying research methods and improving taxonomy in order to promote wider use and inclusion into the planning process [88]. Connelly and Raimbault et. al. find subject-oriented categorization beneficial as it is among the simplest and most readily applicable methods to use for the urban environment [10, p. 133] [89].

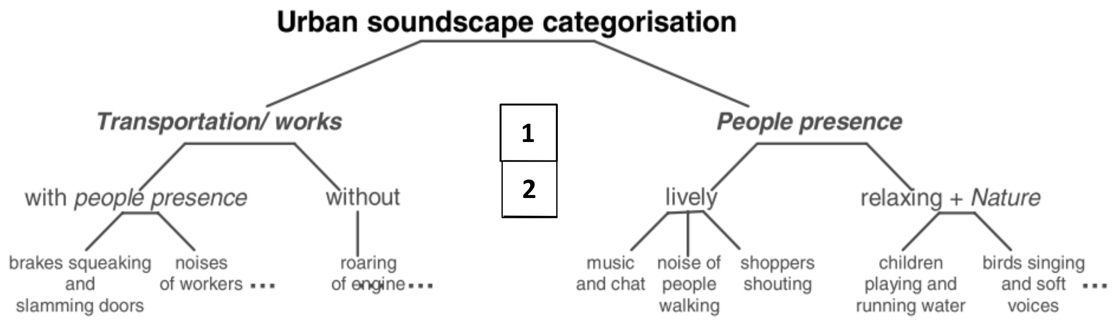


Figure 70: Urban soundscape categorization schematic diagram by Raimbault and Dubois [89]

3.2 Methodology

Performing a full soundscape study exceeds the scope of this thesis. Qualitative investigation of laneway sounds is simplified using *ambient sound analysis*, with primary focus on inventory and taxonomy of source activities to facilitate analysis of patterns and relationships [10, p. 111].

Taxonomy or sound type categorization describes and classifies sounds and sound sources, thereby assigning sounds with a subjective value based on human perception. Major taxonomy methods include the object-centered categorization preferred by planners, which classifies soundscapes into mechanistic/activities-based versus natural. From the city users' perspective, soundscapes may be categorized in a subject-centered manner into *transportation/works* versus *people presence* sounds; *people presence* sounds can be further classified into *lively* versus *relaxing + Nature* sounds [89].

Taking a sound inventory involves recording statistically relevant time periods of ambient laneway sounds, listening to these sound recordings and identifying the sounds. Ambient sounds inside case study laneways were captured in audio recordings during the summer of 2011 (June 28-July 5) by another student, during weekdays (Monday-Wednesday) at three one-hour time segments: in the morning (7-8am), around noon (11-2pm), and in the evening (5:30-7pm). The ambient sonic environment was recorded without known biases during the one-hour recording period. The total duration of the audio data processed for ambient sound analysis is 12 hours.

A possible error in this segment of study is duration quantification (counting seconds and minutes of each sound type), particularly during cacophony or layered events with significant masking. Also, without confirmation by visual and tactile information such as accurate weather, object, directional and positioning data, sound source identification and event reconstruction may be fuzzy since some information cannot be fully discerned by audio only.

Sounds are identified, counted, and measured for total duration in preparation for subject-centered categorization. Assessments are also made for amplitude, frequency, and other temporal characteristics. Where noteworthy, tonal, contextual, semantic and emotional information are observed.

The lane-centered categorization is a simple variation on subject-centered categorization. Sources are first categorized by origin from outside or inside of laneways, *then* into transportation/works and people presence categories. This categorization also aligns with categorization by mechanistic versus natural sound types, relating transportation/works with more mechanistic sounds and people presence with more natural sounds. General observations of noteworthy laneway sounds around Vancouver, and sounds observed during case study field tests for Chapter 2 and 4 are described separately.

3.3 Results

3.3.1 Identification and inventory

All sounds identified are grouped by sound type with source type (e.g., line or point) indicated as presented in Table 13 below. Sound types are items listed in the left column; source types are predominantly point or line sources and indicated in the right column. Exterior traffic noises are line and point sources; all other sounds except for environmental sounds are point sources. Point sources are mostly *movin*g point sources.

Table 13: Laneway sound types identified and grouped

Transportation	**Source type**
Aircraft: jets overhead and/or approaching, helicopter hovering	Point
Special vehicle signals: distinct signals including water vessels, trains, sirens and beeps	Point
Exterior traffic: vehicles activities outside the lane. These include motor vehicles on side streets or on nearby arterial at different distances, moving speeds, noise amplitudes and flow pattern such as stop/go and acceleration	Line & point
Lane traffic (close vehicle incident): vehicle activities through the lane. Due to proximity and tire-ground interaction on some types of laneway ground cover, these can be very loud.	Point
Vehicle brakes: squeaks, skidding and/or screeching	Point
Garage, cars and parking: garage operation, cars entering and exiting garages, opening and closing of car doors and trunk lids, loading and unloading, starting engine, and idle engines inside the laneway	Point
Cycling: bikes whizzing through laneway	Point
People	
Talking/conversation (various languages), intimate or projected communication across the yard, yelling, yelling at dog	Point
Walking/footfall (on gravel, asphalt, wood, concrete or other surface)	Point
Moving things	Point
Interaction with buildings (e.g. opening and closing doors and windows)	Point

Unidentifiable activities, shuffling, shifting sounds (not related to car or heavy work) Playing music; whistling Domestic and living sounds (kitchen and dining) Children and infants	Point Point Point Point
Animals (wild and domestic)	
Crows/seagulls Birds (call, song, chirps, or wing flutters) Dogs Insects (crickets and other buzzing sounds)	Point Point Point Point
Environmental	
Weather-related sounds, such as: wind, thunder, air and atmospheric sounds, rustling of trees and leaves	Omni
Utilities	
Garbage and recycling: truck operations (usually scheduled and short in duration, around 15 minutes along a lane; high power/intensity) **Other trucks and special operations** **Private recycling**: sound of bottles, cans, and carts	Point Point Point
Work and equipment	
Construction and work noises characterized by hammering, impact noises, and heavy objects being moved Machines, including mowers and trimmers HVAC systems such as air-source heat pumps and air conditioners, other mechanical equipment and motors Telephone ring	Point Point Point Point
Sound mark	
Church bell	Point

Each sound type includes various component sounds; for example, a garbage truck generates a wide variety of different sounds, and crows' calls vary dramatically. These are described in more detail in Appendix 2. Figure 71 below presents sound types and total duration for each type.

The top two sound types are transportation. The third most frequently identified sound type is mechanical and equipment noises. The fourth most frequently identified sound type is crows.

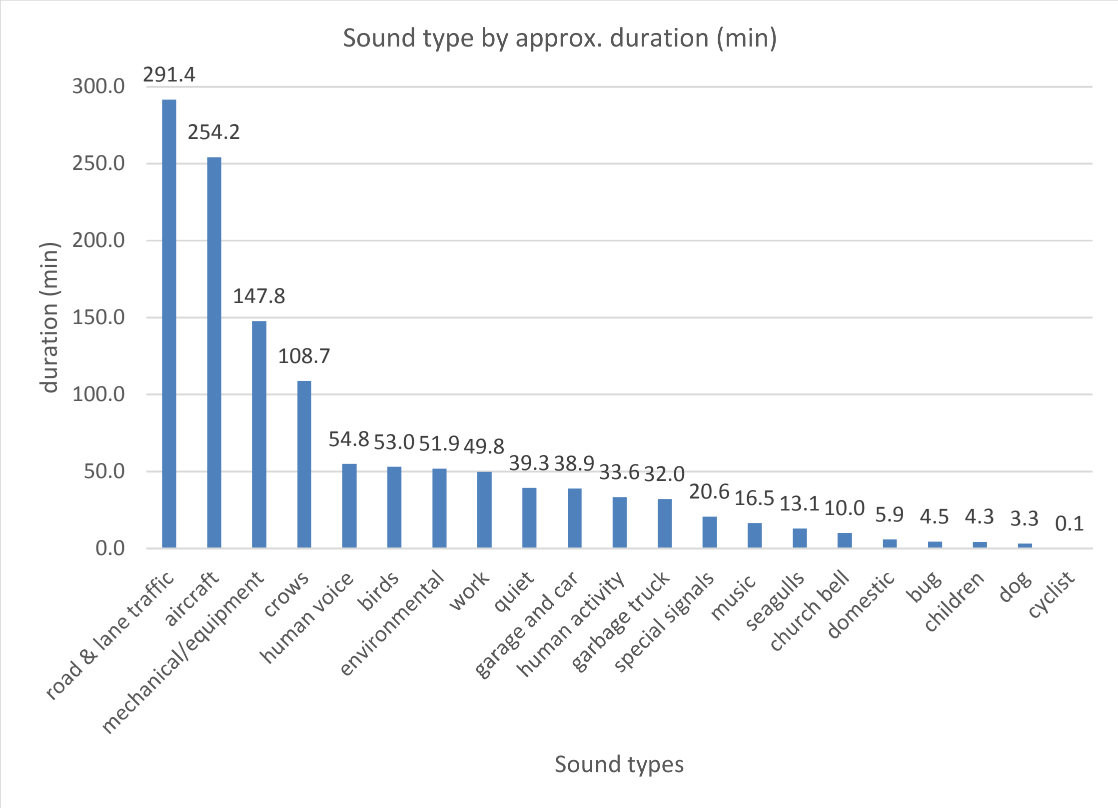
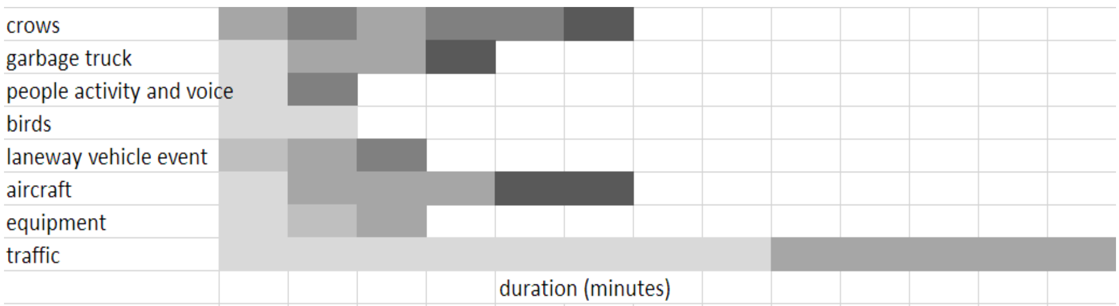


Figure 71: Sound types and duration

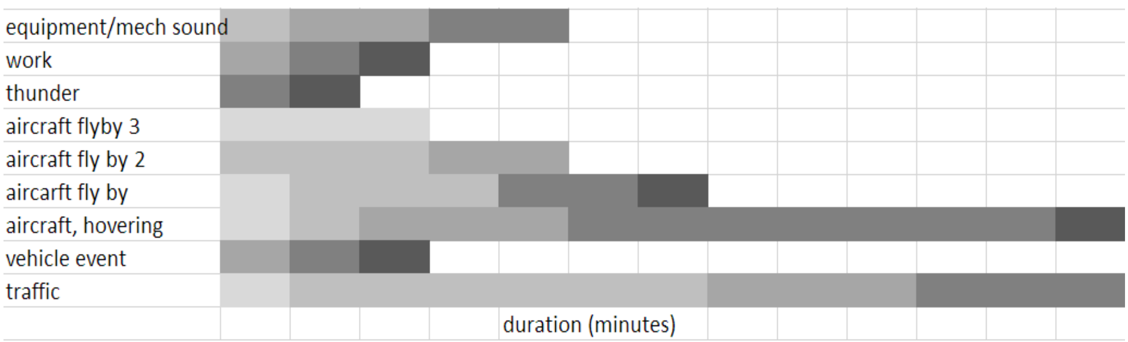
Transportation- and work-related noises inside laneways have particularly high amplitude, with transportation and vehicle noise levels giving the impression of being in the 70-90dB range. In general, sounds have widely varying degrees of amplitude changes over time, from very soft to very loud. Often, multiple sounds overlap and have closely correlating and clustered occurrences. Loud or close-by cars and aircraft sometimes trigger intensification of crow calls, and garage and car (people coming home) sometimes trigger dog barks. Multiple types of aircraft with very different frequency composition and flight patterns can be heard simultaneously, such as a helicopter hovering while jets take off or land on lapped schedules. It can sometimes be difficult to discern between continuous mechanical equipment noise and multiple distant aircraft noises, particularly when there are other similar noises occurring simultaneously like intensified road traffic activities. Sometimes, multiple high amplitude sounds occur simultaneously, for example, a garbage truck operating, a helicopter hovering and a jet flying by all at the same time.

Examples of sound clusters (sound occurring simultaneously) with amplitude patterns are displayed in the figures below. Figure 72(a) and (b) show example clusters of simultaneous sound activities observed in Charles lane and E. Hastings lane. Each sound type has variations in amplitude and duration. For example, traffic noise and aircraft noise can outlast all other concurrent noises while birds and garbage trucks are shorter in duration.

Duration of simultaneous sound types with variance in amplitude



(a) Simultaneous sounds in Charles lane



(b) Simultaneous sounds in E. Hastings lane

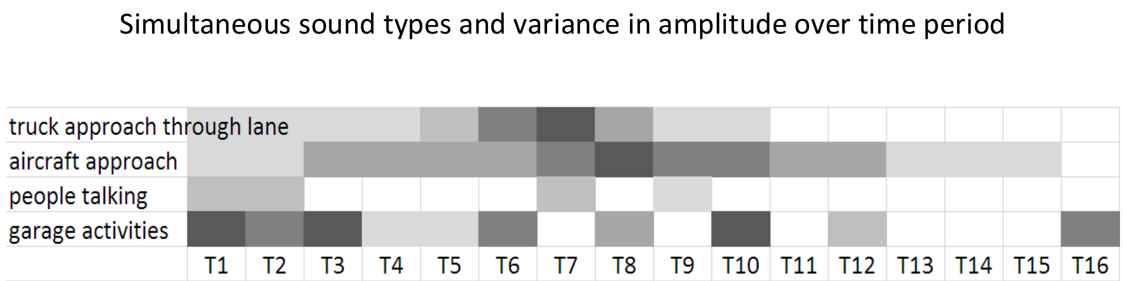
dBA (approx)	20-30s	40s	50-60	60-75	75-100
	faint				very loud

Legend (approximate amplitude)

Figure 72: Amplitude and duration of some simultaneous sounds in (a) Charles lane and (b) E. Hastings lane

Figure 73 below is an example of simultaneous sound types and amplitude changes over time.

T1, T2, T3… are sequential time periods not necessarily of equal duration.



dBA (approx)	20-30s	40s	50-60	60-75	75-100
	faint				very loud

Legend (approximate amplitude)

Figure 73: Simultaneous sound types and amplitude variance over time (snapshot from E. Hastings lane)

Sounds may last a split second, shorter than a minute, short with many staccato instances over several minutes, continuous for several minutes or longer, with changing amplitudes. Some sounds may be masked by others and thus unidentified.

Machine noises and low rumbles do not have to be at high levels to be annoying. Distant, low amplitude construction noise can be very distinct and artificial in a quiet setting. Interestingly, some garbage trucks are relatively quiet and shorter in duration compared to other truck operations, and these garbage truck activities are less disruptive than expected. As annoyance and pleasantness depend on context and the listener, assessment from audio recording without visual and physical immersion reflect this author's subjective reactions. The author found some sounds to be annoying; these include: continuous high amplitude aircraft noise lasting longer than two minutes, continuous high amplitude crows lasting longer than 10 minutes, high amplitude short duration vehicle noises and low machine noise in a quiet setting. The author found some sounds to be pleasant; these include bird songs, children's voices, church bells and distant train horns.

In general, evenings are a lot quieter and less eventful than daytime hours. E. Hastings is particularly notable for being quieter in the evening due to excessive daytime levels.

Other notable unique laneway sounds were observed in the field during Chapter 2 and 4 work, and experienced from walking in Vancouver laneways and living near a commercial-RS lane; these are:

- **Utilities**: BC Hydro trucks for maintenance of power lines and electric equipment
- **Activities**: wheeled carts, scavenging and bottle collection
- **Play and recreation**: basketball through hoops affixed to garages, lane hockey, freestyle bicycle stunts, skateboarding, dining and parties on the patio
- **Commercial-RS blocks**: heavy commercial equipment and maintenance vehicles like pressure washers and grease trucks with significant motorized pump action
- **Other:** interactive and dynamic acoustical effects like flutter echoes

3.3.2 Categorization

After all sounds have been inventoried for sound type and duration, object-centered and subject-centered approaches were both tested to classify the sound types. The subject-oriented categorization method is selected for use as it yields more meaningful pattern from the standpoint of the laneway user. This taxonomy is then modified into “laneway-centered categorization” to better align with the goals of this study. Laneway-centered categorization organizes all sounds first in terms of origin, whether it comes from *outside* or *inside* the laneway. The OUT and IN sound types are then assigned to subject-centered categories “transportation/works” (TW) and “people presence” (PP) on level two. On level three, people presence (PP) sounds are further classified into “lively” for activities, or “relaxing + Nature” for passive or non-anthropogenic sounds [89]. Transportation/works sounds include all traffic, vehicle, work and equipment sounds. People presence sounds include all sounds made by or heard by people. People presence is further categorized into lively sounds, such as communication and activity sounds, and relaxing + Nature sounds, such as birds, water, and weather effects. See Figure 74 for a schematic diagram of laneway sound categorization.

Table 14 shows the result of categorizing all sound types identified from the audio recordings. Level 1 is the OUT/IN categorization; Level 2 is categorization by transportation/works or people presence; Level 3 further categorizes people presence sounds into lively or relaxing + Nature.

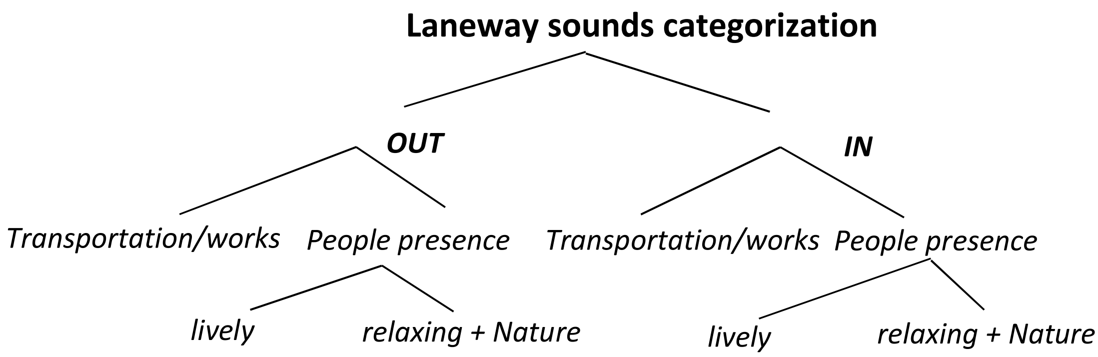


Figure 74: Laneway-centered sound categorization schematic diagram

Table 14: Laneway-centered sound type categorization for all sounds observed

Level	**Laneway sound categorization**					
1	**OUT**—from source outside laneway			**IN**—from source inside laneway		
2	Transportation/ works	People presence		Transportation/ works	People presence	
3		Lively	Relaxing + Nature		Lively	Relaxing + Nature
	aircraft, special vehicle signals, loud road traffic, normal road traffic, low road traffic, breaks/screeches, work, equipment	domestic, music	crows, seagulls, birds, environmental, church bell	close vehicle incident, garage and car, garbage truck, mechanical, work, miscellaneous, cyclist	human voice, human activity, children (talking), dogs, music, miscellaneous	birds (call, fluttering, singing), bugs, environmental, quiet

Table 23 in Appendix 2 provides itemized sound type contents with more detailed description.

The total duration of sound types in each category from all laneways are summed and charted in Table 15. Total duration of all sounds identified from the four case study laneways is 20 hours 33 minutes and 44 seconds (1233.73 minutes), exceeding the original 12 audio recording hours by about 8-1/2 hours due to multiple sounds occurring simultaneously.

From Figure 75 below it is clear that two-thirds of sounds heard inside the case study laneways are *transportation/works* sounds, more than twice the number of *people presence* sounds. Close to two-thirds of sounds heard inside the case study laneways come from outside the laneways.

Table 15: Subject-centered and laneway-centered categorization data table by duration

Duration (minutes)	**Transportation/works**	**People presence**
	833.78	399.95
	OUT	**IN**
Transportation/works	590.87	242.92
People presence	193.28	206.67
Total (OUT/IN)	**784.15**	**449.58**

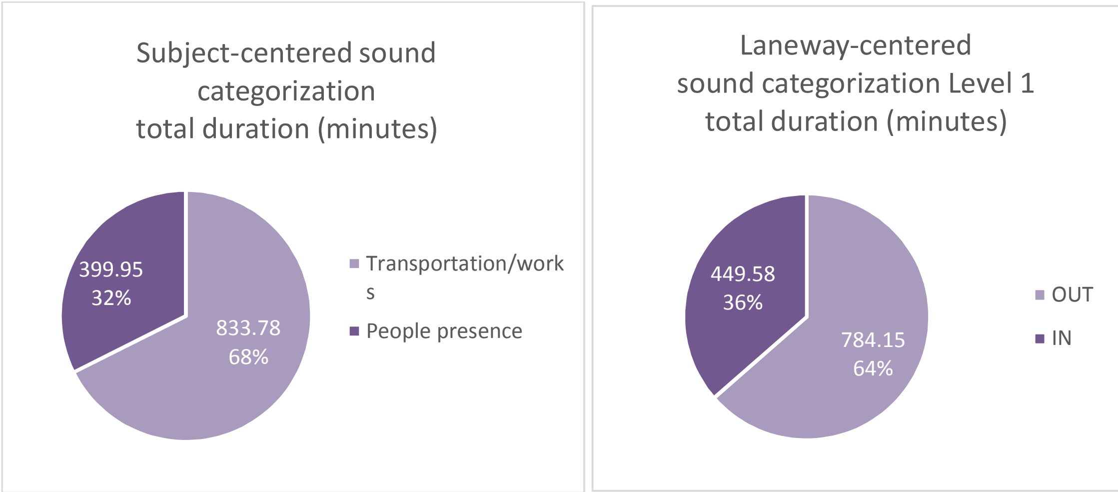


Figure 75: Subject-centered (left) and laneway-centered (right) categorization by sound duration

Figure 76 below takes the laneway-centered Level 1 categorization one step further, classifying the "IN" and "OUT" categories into Level 2 subject-centered categories. Results show that of all the outside sounds heard inside the laneways, 75% or three-quarters are *transportation/works* sounds and 25% or a quarter are *people presence* sounds. Sounds originating inside laneways are much more balanced, with *transportation/works* at 54% and *people presence* at 46%.

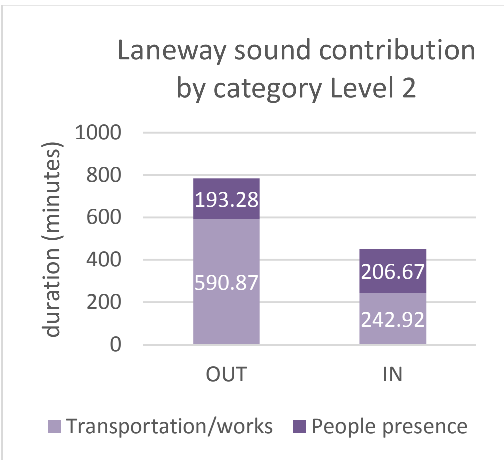


Figure 76: Laneway sound contribution by category, total duration

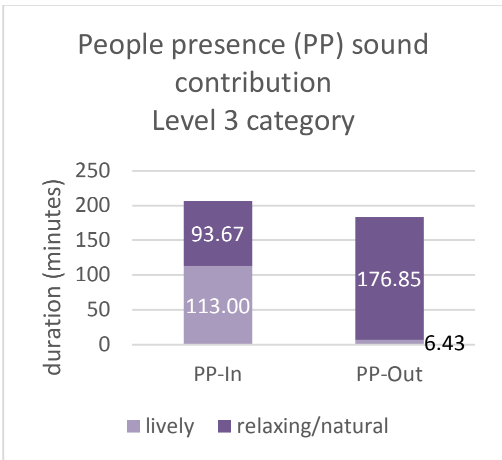


Figure 77: People presence sound contribution by lively or relaxing + Nature sounds

In the figure above (Figure 77), it can be seen that the people presence sounds originating inside laneways are fairly balanced between lively sounds by people's activities, and relaxing + Nature (passive or non-anthropogenic) sounds, mostly of bird song and quietness. People presence sounds coming from outside laneways are 96% natural, primarily crows and environmental sounds. This demonstrates that there are more people activity sounds inside laneways than outside laneways.

At Charles lane (Figure 78), about three quarters of sounds are transportation/works (TW) and one quarter of sounds are people presence (PP). The distribution of OUT/IN sounds is almost identical to TW/PP distribution, with three-quarters of the sounds coming from outside and one quarter from inside Charles lane. The proportion of lively activity sounds by people in Charles lane is high, at 88%.

Charles lane sounds categorization

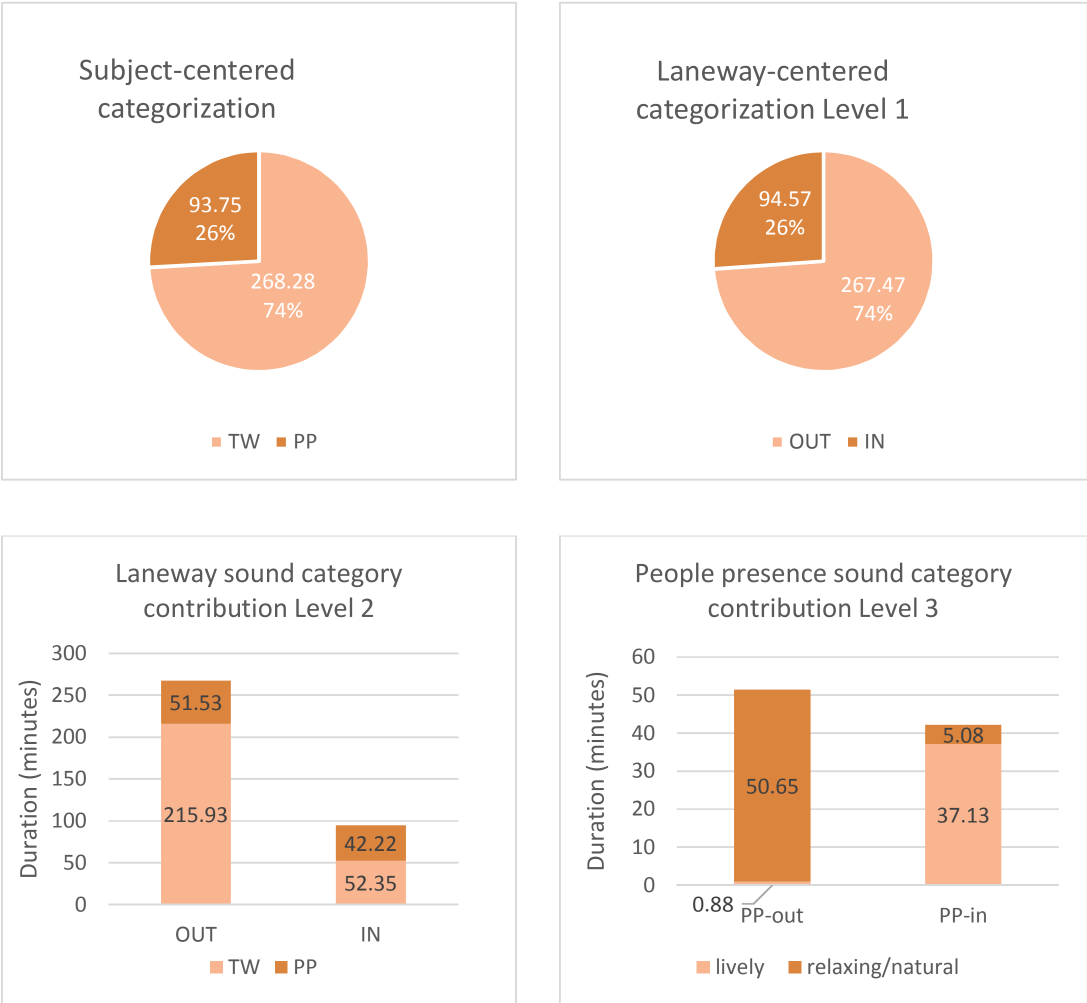


Figure 78: Charles sounds categorization (duration in minutes)

In E. Hastings lane (Figure 79), significantly more sounds come from inside the lane than the other case study laneways, marginally exceeding sounds from outside the laneway. This is expected as E. Hastings, being a high density laneway, lined with mixed-use buildings on one side and located right by a busy commercial area, has much higher levels of activity within it than do other laneways. As laneways become more populated and increase in residential density, activity levels, total noise levels and noise duration will increase as seen from the E. Hastings case.

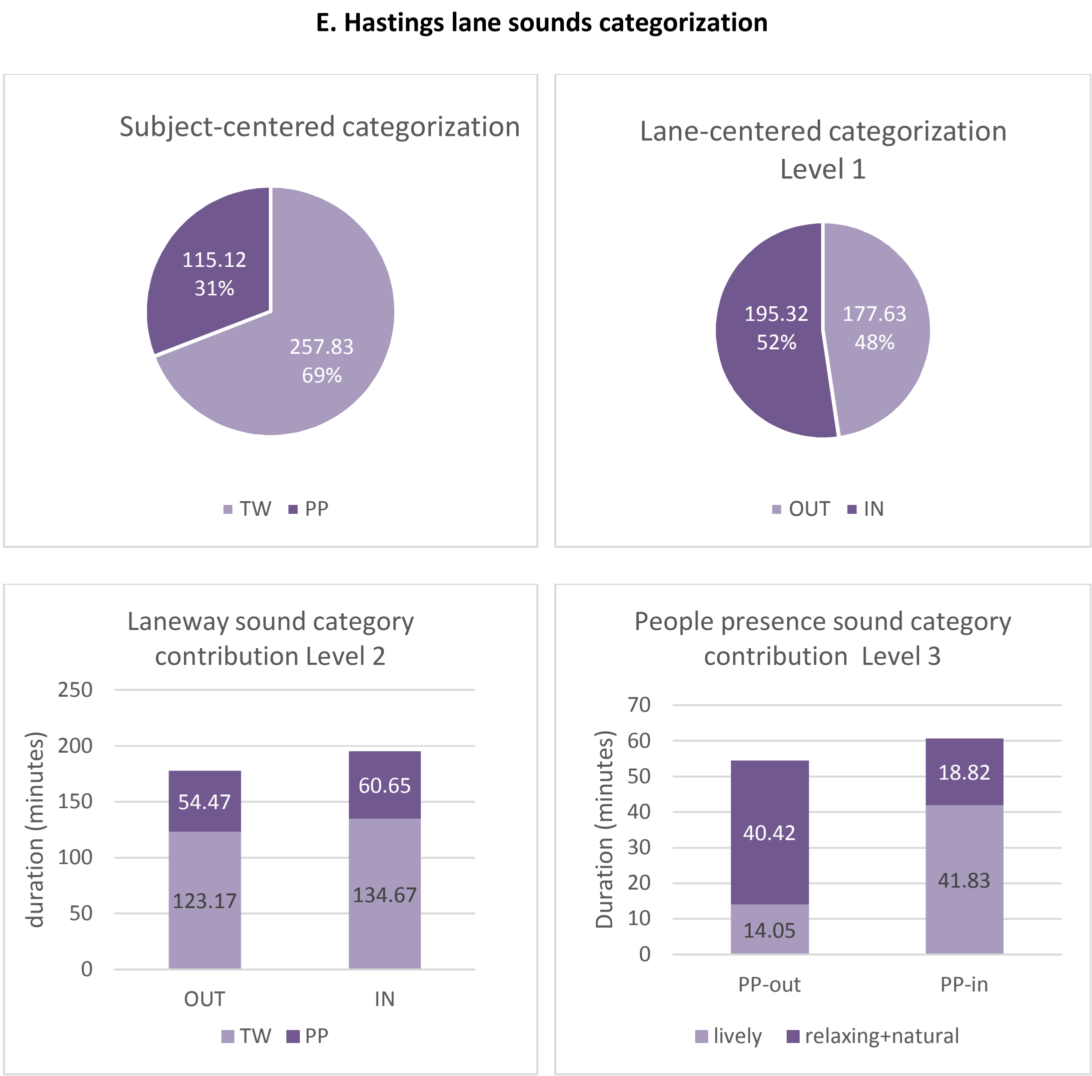


Figure 79: E. Hastings sounds categorization (duration in minutes)

William and W34th, the more "normal" Vancouver laneways, reflect the general pattern, where most noises come from outside and are of transportation/works-category (see Figure 80 and Figure 81). For sounds from inside laneways, Williams has a much lower proportion of transportation/works sounds, while W34th is balanced between transportation/works and people presence. W34th is the lowest density case study laneway with the highest amount of vegetation.

William lane sounds categorization

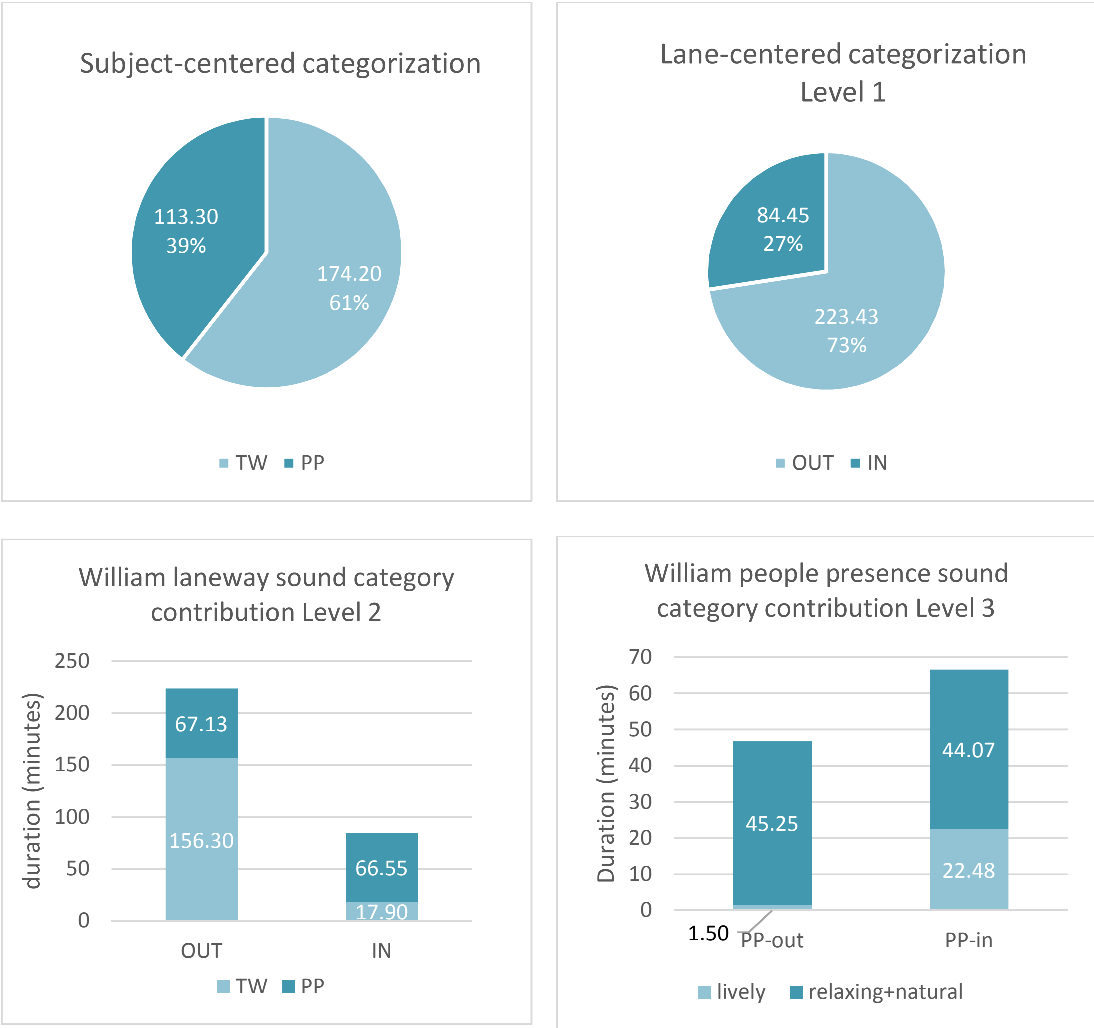


Figure 80: William sounds categorization (duration in minutes)

W. 34th sounds categorization

Figure 81: W34th sounds categorization (duration in minutes)

3.4 Discussion and chapter conclusion

In summary, a significant proportion of sounds heard in the laneway are outside noises, in particular transportation/works noises. Road traffic noise, a component of transportation noises, are line sources, and distinct vehicle noise and work noises are examples of point sources as explored in Chapter 2. E. Hastings is unique for having a majority of sounds coming from inside laneways, which is attributed to its high density setting, which the City is moving towards. Compared to sounds from outside laneways, sounds from inside laneways are much more balanced between people activity sounds and transportation/works. It must be noted here that transportation/works noises inside the laneway can be very loud due to close-approach. When loud noises by close approach or other reasons occur excessively or last for long periods of time, it will be disruptive to LWH residents.

People activity sounds inside laneways include a noticeable contribution by intimate casual conversations, including those between parents and children, reflecting that the laneway should ideally be an intimate, nurturing and at-home space. Conversations in multiple languages—four in total—were observed, reflecting the multicultural social fabric of Vancouver.

CHAPTER 4: The laneway house and exterior noise insulation

This chapter investigates the laneway house; specifically, the outdoor-indoor sound transmission loss of LWH facades. Where outdoor noise levels exceed CMHC criteria, the building envelope must provide adequate noise protection for indoor spaces. Study of in-situ outdoor-indoor transmission loss (TL) involves many bodies of knowledge and acoustical principles, and following sound through multiple paths of the building envelope. Outdoor levels and source characteristics need to be determined; this involves analysis of facade siting and orientation in relation to sources. The architectural programming and layout is important as it determines the usage and noise sensitivity of a space. The facade size, its constituent components such as fenestration and ventilation openings, attached assemblies such as adjoined walls and roofs, and construction quality all contribute to the envelope's overall performance. The physical properties of each building material in a component, and a component's geometrical configuration, results in combined absorption and transmission mechanisms. For example, in an exterior wall assembly, the cross-sectional multi-layers of different materials, each at a unique thickness possibly with unique air gaps, will transmit sound in a combined manner unique to that assembly. In terms of construction, flanking paths and air leak paths degrade acoustical insulation of the building envelope. Finally, room absorption and facade size also affect receiver level inside a LWH living space.

TL data of a building facade is used to calculate the sound insulation rating for practical application. In this chapter, theory and literature on transmission loss and outdoor noise insulation are reviewed and methods of study are introduced. The results section includes assessing case studies for compliancy with CMHC criteria for facade insulation against outdoor traffic noise, revealing at-risk conditions, and proposing mitigation strategies.

4.1 Literature review

4.1.1 Architectural design considerations in CMHC

Acoustical strategies in architectural design help ensure that the designated use for each room or living space is not affected by inappropriate levels of road noise. CMHC determines indoor criteria based on room use. CMHC also considers many architectural factors to determine required facade insulation for a room. Siting and building form influence the exterior SPL of the facade. Room floor area relates to room absorption. The number of components in the relevant facades determines effective facade insulation. Component category, type and size determine component contribution to overall facade insulation.

With respect to LWH, size limitations, architectural preference (such as the qualities of spaciousness and openness) and the privacy/onlook specifications in the LWH Design Guide may be incompatible with acoustical design principles such as those found in CMHC, Sound Smart and similar literature for residential noise control [8] [14] [18] [93].

When assessing sound insulation of a living space, room size and room absorption influence the indoor receiver level of outdoor sources. Room absorption and facade size are often used in calculations for outdoor-indoor transmission loss provided by the building envelope (Eq.(9)). Smaller rooms have less room absorption for sound attenuation, and will need to rely on higher facade and component insulation to reduce outdoor-indoor receiver level. Indoor absorption can be increased by increasing absorptive surface area and furnishing rooms, particularly using absorptive finishing such as heavy curtains, tapestry, carpeting, and plush furniture in thick upholstery. Heavily furnished spaces attenuate sound significantly more than empty spaces with reflective bare surfaces. NRC-Quirt TNM considers room finishing in modelling procedures [37].

LWHs often have modern, minimalistic interior design featuring hardwood or bamboo flooring and other smooth, hard surfaces with low sound absorption. While these surfaces are trendy, easy-to-clean, and improve the sense of spaciousness, they provide little noise reduction compared to rooms with ample amounts of absorptive material.

In the CMHC TNM, facade insulation requirements and estimation of a component's effective insulation depend on component types (exterior wall, door or window), component size, facade size, receiver room floor area and room characteristics [14] [37]. Smaller facade or component size in relation to the room floor area is assigned higher insulation rating (AIF); larger facade or component size in relation to the room floor area is assigned lower insulation rating [14, pp. 57-9]. In other words, the facade/floor area ratio inversely relates to perceived capacity to insulate the room. Component sizes have a similar effect. For example, using large windows, glazed double doors, or a whole facade of sliding glass doors for a small room is not helpful in terms of acoustics unless these are made for higher insulation.

In reality, smaller living spaces such as those in LWHs quite often do have relatively large facades and relatively large fenestration compared to floor area. Because fenestrations are often weaker than walls, their effect on overall facade insulation is negative. The fenestration/facade area ratio inversely affects facade insulation. In the ways described above, LWHs can have higher facade/floor ratio *and* fenestration/facade ratio than what are acoustically beneficial.

Studio, open-plan, and loft layouts popular in LWH consolidate indoor room volume and floor area by eliminating partitions. On the one hand, this increases receiver room size for sound absorption. On the other hand, this exposes sensitive areas like sleeping quarters to active spaces with more noise. In a studio layout or open plan where there is no separation between sleeping area and areas for other use, the space should ideally comply with the most stringent criteria: 35dBA for bedroom. Achieving this more stringent standard may require acoustical upgrade of facade components. In addition to road traffic noise, noise contribution by ventilation and indoor appliances can also compromise indoor acoustical environmental quality.

4.1.2 Transmission loss theory

In addition to architectural dimensioning and room absorption, the in-situ sound insulation of building facades is largely based on the construction's transmission loss (TL). Transmission loss (TL) is the fundamental metric describing the sound insulation of building partitions. TL theory considers mass, frequency, panel impedance (which relates to stiffness), thickness and incident angle key factors in sound energy reduction. In fact, mass (mass density) is so important that the *mass law* is central among theories describing TL. A practical form of the mass law is [17, p. 321 eq.9.21] [93]:

$$TL_f = 20\log[fm] - 47 \qquad \textbf{Eq.(8)}$$

where TL_f is the diffuse field sound transmission loss in dB, f is frequency of concern, and m is the mass density (kg/m^2) of limp panel material. Mass density (kg/m^2) controls TL, especially in the lower frequencies. The higher the mass, the more resistant a material is to sound transmission. The lower the frequency, the higher surface mass density is required to achieve a given TL. Other factors influence TL. TL also increases with increase of frequency, stiffness, impedance and thickness. TL decreases with increasing panel size. TL data is presented in decibels (dB) at one-third octave band frequency (Hz), over the architecturally relevant frequency range.

Thin panel and thick panels behave differently and are governed by different phenomena at different frequency ranges. Thin panels such as those commonly used in wall assemblies exhibit a coincidence dip at the critical frequency, and are controlled by stiffness at frequencies above critical frequency [ibid]. Thick panels are controlled by shear impedance above critical frequency [ibid]. Variations of TL equations used to cover the whole range of TL behaviors in different panel types and multi-panel arrangements include factors of radial frequency, surface mass density, panel thickness, speed of sound (room air condition), angle of sound approach, and different impedance factors like bending stiffness and shear modulus calculated by Young's modulus and Poisson's ratio [17, p. 329]. Thick panel behavior is less relevant in LWH facade except for the foundation wall and where structural insulated panels (SIPs) are used.

For double panel and triple panel TL more applicable to wood stud walls and double glazing units common to LWH, there are additional considerations, such as individual layer thicknesses, layer separation (cavity or airspace width), and the mass-air-mass resonance phenomenon (M-A-M) [17]. M-A-M is a significant disadvantage that can be helped by increasing surface mass, optimizing air cavity width and/or using absorptive damping material in cavity [17] [35] [93] [94] [95]. Cavity TL contribution comes more from cavity depth (thickness) and absorption [17] [96].

Absorption for porous materials is related to porosity and air-flow resistivity; for fibrous materials, fiber material radius and density are important [97].

TL varies over different incident angles. TL is greatest for normal incidence where sound approaches perpendicular to the receiver surface and there is no coincidence effect [17, p. 324]. Field or diffuse field TL at random angles is generally 5dB lower than normal incidence [17, p. 322]. TL becomes progressively lower for sound approaching at grazing angles of 80° or greater [37] [98]. In research, a diffuse field scenario is used in modelling and empirically, the diffuse field is modelled by multiple angle positions of the sound source to average out the angular variance of TL [99].

Where TL is determined by level reduction (LR) rather than the partition's physical properties, facade surface area is accounted for and room absorption is subtracted from the level reduction (LR) in order to isolate the in-situ partition outdoor-indoor transmission loss (OITL) [93]:

$$TL = L_1 - L_2 + 10\log\left(\frac{4S\cos\theta}{A}\right) + k \qquad \textbf{Eq.(9)}$$

where L_1, L_2 are outdoor incident sound level and indoor received level, respectively; the expression $L_1 - L_2$ is the level reduction LR; S is surface area of transmitting element in m^2, A is receiver room absorption in m^2 (see Eq.(10) below), k is an adjuster for receiver location, and TL is transmission loss of element in dB; and

$$A = \alpha_{room}S_{room} \qquad \textbf{Eq.(10)}$$

where α_{room} is the absorption coefficient of the room interior surface, theoretically a fraction no larger than 1, and S_{room} is the room interior surface area in m^2 [100]. *A* is determined by Eq.(11) in field testing.

The next section provides practical outdoor-indoor transmission loss (OITL) and insulation information applicable to LWH.

4.1.3 Sound insulation principles and strategies in LWH construction

The building envelope is an essential path for noise to reach the indoor receiver and TL through this segment is the most relied upon to reduce indoor level. The building envelope is a multi-component assembly with dynamic TL effects. The primary paths for noise transmission through the envelope are walls and roofs. These include all flanking paths and secondary paths such as fenestration, ventilation openings, connections and joints, penetration details (such as utilities and services), and air leakage paths, each contributing to the outdoor-indoor level.

Literature provides guidelines for homebuilders to help achieve good insulation against exterior noise. The City of Vancouver's "Sound Smart Guide", the FHWA's "Guide to the Soundproofing of Existing Homes against Exterior Noise", NRC's "Insulating Buildings against Aircraft Noise," and other authoritative publications offer practical advice [8] [93] [101] [102]. Sound insulation strategies are best incorporated early in the design process to be considered synergistically with other architectural and engineering concerns. Acoustic remediation or retrofits can be complicated and costly, while possibly providing only limited improvement.

As discussed in theory, TL increases with surface mass and stiffness. Most cladding materials are stiff, but not all are heavy and dense. Heavy and dense material like brick, concrete, fiber cement board, and cement stucco are generally better sound attenuators than vinyl, wood panels and externally-insulated facades (EIFS) using rigid foam insulation, especially in the lower frequencies.

Increasing thickness can increase TL by adding to bulk density. An example would be adding an extra gypsum board to a wall assembly. Thicker panes of glass and laminated glass perform better than thinner counterparts, e.g. 6mm instead of 3mm, within a certain limit.

Low frequency noise insulation requires down-shifting the normal incidence mass-air-mass resonant frequency by means of wider air cavity and thicker wall leaves with higher surface mass density, or alternatively by massive monolithic construction [103]. However, these are impractical for LWH. Depending on the thickness required, increasing wall thickness unfavorably decreases floor area for the already space-conscious LWH. Additionally, denser, heavier wall materials can be more expensive to source, transport and handle, and more difficult and slower to build than standard wood stud walls or light modular panel systems.

Damping and separation of elements cut off sound paths and limit sound transmission. Interconnected or continuous stiff elements can form flanking paths; operable components and impact surfaces may need cushioning or absorptive treatment. Literature suggests decoupling parts, spacing wall studs further apart, inserting vibration breaks, and using larger air gaps between layers of rigid wall leaves and between double glazing lites—minimum of 25mm—to achieve noticeable attenuation [8] [93] [101] [102]. Storm windows, storm doors and vestibules providing additional partition layers and air space, split wall cavities, and proper use of resilient channels and/or staggered studs can all be very effective [94] [104].

Absorption improves TL in various ways. Multi-panel structures benefit from having adequate absorption between stiff panels, like filling the cavity space with rockwool or cellulose [8]. Outside airborne sound, entering through ventilation openings, chimneys, air intakes, and even open windows, can be reduced by dampers and sound-absorptive lining around opening perimeters and along air paths. Sealant material can also provide benefits with absorptive and dampening effects in addition to air barrier or sealing function. It should be noted here that sound-absorptive insulation and liners can collect dust and thus require accessibility for proper maintenance.

Literature considers air-tightness highly important for good noise reduction. High frequency airborne sounds transmit through air leaks; small or hidden gaps around penetrations and joints can degrade TL for the entire facade. A miniscule gap of 0.4mm (1/64") around the perimeter of a 1mx2m (3'x7') door reduces the STC rating of the door from STC 36 to STC 29 [105]. Eliminating gaps, sealing off and taping the seal around windows, doors and other joints, using the correct sealant material and carefully installing well-designed weather-stripping are common advice for maintaining good facade insulation [8] [93] [101] [102] [104] [94]. Good air-tightness implemented for thermal performance can benefit acoustic performance, but air-tightness alone does not fulfill sound insulation goals.

Acoustically-balanced design is important. Highly sound-insulating walls are best matched with highly sound-insulating fenestration. The weakest element of a facade will degrade insulation performance for the rest of the assembly, thereby negating the investment placed in the highly-insulating element. Some consultants apply a principle of requiring the outdoor-indoor transmission class (OITC) of walls and roofs to be 10dB higher than the desired level reduction in order to account for the lower insulation ratings of attached components, commonly one door and two basic non-acoustic windows [106].

Smaller LWH envelope size relative to that of the normal house correlates to a higher concentration of flanking paths, joints, penetrations and fenestration coverage, which lowers building envelope sound insulation. Windows, particularly operable open windows, are often the weakest link in a facade. This is particularly true of ground-oriented living in detached LWH, especially during the summer when people keep windows and patio doors open for cooling, natural ventilation, and closeness to the outdoors.

Acoustically-optimized double glazed windows, such as those with 25mm-or-wider inter-pane spacing (possibly filled with argon gas) and special glazing mounts, can increase insulation against noisy locations. Open windows can be improved by absorptive reveals and baffles [93]. To get the best value from acoustical windows, seal them properly with the correct sealant, tape the seals, and set them in an acoustically robust wall that has at least a comparable insulation rating and is unencumbered by serious leaks or flanking from other building components [93] [107]. Electric, ventilation, and other facade penetrations and/or installments should all be planned and executed with good acoustics in mind.

Environmental noise in three-dimensional space affects the whole building envelope; outdoor-indoor levels at a receiver space may be the result of contribution from multiple facades. This is especially relevant for walls (including any windows) connected to each other at the building corner, and for roofs (including any skylights) on small one-storey buildings and/or over a lofted space, which are all common in LWH. ASTM E966 specifies a prequalification test to exclude facades with excessive flanking and discourages use of the standard to rate facades connected to roofs, since significant outdoor-indoor level may be attributed to the roof and not just to the test facade [99].

Having an acoustically weak roof can degrade the performance of otherwise acoustically robust walls, much like poorly performing windows [101] [106]. In published tests, roofs have the same or higher OITC values than walls, depending on cavity depth and insulation between the roof and ceiling, ventilation, and flanking details [8, pp. 49, B-4] [14, p. 55] [93]. Green roofs improve transmission loss of roofs and increase sound absorption [10]. Although roof TL is important considering the high levels of aircraft noise in Vancouver and popularity of loft-style laneway bedroom spaces, roofs are difficult to measure and are beyond the scope limits of this study. CMHC excludes roofs from its road traffic insulation considerations [14, p. 55].

4.1.3.1 New wall types and rigid foam insulation

In the current state of building science, there is increasing use of energy-efficient wall systems for residential application as seen in sustainability standards like the Passivhaus. Builders now have more choices and more incentives to use materials and systems different from the standard fiberglass batt-and-wood stud walls. These include higher-efficiency rigid foam or board insulation, such as expanded polystyrene (EPS), extruded polystyrene (XPS), and polyisocyanurate ("polyiso" for short) closed-cell foam insulation with higher thermal performance (R-value); and prefabricated modular exterior-insulated facade systems (EIFS), structurally insulated panels (SIP), and super insulated panels based on advanced thermal insulation materials. SIP systems and board insulation are also lightweight, and are faster and easier to ship, handle, and assemble with more consistent quality. For simplicity, these products will be collectively referred to by their simplest common type, the SIP and/or board insulation. Though not yet common practice, there are a few Vancouver LWH built with SIP in response to current trends towards high energy performance building design. These LWHs have received green building awards for energy performance [108] [109] [110].

SIP and board insulation appear to have significantly lower acoustical properties than the traditional batt-insulated wood-stud wall of comparable thickness. The standard 114mm SIP (OSB-EPS-OSB) has a laboratory tested rating of STC-22, at least 9 points lower than a standard batt-insulated wood stud wall of the same size [107, p. 72] [111]. EPS, which is essentially Styrofoam, is a poor sound insulator [8, pp. 22, 23, 28]. XPS and polyiso are similar materials with slightly different density and cell-structure. These rigid materials are generally non-absorbent to acoustic waves. Due to low mass, they are poor at stopping sound transmission over important frequency ranges, and prone to transmission, resonance and vibration. Industry professionals even advise against using SIP as floors over an open interior space without the application of a sound barrier [112].

Furthermore, double- and particularly triple-glazed thermal windows used in LWH may not have wide enough glazing separation for noise reduction. In the worst cases, these thermal windows may have no acoustical benefit over single-pane windows due to mass-air-mass resonance effects [93].

While Passivhaus has very high acoustical standards, this is often achieved as a result of thick walls (approximately 254mm or more) and completely airtight construction still uncommon for Vancouver's RS buildings [113] [114]. The new Vancouver Building By-law VBBL-2014 requires effective R-values of 3.85RSI or R-22 for frame and foundation walls [115]. To save space and meet R-value requirements, LWH may begin to adopt thinner and lighter board insulation or SIP at the expense of acoustical living quality, if builders and users remain uninformed of the acoustical limitations of these materials. It is expensive and difficult—due to plumbing and electrical penetrations, to try to increase construction STC when SIP is used, though there is a published case of a successful acoustical retrofit of an SIP home exposed to highway noise, using resilient channels [116]. This study includes a supplemental investigation on SIPs in anticipation of its growing application in LWH.

4.1.4 Facade sound insulation rating systems

While TL data is best represented by the TL curve over the full architecturally-relevant frequency range, in industry application and building construction, single-number ratings are widely used for convenience. TL given as an SPL (dB) or by a transmission coefficient (τ) is applicable to only one frequency band and one incident angle. This study uses the AIF, OITC and STC in addition to the TL curve (TL data over relevant frequency ranges) for analysis.

CMHC and NRC TNMs use the *acoustical insulation factor* (AIF) in its calculations and wall insulation specifications [14]. AIF covers 100-5000Hz and includes frequencies for aircraft noise [93] [104]. The *outdoor-indoor transmission class* (OITC) covering 80-4000Hz is designed for exterior walls by including low frequencies common in traffic and transportation noises. The *sound transmission class* (STC) covering 125-4000Hz is the most popular rating system for building elements, although it is intended for indoor noise and speech communication privacy at frequencies above 125Hz. The OITC and AIF are the correct metrics for outdoor-indoor noise application, but they differ by some frequency bands (80 and 5000Hz) and the AIF includes component and room size considerations; thus they are not suitable for direct comparison. There is no direct method of conversion between AIF and OITC except to recalculate each separately with one set of facade TL data containing the 80-5000Hz spectral range, which is not available in this study. The STC is included where necessary for comparison and for general information. Government publications use both OITC and STC for rating exterior walls [8] [101] [94].

The AIF is calculated by TL data and component area as a percentage of room floor area and so includes relative contribution by facade size and room absorption, but does not consider actual room height [117, p. 33]. This is a point of concern when a room has double height volume not fully accounted for by the facade area. The STC and OITC only include TL data of the respective frequency ranges [98] [118]. A component's OITC, which includes the lower frequency bands 80 and 100Hz that the STC does not, is generally 5-10dB below the same component's STC [119]. Low frequency noises are harder to insulate against, especially in small light-frame buildings, so the OITC is the most important metric in this study.

Older sound insulation data is available by government lab tests for common construction components. In 1999, CMHC conducted the "Research Project on the Noise Insulation Provided by Exterior Walls in Wood Construction" to provide some OITC and STC values for common low cost residential Canadian wood-frame walls [94]. A 2000 NRC-IRC (National Research Council-Institute for Research in Construction) publication by Bradley and Birta, "Laboratory Measurements of the Sound Insulation of Building Facade Elements," provides a good database of facade element TL data, OITC and STC ratings for reference and comparison, including common exterior wall assembly components, windows, and roofs [107]. J.D. Quirt conducted an extensive TL measurement study on windows in 1981, which are summarised by STC rating [120]. These ratings may need updating to represent the latest construction methods and components used in LWH.

4.2 Hypothesis

As discussed in Chapter 1 Sections 1.1.5 – 1.1.6 and in Chapter 4 Section 4.1.1, LWH exhibit at least four major unfavorable factors in terms of acoustics. Firstly, LWH is extremely close to laneway noise sources, and may also be exposed to excessive road traffic noise. Secondly, LWH is small in size, which causes it to contain insufficient absorptive surfaces and contents, and to have relatively larger facade/floor area ratio and fenestration/facade ratios which decrease sound insulation, particularly when these face a noisy side of the building. Thirdly, LWH is built of lightweight building material that may not provide enough mass for damping or adequate insulation where outdoor levels exceed 55dB. Fourthly, the LWH Design Guide and LWH Guidelines do not inform LWH builders of acoustical needs and LWHs are currently designed and constructed without sufficient acoustical awareness. Based on a combination of these factors, it is anticipated that at least two case study LWHs will have indoor and/or outdoor living conditions that do not meet CMHC criteria, and at least two facade tested will not meet its unique CMHC-required insulation value.

4.3 Methodology

This chapter investigates real facade sound insulation performance through analysis of six case study laneway houses in Vancouver (see Case Study Laneway Houses section in Chapter 1). One test facade from each case study was field-measured per ASTM standard, and modelled for SPL at exterior face, insulation requirement to meet room criteria, and facade sound insulation rating as constructed. The test facade is one exterior wall, including any windows and doors set within, enclosing one room. The primary goal is to sample and evaluate the acoustical performance of each construction and rate the facades and indoor spaces for compliance with CMHC criteria. The second goal is to validate modelling tools by comparing TL results yielded by different investigative methods: field measurement, CMHC modelling, and modelling with NRC laboratory test data and AFMG Soundflow. In addition to six facade samples from the six case studies, there will also be supplemental investigation of SIPs using manufacturer laboratory test data and AFMG Soundflow.

4.3.1 CMHC: Modelling road traffic noise to LWH

The CMHC TNM is used to predict road traffic noise levels at facade exterior, and to determine the facade insulation necessary for indoor space to comply with criteria. CMHC prediction of ambient level at the facade exterior, as explored in Chapter 2, is based on the fundamentals of acoustics such as source directivity, receiver height, and shielding effects to derive noise exposure levels. This lends importance to siting and building form during the design process.

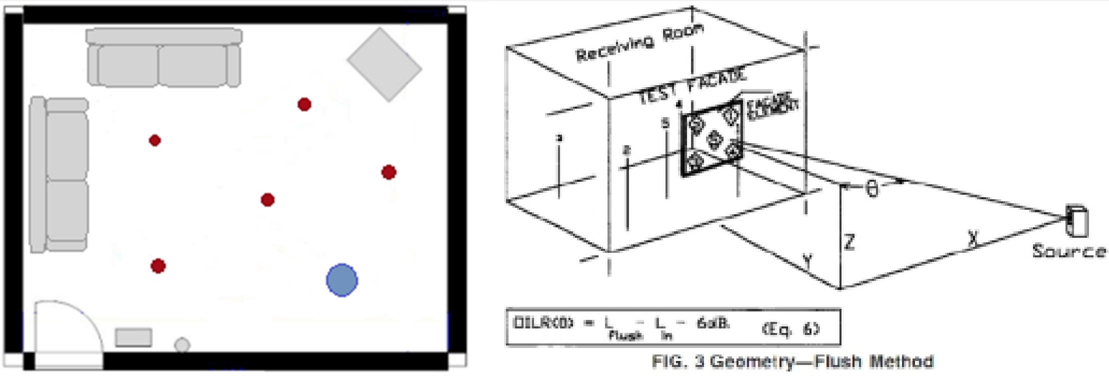
The test facade is modelled with the predicted outdoor noise level, facade construction and indoor space information to specify the acoustical insulation rating (AIF) required for each facade. These include room use, facade size, room floor area, and total number of components in the facade and adjacent facades, collectively considering contribution by room absorption, less insulating elements and flanking transmission. CMHC does not accommodate complex room volumes such as open lofts and vaulted ceiling designs. Ventilation openings and roof are also excluded, and all components are assumed to be without noise leaks [14, p. 55]. Tabulated procedures are used to estimate individual facade component AIF (based on component category, component size-to-floor size and type of construction) to check for individual component compliance [14, pp. 54-60]. To compare other sound insulation rating information with CMHC standards, the AIF is converted to STC per methods specified in NRC Building Research Note 148 p33 [117].

NRC TNM methods were also reviewed for cross-comparison; NRC includes angle of approach and spectral composition in source considerations, and degree of room furnishing in receiver considerations [15] [37] [117]. NRC is more stringent in terms of criteria than CMHC by about five points.

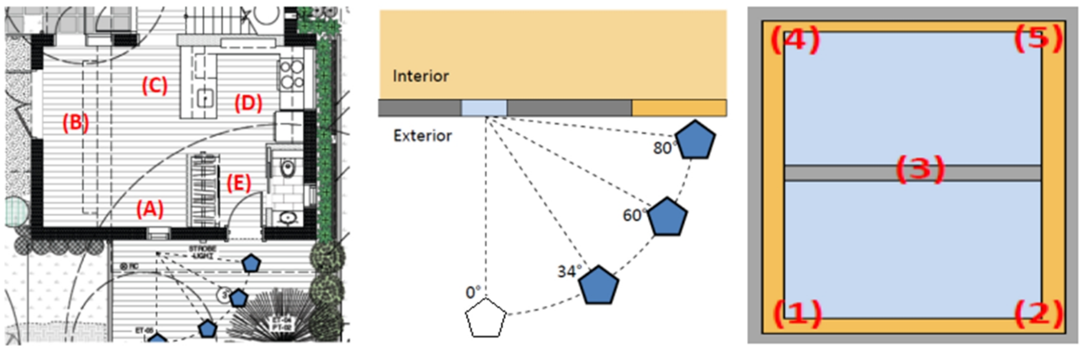
4.3.2 Field measurements of LWH facade

Field test procedures for building facade TL are prescribed in ASTM E966: “Standard guide for field measurements of airborne sound insulation of building facades and facade elements” [99]. Figure 82 below provides visual images of the field test setup for measuring the outdoor-indoor level reduction (OILR) and the room absorption.

ASTM E966 Schematic diagram



Above left: source and indoor receiver positions for room reverberation-absorption tests.
Above right: source and outdoor receiver positions for OILR tests by the flush method [99].



Above left: indoor receiver positions for OILR tests [114]. Above center: outdoor source positions for OILR tests. Above right: example facade exterior receiver positions for OILR tests [114]. Field conditions require variations that follow the basic principles outlined in the standard procedure.

Figure 82: ASTM E966 schematic diagrams for field testing of OITL

ASTM E966 offers various methods to position the source and outdoor microphones. Of these, the flush method is adopted, being the most suitable in the LWH context. The ISO standard for reference is ISO 15712-3 "Building acoustics -- Estimation of acoustic performance of buildings from the performance of elements Part 3: Airborne sound insulation against outdoor sound [121]." ASTM E966 requires field measured room absorption. This is performed by ASTM C423: "Standard test method for sound absorption and sound absorption coefficients by the reverberation room method [122]." Receiver room absorption, A_r is given by Eq.(11) below [99]:

$$A_r = 0.921Vd/c \qquad \textbf{Eq.(11)}$$

Where V is the receiver room volume, d is the decay rate and c is the temperature-dependent speed of sound in the room; A_r must be less than $V^{2/3}$ for furnished rooms for official rating [99].

The in-situ transmission loss (OITL) is calculated from a difference between the outdoor and indoor signal levels (OILR for outdoor to indoor level reduction), and adjusted for source position, background level, room absorption and facade surface areas. This is done via the following equations [99].

$$OILR(\theta) = L_{flush} - L_{in} - 6dB \qquad \textbf{Eq.(12)}$$

$$OITL(\theta) = OILR(\theta) + 10\log\left(\frac{Scos(\theta)}{A_r}\right) + 6dB \qquad \textbf{Eq.(13)}$$

where OILR is the outdoor to indoor level reduction, L_{flush} is sound pressure level (dBA) at various points flush upon the exterior facade surface, L_{in} is sound pressure level (dBA) at indoor positions around the receiver room, S is surface area (m^2) of test facade enclosing the receiver room, A_r is the receiver room absorption (m^2), and θ is the angles 34, 60, and 80 degrees to approximate a diffuse sound field. Adjustment calculations for background noise were done according to ASTM E966 Section 10.

Inside the room, the receiver is located throughout the space at five positions. Outside the facade, the receiver is flush with the facade at five positions. The source must be placed at least 2m from the facade at three separate angles (34°, 60° and 80°) representing a diffuse incident sound field, not including normal or zero degree position. Diagrams of source-receiver configurations are found in Appendix 3.

Through the testing process, sound measurement data include the following:

- Indoor signal decay for reverberation time at 3 source positions and 5 receiver positions
- Indoor and outdoor ambient levels- these are used for determining signal strength requirements. These can be also used for preliminary evaluation against CMHC residential health criteria.
- Indoor and outdoor source signal levels at either side of the test facade, spatially averaged over several positions: 5 indoor receiver positions, 5 receiver positions outside flush against the facade, and 3 source positions of varying incident angles of sound approach.

Non-acoustical data include component size, indoor floor area, room volume, air conditions, furnishing and surrounding conditions such as shelving, cupboards, penetrations and openings.

Working data is in 1/3 octave band frequency values of SPL. Results are then converted into single-number ratings calculated per procedures specified in ASTM E1332-10a “Standard Classification for Rating Outdoor Indoor Sound Attenuation” and ASTM E413-10 “Classification for Rating Sound Insulation” [98] [118].

The test facade for each case study LWH was selected to ensure that the conditions of the site best fit with the ASTM test requirements. The LWH's small dimensions, narrow spacing around its perimeter and odd obstructions around it such as landscaping, fencing, uneven ground or other site conditions increased difficulty to meet the ASTM E966 requirements for minimum distance and angular positioning between source and test facade. Some rooms did not meet minimum receiver room volume for reverberation tests. Also, flanking tests were not performed due to scope limitations. Without meeting absorption, room size and flanking requirements, the test is still valid to label results as *apparent* OITC, which is sufficient for the purpose of this study. The results are on the conservative side because normal incidence is excluded from test angles for *diffuse* sound field TL. TL data is a consolidated measure of the entire facade that includes all facade components.

4.3.3 Modelling facade TL using government laboratory data and AFMG Soundflow

A non-empirical procedure involving two data sources is used to calculate composite TL for each facade. This procedure is hereafter referred to as the "LWH model." The LWH model uses input TL data from NRC-IRC's laboratory measurements by Bradley and Birta according to ASTM E90 and ISO 140, and from Soundflow models (software by Ahnert Feistel Media Group or AFMG) [107]. Final results are compared to field measurements and to CMHC criteria. Soundflow-modelled STC for SIP rigid foam insulation wall panels are compared to available manufacturer data for separate discussion.

Soundflow models frequency-dependent TL data and STC rating based on cross-sectional flow-through details of a multi-layered panel, accounting for material properties, thickness, incident angle, band frequency and panel size. Soundflow allows users to add any number of layers, but does not consider cladding geometry. Air leak paths through cladding are addressed by assigning minor perforations to the cladding.

Material properties, such as specific material mass density and flow resistivity in Rayls/m, are required when specifying materials not contained in Soundflow's default library, such as various types of rigid foam insulation, oriented strand boards (OSB), stucco, and tar paper. Trials are run on various configurations for very narrow (<1mm) airspace gaps between individual materials as would exist in field condition; Soundflow results are more realistic when including air gaps between each material layer.

The three-dimensional complexities of these glazed fenestration components are difficult to model using Soundflow [107] [120] [123]. Glazed double doors were modelled with data for NRC's unsealed vinyl casement windows (TLA-99-143a) and windows were modelled with data of unsealed vinyl slider windows (TLA-99-149a), both using aluminum spacer [107, pp. 120, 128]. These samples are type-matched (i.e. vinyl slider windows and/or casement-like glazed doors with 13mm inter-pane spacing), but not matched for details like taped-seals, core material and spacer information. Actual glass thickness is unknown, as window specifications were unobtainable for four out of six case studies.

The LWH model combines component TL (exterior wall, windows, glazed doors, and non-glazed doors as applicable) into composite TL for each case study facade using Eq.(14) below [17]:

$$TL_{composite} = 10\log\left(\frac{S}{(S_1\tau_1)+(S_2\tau_2)+(S_3\tau_3)+\cdots}\right), \quad where\ \tau_n = 10^{\frac{-TL_n}{10}} \qquad \textbf{Eq.(14)}$$

S is total surface area of the whole facade, $S_{1, 2, 3...}$ is surface area of each individual component, and TL_n is TL of the respective component (n = 1, 2, 3…).

Soundflow is used to model input TL data of exterior walls and non-glazed doors. For TL of wood stud exterior wall assemblies, stud-cross section and cavity-cross section are modelled in Soundflow separately then combined based on stud-to-cavity ratio (406mm on center) per Eq.(15) [17].

The composite facade TL is used to calculate the LWH model AIF, OITC, and STC for comparison to corresponding values by CMHC and field test. Soundflow does not have a built-in OITC rating function and TL data require separate processing by ASTM E1332 for an OITC value. The ASTM E413 is used to calculate STC from TL for exterior walls and facades. NRC BRN148 by Quirt is used to calculate AIF from TL for facades.

4.3.4 Summary of methods

The CMHC TNM is used to model predicted road traffic noise levels at the exterior of LWH and to determine the required sound insulation of the LWH facade. Field-measured values, CMHC model values and LWH model values are compared to CMHC criteria. Due to the involvement of multiple rating systems (AIF, OITC and STC), conversion procedures are necessary. Finally, field-measured outdoor and indoor levels (ambient sound level checks) are taken to assess the overall agreement between real and predicted values. Appendix 4 outlines the course of LWH sound insulation study and lists the research methods, tools, and data sets involved.

4.3.5 Scope

Chapter 3 revealed that laneways are subject to significant aircraft noise. However, roof investigation is beyond the scope of this study due to CMHC not including it and difficulties in empirically measuring roof transmission loss [14, p. 55]. Only one facade from each LWH can be assessed due to ASTM requirement, and resource and time limits. It is assumed that each LWH uses the same exterior wall construction on all facades.

4.4 Results

4.4.1 CMHC predicted levels

Predicted outdoor levels are tabulated in Table 16 below. CMHC criteria for outdoor level is 55 LAeq24. Outdoor levels above 55LAeq require high facade insulation, and outdoor areas need some form of protective structure.

Ambient sound level checks ("SPL checks") are random 30 to 90 seconds of ambient SPL. SPL checks are very different from modelled LAeq24 and ideally should not be compared to the LAeq24. SPL checks were taken during segments of minimal interference, and are only shown to demonstrate the range of ambient noise levels at time of field test.

Bolded levels in Table 16 indicate noncompliance and need for extra facade insulation. SPL checks do not exceed CMHC prediction at lane side facades except at F's second level deck. An SPL check at a street side facade of a corner lot LWH (D west facade) exceeds CMHC prediction *and* criteria.

SPL checks agree with CMHC predictions (differing less than 3dB) for at least one facade in five out of six case studies. The exception is F, which is measured to be at least 5dB higher than CMHC prediction. SPL checks exceed CMHC prediction at D, E and F. SPL level checks on the lane side facade are close to CMHC prediction (less than 3dB difference) at A, B, and C.

CMHC prediction at second floor LWH facades are sometimes higher due to less obstacle attenuation from surrounding garages as these are not tall enough to block the sound path for second floor receivers. This is in agreement to the CoV warning that second floor facades and living areas may be exposed to higher noise levels because there are less tall obstructions and barriers along propagation paths [124].

Table 16: Predicted and on-site outdoor levels

Outdoor LAeq at facade exterior													
Uncertainty: ±1dB for CMHC values. Bolded values exceed criteria (55LAeq); some facades on 2nd floor were inaccessible for measurement.													
Floor level	Orientation	**A**		**B**		**C**		**D**		**E**		**F**	
		CMHC LAeq24	SPL check	CMHC LAeq24	SPL check	CMHC LAeq24	SPL check	CMHC LAeq24	SPL check	CMHC LAeq24	SPL check	CMHC LAeq24	SPL check
G	N	**61**	52	**64**	46	54	52	54	46	52	**57**	44	
	S	52	49	54	52	50	49	54		54	54	44	
	E	**58**	49	**62**		51		**56**		**56**		42	
	W	**57**	49	**61**	51	49		54	**57**	51		44	50
2	N	**61**		**64**				55		53		47	
	S	52	48	54	46			55		**57**		46	51
	E	**58**		**62**				**56**		**56**		45	
	W	**57**		**61**				54		53		49	

Indoor ambient SPL checks) measured on site during ASTM E966 field tests are tabulated in Table 17.

Table 17: On-site indoor ambient levels

Indoor ambient SPL checks (general ambient level inclusive of road noise intrusion)							
30s to 90s measurements, ±3.5dB							
	CMHC Criteria	**A**	**B**	**C**	**D**	**E**	**F**
Equipment on		**53**			**55**	**47**	
Work				**44**			
living	40	37	34	34	38	36	
kitchen/dining	45	35	36	36	**47**	37	27
bedroom	35	**37**	33	**35**	**41**	**37**	30
study/bedroom	35	34	32		**44**		
entry/foyer, stairs	40				**44**	38	27
bath	45					43	

These indoor ambient levels must not be confused with outdoor ambient traffic noise levels, though there may be some contribution from the latter. With the exception of D (the old house), all instantaneous living room measurements are lower than 40dB *if no equipment is on*. When equipment (HVAC, furnace, refrigerator or other appliance) is noisy, indoor spaces exceed 45dB by up to 10dB. The bedrooms in 4 of 6 case study bedrooms were measured 35dB or higher. D measured highest in ambient level checks, exceeding 40dB in all spaces except for the living room. At E, the bathroom (with window facing E. Broadway) is connected to the lofted bedroom space and may have caused bedroom level to exceed 35dB. At F, indoor ambient level checks are lowest out of all case studies measured, despite having comparable outdoor levels with other case studies.

CMHC model values of facade components are tabulated in Table 18 below [14, pp. 56-60]. Glazed double door values are approximated. A facade with one or more non-compliant components is considered non-compliant.

Table 18: AIF of case study facade components by CMHC Table 6.1-6.5

AIF of case study wall components						
Case Study	**A**	**B**	**C**	**D**	**E**	**F**
AIF required for facade	28	21	26	20	26	26
Exterior wall	34	36	33	32	37	41
Window	30	31	n/a	n/a	32	37
Door(s)	n/a	n/a	28; **24**—glazed double doors	n/a	**22**—glazed double doors	28

All facade components qualify except for the glazed double doors at C and E. The CMHC standard door D1 *minus two points* was used to model the AIF since this door type was not accounted for in CMHC. Without adjustment, the glazed doors at C could match requirement but those at E would still be insufficient. For A, if the room is used as a bedroom, it would not comply with criteria (requirement would be raised by five points to 33).

In consideration of open windows, AIF values are given per room size. The larger the size of the room, the less the interior sound levels are affected by an open window, as seen in Table 19 [14, p. 75] [117].

Table 19: AIF of open windows by CMHC/NRC [14, p. 75]

AIF of open windows						
Case Study	**A**	**B**	**C**	**D**	**E**	**F**
Test room floor area (m^2) (approx. ±1 m^2)	7.2	19.0	30.0	20.7	19.5	27.0
AIF required for facade	28	21	22	20	26	26
AIF of open window [14, p. 75]	**10**	**15**	**17**	**15**	**15**	**16**
AIF of wall	34	36	33	32	37	41
AIF of door			28			28

4.4.2 Room absorption

Room absorption, based on indoor furnishing, room volume and surface materials, can help protect indoor receivers against excessive noise levels. As discussed earlier, smaller spaces such as LWH have less room absorption for noise attenuation in comparison to larger houses, thus possibly requiring higher facade insulation. Figure 83 shows the room absorption calculated from empirically-measured field data (by ASTM C423-07) for the indoor space enclosed by the test facade in each case study. Due to room nodes in small room volumes, taking empirical field measurement of the decay rate is challenging, particularly in the low frequency range. In Figure 83 below, the Schroeder small-room cutoff frequency is set to 500Hz [17, p. 298].

The room absorption results correlate with room size and furnished condition. Cross reference Figure 83 with Table 7 (in Chapter 1) and it is clear that the three furnished rooms have higher room absorption (in order of highest to lowest: C, B and D). C having the biggest room volume and being fully furnished has significantly higher room absorption above all other case studies. D is slightly larger in volume than B and this is reflected by the absorption curve. A being very small in size and completely empty and reflective is the least absorptive room by a large margin. See interior photographs of the furnished versus unfurnished case studies in Chapter 1 Section 1.4 on the case study laneway houses.

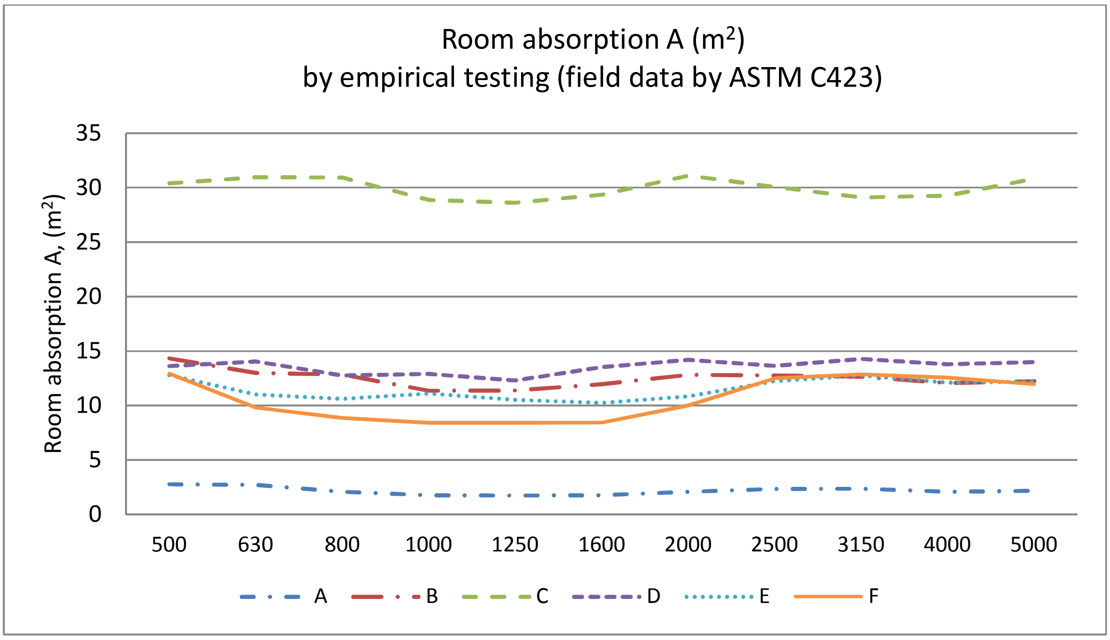


Figure 83: Room absorption of case study living spaces tested for facade TL

4.4.3 Transmission loss of construction

4.4.3.1 Empirical results by field test ASTM E966

ASTM E966 yields a set of frequency-dependent TL data labelled *apparent field outdoor-indoor transmission loss* (AFOITL). In Figure 84, test facade D shows the highest overall TL across frequencies, followed by B. Test facades A, C, E and F work about the same up to 1600Hz. Beyond 1600Hz, A is more insulating and F less insulating. In the lower frequencies (80-200Hz), the trends somewhat reverse: D is least insulating and E and F rank higher.

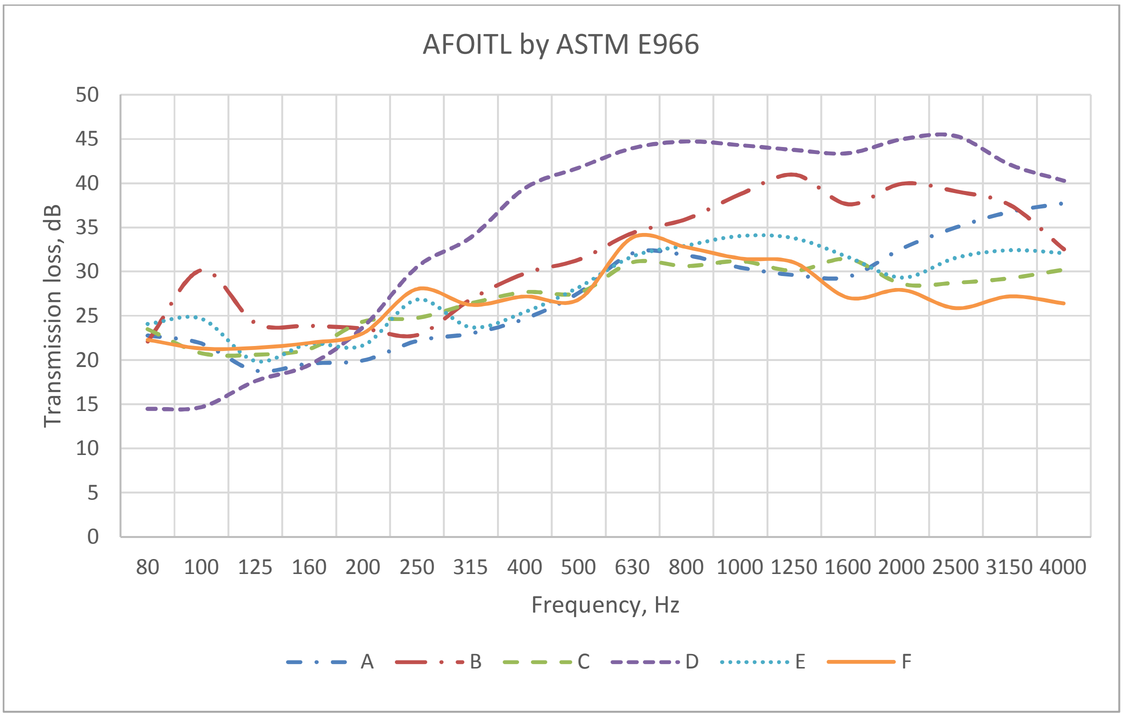


Figure 84: TL of all case study facades, empirical data by ASTM E966

Each TL curve is specific to its respective facade, as each facade is unique in terms of window and door compositions, interior wall attachments, flanking transmission, and site conditions. Thus, they do not represent *overall* construction for each case study LWH. Test facade D is composed of only the exterior wall with no fenestration; the actual construction details of the wall are uncertain. Test facade B is more than half covered by kitchen counter, cupboards, and a refrigerator, meanwhile having the lowest facade/floor ratio. Test facade E is in the lower half for TL curves, with high fenestration coverage but low facade/floor ratio. Test facade F is the only one using an 89mm (2”x4”) stud wall while the rest of the new LWH walls (A, B, C, and E) use 140mm (2”x6”) studs.

4.4.3.2 LWH model results

4.4.3.2.1 Model transmission loss of wall construction (Soundflow)

Three exterior wall types found in case study LWHs are modelled in Soundflow for comparison with results shown in Figure 85 below. In frequencies below 450Hz, exterior wall of D has the highest TL and all others have similarly lower TL. At frequencies above 450Hz, exterior wall of F has the highest TL and D the lowest. Exterior walls at D and F have higher OITC values (OITC 35 and 34 respectively) than those at A, B, C and E (OITC 30). Exterior wall at F has the highest STC (STC 42), followed by D (STC 37), then A, B, C, and E (STC 33).

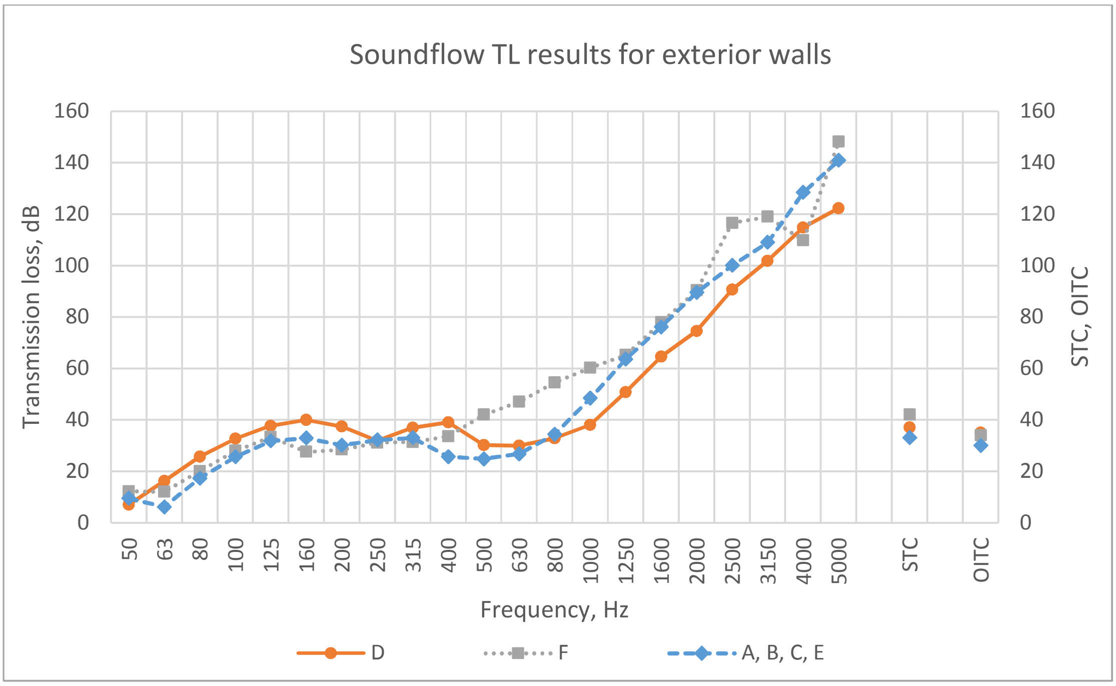


Figure 85: Soundflow models of exterior walls

Separate tests comparing Soundflow to NRC lab test data for a basic wall indicate that Soundflow may predict higher than realistic values of TL in frequencies above 2000Hz (see Appendix 5 for more details).

4.4.3.2.2 Model transmission loss of whole facade

The LWH models for whole facades include NRC laboratory test data for glazed fenestration. D reflects Soundflow modelled data of exterior wall only, without window or door contribution. Figure 86 shows that LWH model curves are in reasonable agreement with one another and with field measurements in Figure 84 except D, which is too low for frequencies below 1600Hz and too high above 1600Hz. In general, modelled data reflects the measured data trend that D has the highest TL. In the model, room size, absorption and flanking are completely irrelevant. Facade B performs lower than A, though B is modelled with cupboards. This means that theoretically the cupboards and kitchen counters do not improve the facade performance more than the window degrades it. The real B cupboards would have more flanking paths than modelled but also more contents to block and absorb sound. The real B wall has a refrigerator behind it that was not modelled in Soundflow. E has the lowest TL in low frequency range up to 400Hz, then A is lowest for 500-600Hz, and C and F have the lowest TL above 800Hz to 3159Hz, beyond where E has lowest TL.

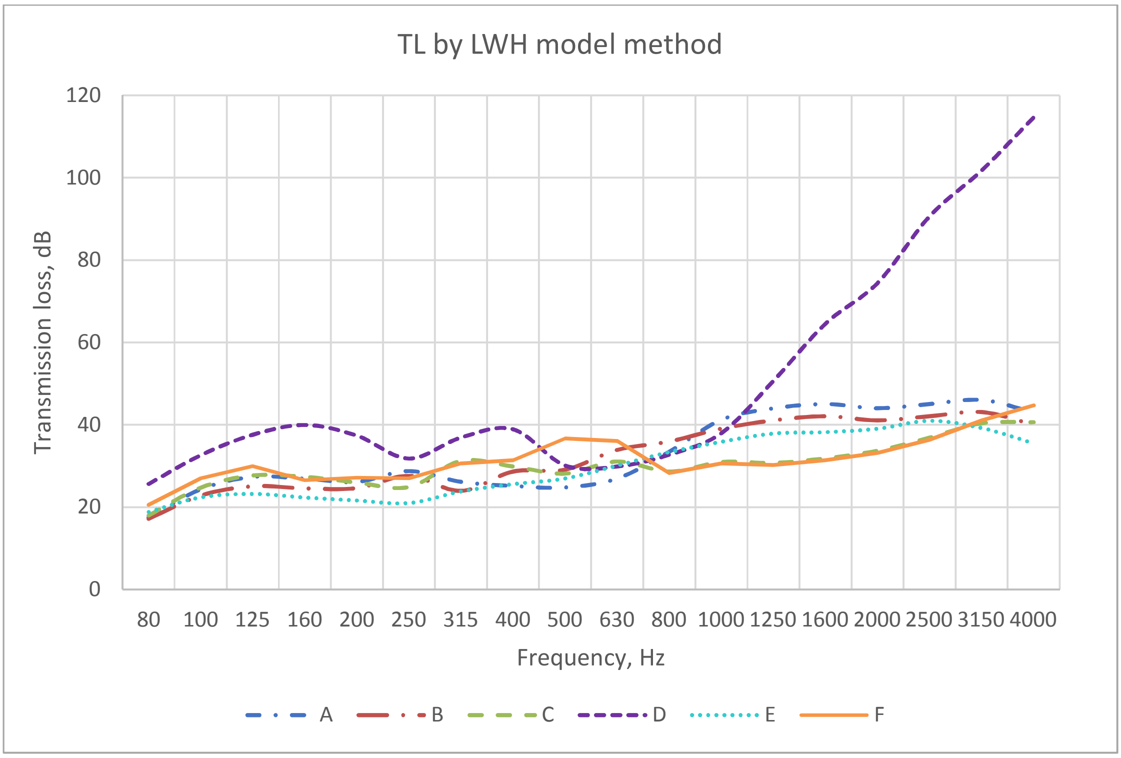


Figure 86: Modelled TL results of all case study test facades

4.4.3.3 Comparison of transmission loss by field test and by LWH model

The following figures (Figure 87 to Figure 92) compare facade TL from ASTM E966 field tests (*apparent field outdoor-indoor transmission loss* or AFOITL) to facade TL by the LWH model method.

In general, resulting TL curves roughly agree between the two methods, except at facades A and F, where LWH model curves are higher than AFOITL curves, and in the higher frequencies for facade D. Overall, there is agreement in the mid frequency range (250Hz $\leq f \leq$ 1000Hz), where AFOITL and LWH model TL curves coincide at several points and average differences range from -4dB to 2dB (LWH model TL minus AFOITL). Average differences at the lower frequencies ($f <$ 250Hz) range from -2dB to 8dB. The largest average differences occur in the higher frequencies

(f > 1000Hz), ranging from 4dB to 20dB, indicating that the LWH model can overestimate TL significantly in the higher frequencies.

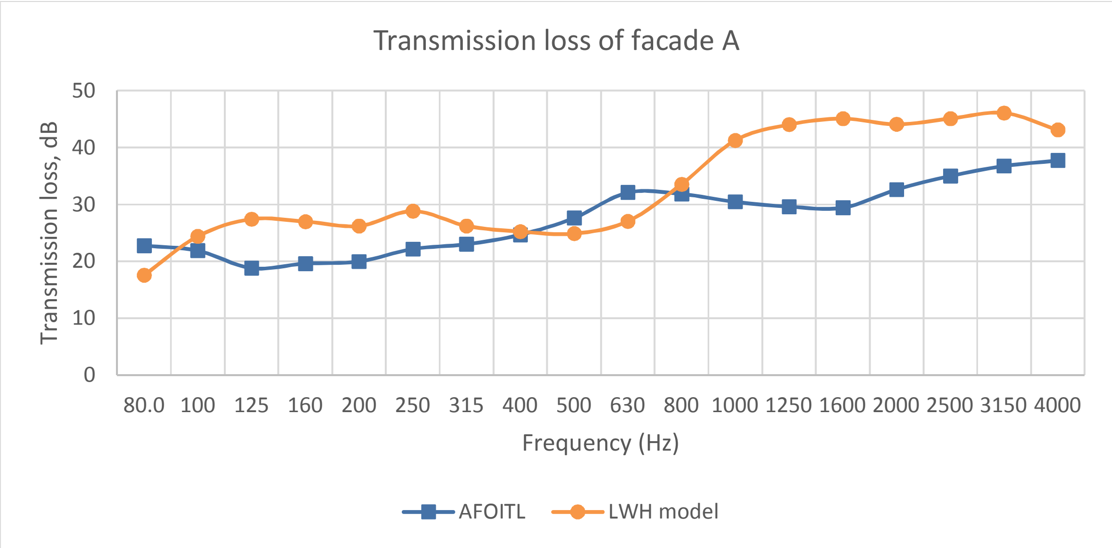


Figure 87: A north study facade

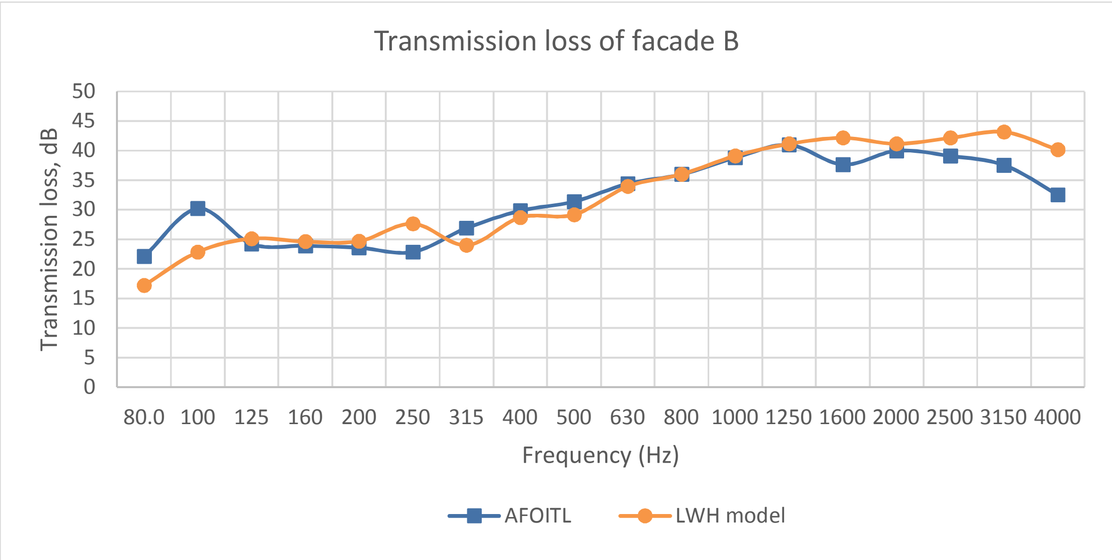


Figure 88: B south open plan kitchen facade

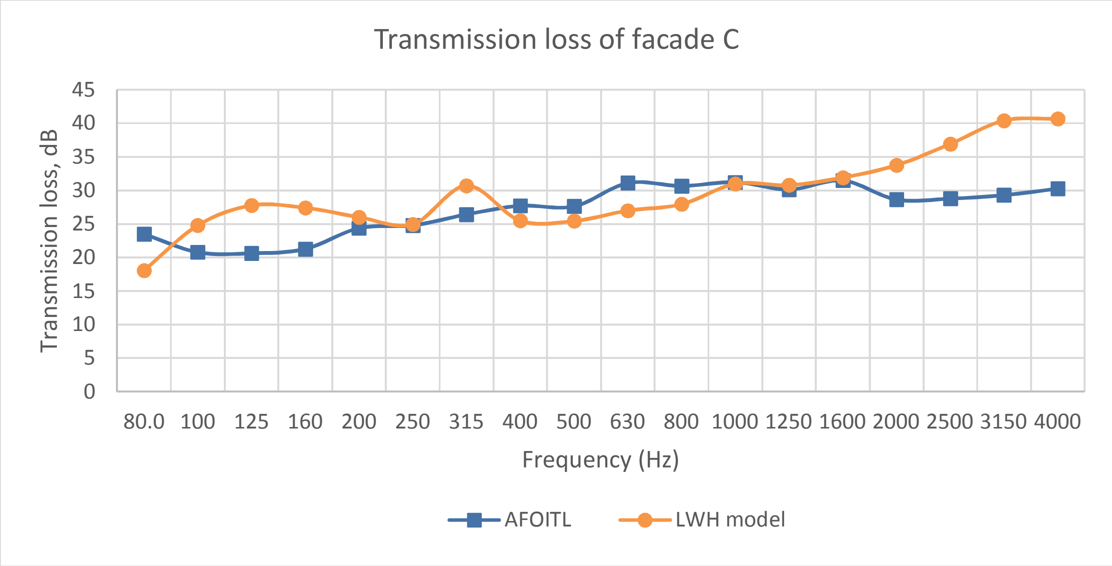


Figure 89: C south open plan living facade

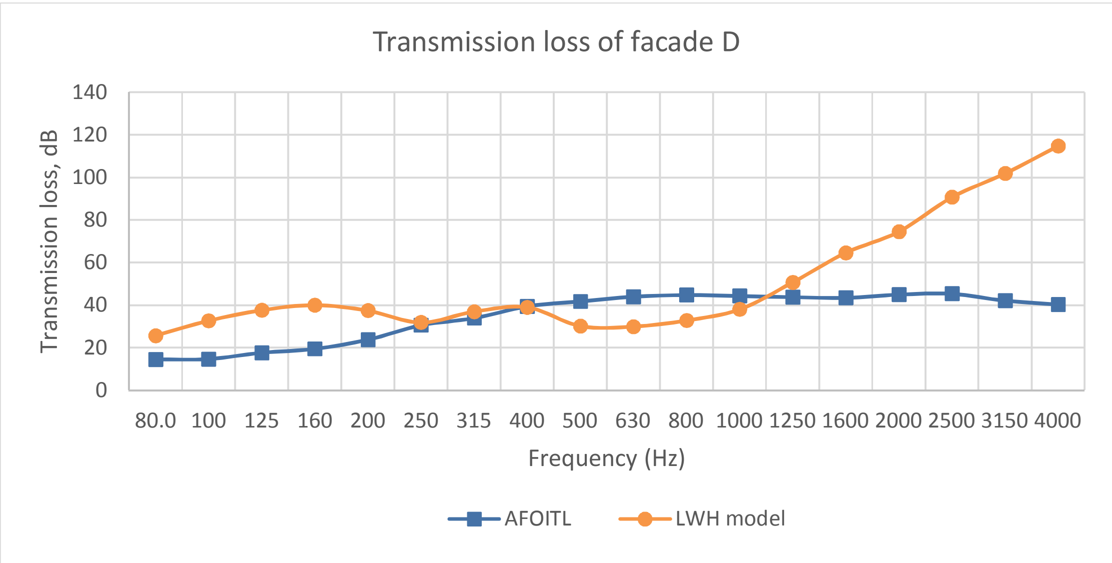


Figure 90: D north living room facade

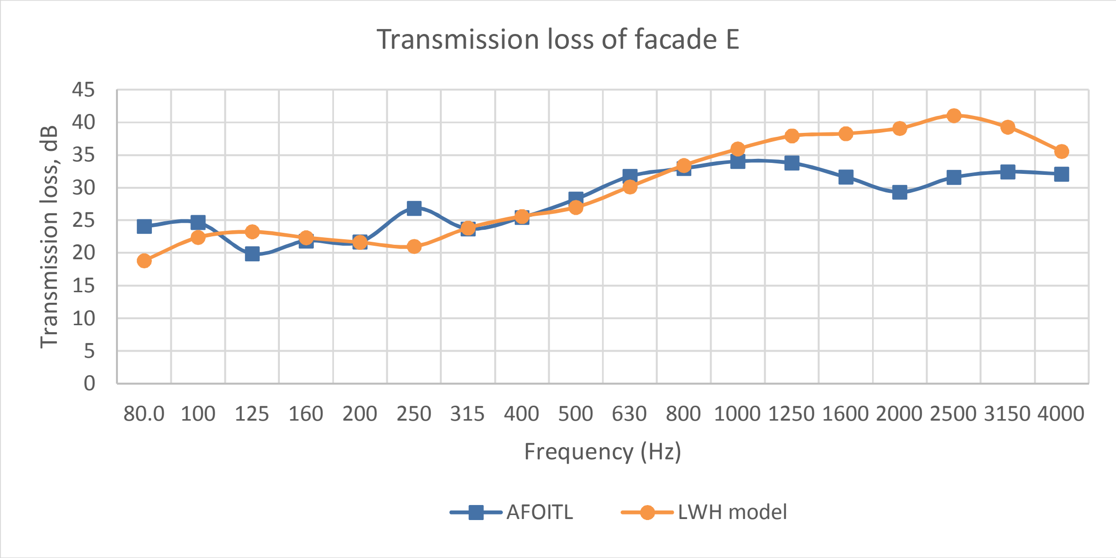


Figure 91: E south open plan living facade

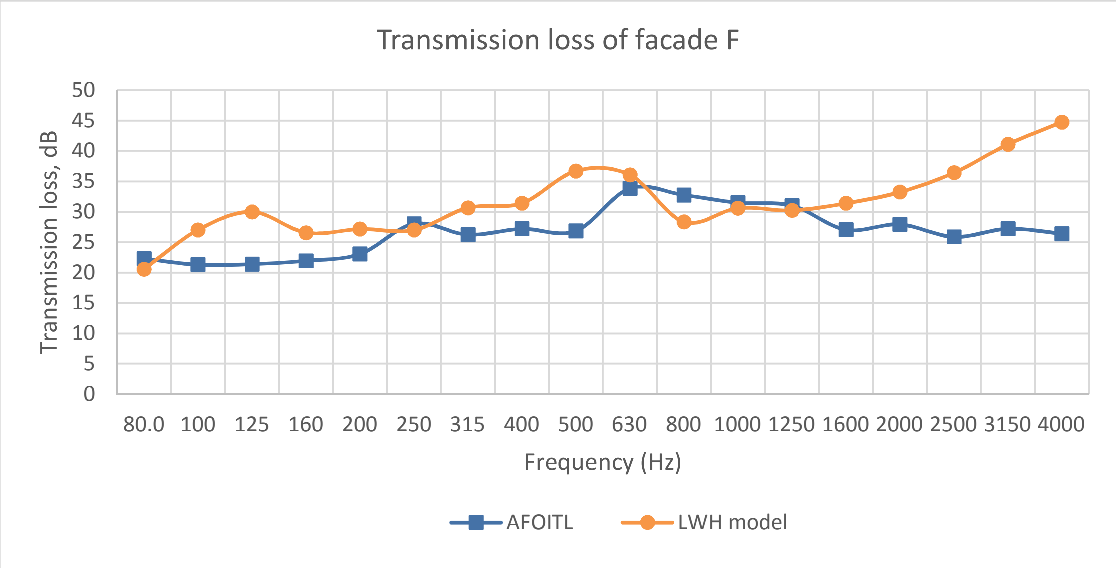


Figure 92: F west open plan living and kitchen facade

4.4.4 Sound insulation rating results by CMHC, LWH model and field test

This section presents results in single number sound insulation values: AIF, OITC, and STC. Where applicable, these values are compared to criteria. OITC and STC are calculated from TL data per applicable ASTM standards.

Figure 93 and Figure 94 compare OITC and STC by field test and by LWH model. Comparison of outdoor-indoor transmission class rating (OITC) of test facades show relative agreement between empirical and modelled results, except for D (uninsulated model in lighter-shade dot). The uninsulated model for D at OITC 25 is closer to the field measurement. In laboratory tests, an OITC of 25 is considered on the low end [107, p. 14]. E with highest glazed surface area (fenestration/facade ratio) has the lowest OITC (24). D, with no windows, has the highest modelled OITC. B, with refrigerator, sink counter and cupboards on the interior side, has the highest measured OITC.

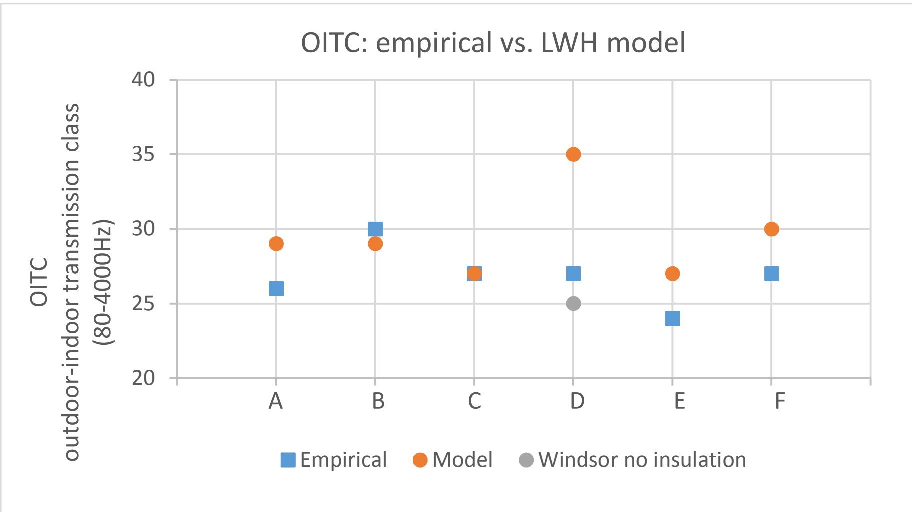


Figure 93: OITC comparison

The model STC ratings (Figure 94) are higher than empirical values by 1 to 6 points, showing best agreement for B and worst for E. This agrees with the 5 point difference generally existing between laboratory-tested data and field-measured data, where field-tested STC (FSTC) is 5 points lower than laboratory-tested STC [17].

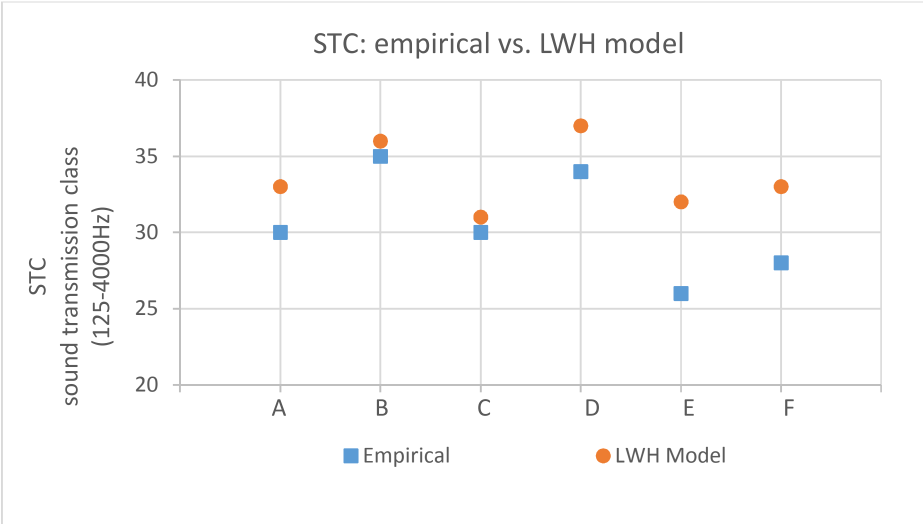


Figure 94: STC comparison: empirical versus model rating

Sound insulation values are evaluated against criteria. In terms of AIF, all LWH model facades comply with criteria (Figure 95). A needs to meet the highest requirement and complies by a narrow margin. Facades complying by a narrow margin will likely not comply if aircraft and other community noises exceed predicted road traffic noise levels.

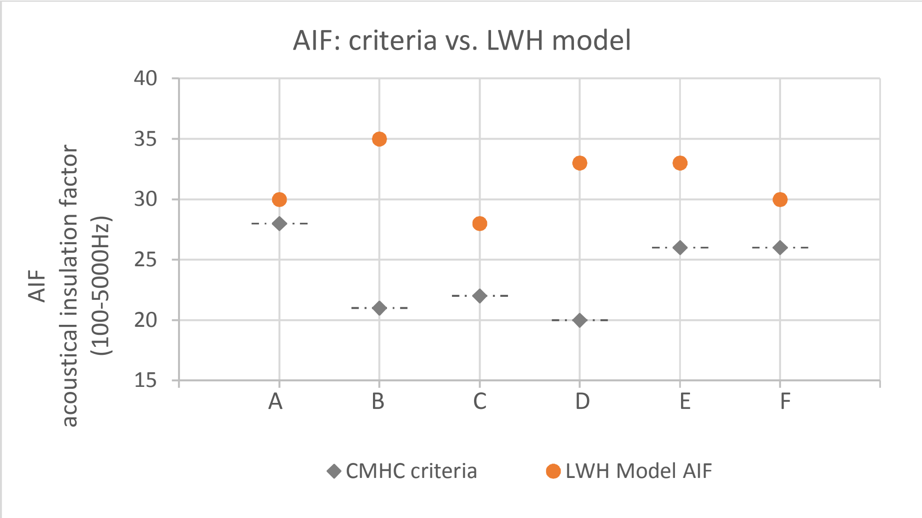


Figure 95: AIF comparison: model to criteria

In Figure 96, the CMHC criteria (converted from AIF values per NRC procedures [117]) is marked by light grey diamond markers. Facades A, E and F do not comply with CMHC criteria and C marginally meets it.

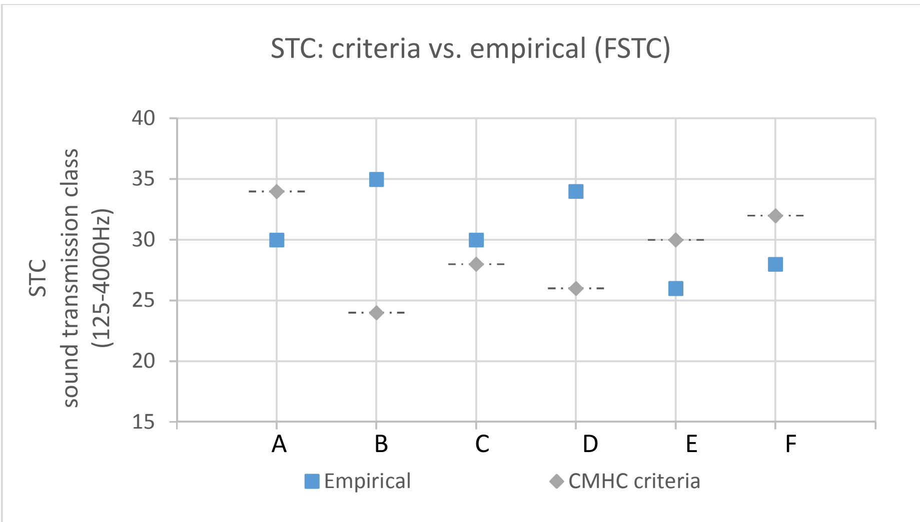


Figure 96: FSTC comparison: empirical to criteria

All cases will not comply with open windows, given a TL reduction by window opening of roughly 15dB [93, p. 25].

When evaluating LWH model STC to criteria, A does not comply because of its more stringent criteria, despite having the same or higher STC than three other facades (Figure 97). E and F are close to requirement (much closer than they are in AIF) and may need a wider margin to account for non-road traffic noise. Although STC criteria compliance is different from AIF (Figure 95), the patterns are similar: facades A, E and F need attention.

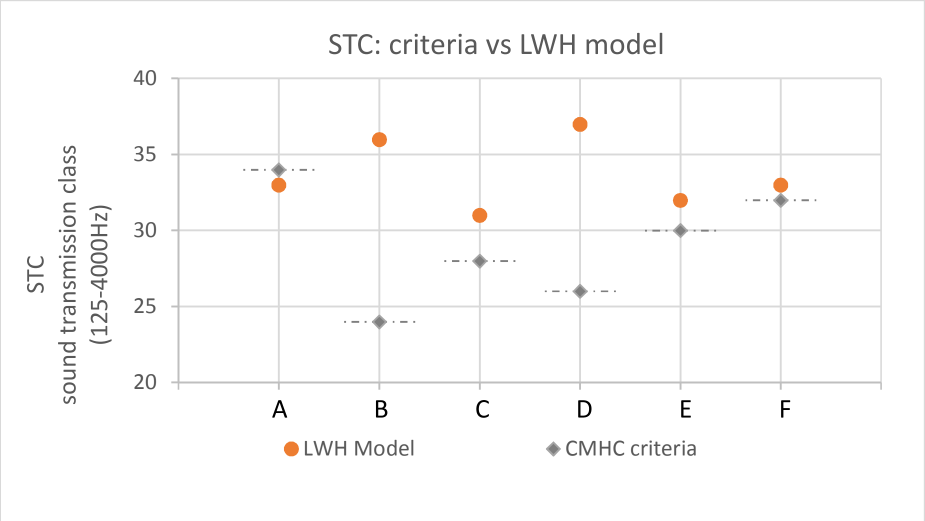


Figure 97: STC comparison: model vs criteria

By comparing the trends in Figure 95, Figure 96 and Figure 97, the LWH model (using Soundflow and laboratory tested data) is not 100% accurate for criteria compliance assessment due to overestimation of insulation values. However, it is a fair prediction tool for situations that need attention.

4.4.5 Structural insulated panels (SIP) and rigid foam insulation in LWH

Given great interest and the current industry direction of using structural insulated wall panels (SIP), a supplemental investigation is done for this type of construction material. This section presents findings from literature and from Soundflow model. None of the case studies use SIP panel wall system and therefore SIP are modelled in Soundflow for comparison to manufacturer-published laboratory test data.

A preliminary BCIT student study done on a LWH using 254mm-or-thicker SIP wall system reported “good” airborne outdoor-indoor sound insulating results, though this was achieved by significantly-thicker walls panels (254mm), and possibly airtight construction and high window and door specifications [114] [125]. In practice, construction industry authorities do not recommend using SIPs for floors and ceilings due to inadequate acoustical performance [112]. Acoustics professionals frequently recommend against using rigid foam for wall insulation.

In Soundflow, insulation material is placed between two sheathing boards (Figure 98). The insulation materials modelled are: EPS (expanded polystyrene), XPS (extruded polystyrene), polyiso (polyisocyanurate), fiberglass matt, mineral fibre, and rockwool. The first three are rigid foam insulation and the latter three are conventional absorptive insulation. In non-laminated wall panels of absorptive insulation, a 1mm air gap is introduced between material layers. Models assume all panel assemblies to have infinite surface area.

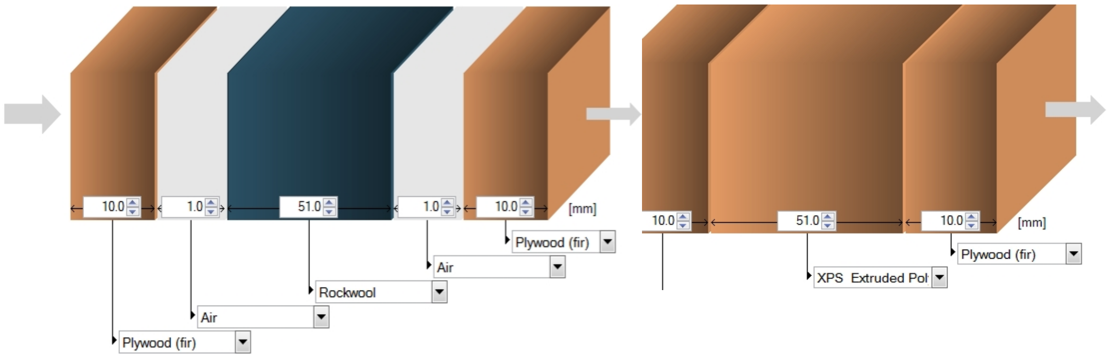


Figure 98: Soundflow model of insulation assembly.
Left: batt insulation assembly; right: rigid insulation assembly.

In Figure 99, Soundflow predicts the general trend that absorptive insulation assemblies perform similarly to one another, with higher TL above 200Hz than the rigid insulation assemblies, which also perform similarly to one another. EPS, the most commonly used rigid board insulation and the primary insulation material in SIP products, is the lowest performer in the 200 to 1600Hz range.

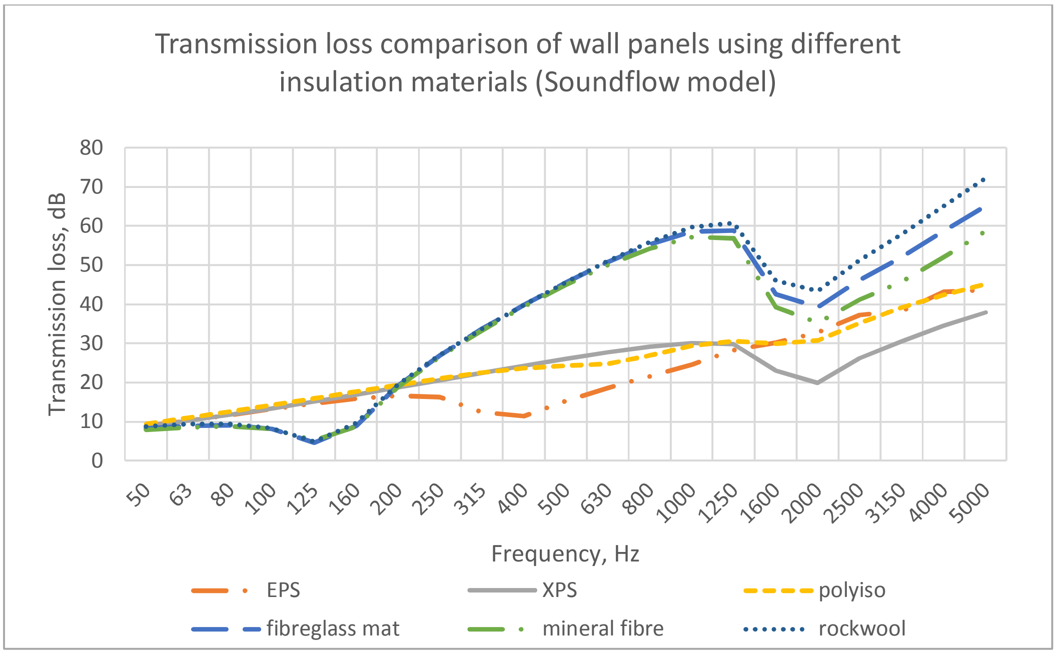
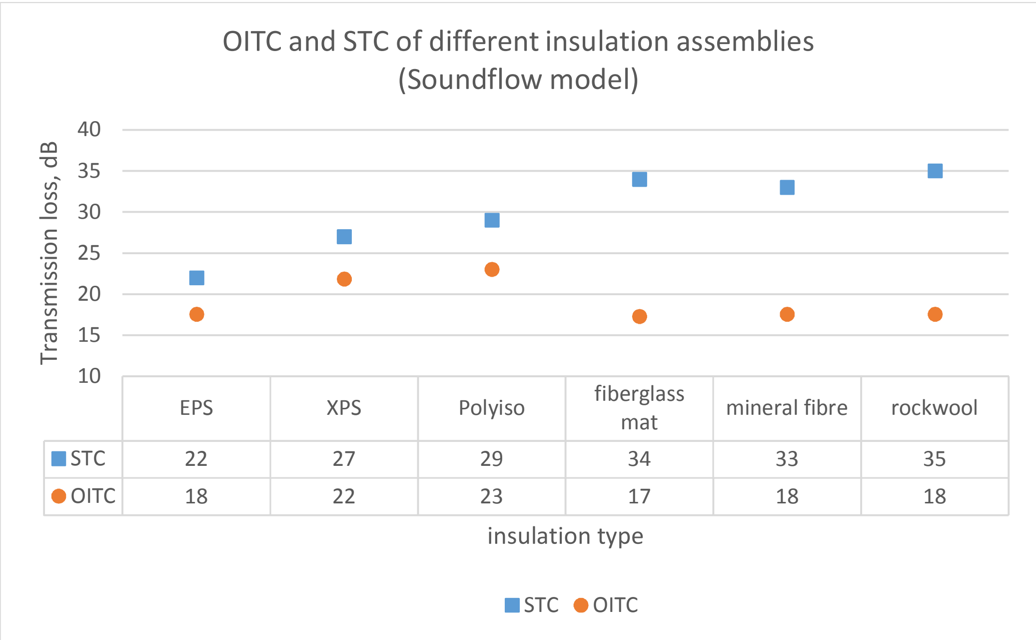


Figure 99: TL modelled in Soundflow for different insulation assemblies

OITC and STC values calculated from Soundflow model data and shown in Figure 100 below. Rigid insulated assembly STC values are lower than absorptive assembly STC values by as much as 13 points (rockwool to EPS). On the other hand, rigid assemblies have the same or higher OITC than absorptive assemblies by as much as 6 points (polyiso to fibreglass). The mass-air-mass resonance effect in absorptive assemblies creates a TL dip around 125Hz which lowers their rating for lower frequency TL. This resonance dip frequency varies depending on cavity width and the panel materials.



	EPS	XPS	Polyiso	fiberglass mat	mineral fibre	rockwool
STC	22	27	29	34	33	35
OITC	18	22	23	17	18	18

Figure 100: OITC and STC by Soundflow data for different insulation assemblies

Rigid insulation materials are modelled based on closest approximated material data and require further testing and improvement. Material data for rigid foam insulation types range widely; for example, the mass density for EPS insulation products in construction ranges from 16 to 35kg/m^3. This contributes to very different results in Soundflow. Stiffness, strength, and surface treatment also vary widely for different products. In practice, the placement of these materials, such as on the surface or in the cavity, and other construction variables, will also affect in-situ TL.

Published ASTM E90 laboratory test data for EPS-SIP (structural-insulated panel) wall types is consistent across different manufacturers. Manufacturer-published lab STC value match Soundflow STC value for the basic SIP panel (11mm sheathing, 92mm EPS, 11mm sheathing at STC 22) [111] [126] [127] [128]. A basic SIP panel at STC 22 is lower than a standard 89mm batt-insulated wood stud wall of STC 34 by more than 12 STC points. An EPS SIP panel needs two extra panels of 16mm drywall to be comparable to the standard stud wall (STC 34), which makes it 32mm thicker [111] [126] [127].

The NRC published laboratory test TL data of a standard batt-insulated wood stud wall with an extra 25mm board insulation (EPS) under vinyl cladding. In comparison to a standard rainscreen wall, EPS cladding performs slightly worse in frequencies from 400 to 1250Hz and at 500Hz [107]. In the other frequency ranges, the two walls perform similarly [107].

4.5 Discussion and chapter conclusion

As was anticipated in the hypothesis in Section 4.2, some LWHs do not meet minimum acoustical standards for residential health. For example, two LWH case studies do not comply with CMHC criteria based on modelling by CMHC Part 7 procedures, and four LWH test facades do not comply based on empirical test results. Detailed evaluation of acoustical performance of test facades in relation to their room size, assembly materials, orientation towards major traffic sources, facade/floor area ratio, and fenestration/facade ratio are given in the following sections.

4.5.1 Criteria compliance and performance of case study facades

4.5.1.1 Consolidated criteria compliance chart

Compliance of each case study according to rating system and method of study is summarized in Table 20 below. Results are referenced by row number in the text that follow.

Table 20: Criteria compliance chart for ambient levels and for minimum facade insulation rating

Criteria compliance by method of comparison								
Legend: O= compliant X = non-compliant ! = compliant, but likely not with open windows or noise sources other than road traffic.								
No	**Item compared to CMHC criteria**	**A**	**B**	**C**	**D**	**E**	**F**	**Reference**
1	CMHC model outdoor levels	X	X	!	X	X	O	Table 16
2	CMHC model AIF (component)	O	O	X	O	X	O	Table 18
3	CMHC model AIF (open window)	X	X	X	X	X	X	Table 19
4	LWH model AIF (facade)	!	O	O	O	O	O	Figure 95
5	LWH model STC (facade)	X	O	O	O	!	!	Figure 97
6	Field STC vs unadjusted criteria (facade)	X	O	!	O	X	X	Figure 96
Other								
7	On-site outdoor SPL checks	!	!	!	X	X	O	Table 16
8	On-site indoor SPL checks	X	O	!	X	X	O	Table 17

CMHC predicts four out of six case studies (A, B, D and E) to have outdoor road traffic noise levels that exceed criteria (Table 20 item No. 1). One case study (C) is close to criteria. Those that meet criteria by a narrow margin will be insufficient when windows are open, when the room is used for a more noise-sensitive purpose, and when ambient levels include contribution from other noise sources not accounted for, such as aircraft, rail, construction or laneway noises.

CMHC predicts AIF of individual facade components to be insufficient at two of the six case studies (C and E, in Table 20 item No. 2). The insufficient components were glazed double patio doors; these were assumed to have lower AIF (-2) than regular doors in CMHC modelling. CMHC model assumes equal room height, but in reality, the double height ceilings at C and E will improve indoor receiver levels beyond CMHC's prediction and the two case studies may have sufficient AIF for all components.

Stewart recommends using exterior wall with insulation rating (OITC) 10 points higher than criteria to compensate for the lower rating of one door and two windows common for facades [106]. CMHC notes a similar treatment: if an exterior wall AIF is 10 points higher than requirement, the facade requirement may be reduced, thereby reducing component AIF requirement [14, p. 55]. This is considered and does not change the results presented in Table 20. A and C do not have estimated exterior wall AIF 10 points higher than requirement.

As shown in Table 20 item No. 3, no case study facade complies with criteria if open windows are predicted using AIF values from NRC-BRN148 in CMHC. In item No. 4, the LWH model predicts that all facades comply with CMHC AIF criteria but one is barely so (A).

In item No. 5 where CMHC criteria is converted to STC by the simple method to evaluate LWH model STC, one case study facade does not comply and two are barely compliant (A, E and F, respectively) [117].

In item No. 6, three facades do not comply and one facade is barely compliant, making a total of four facades in need of higher sound insulation.

Items No. 7 and No. 8 compare on-site instantaneous ambient sound level checks to levels equivalent to CMHC criteria. Two exceed outdoor levels of 55dB (D and E). Three exceed respective indoor levels (A, D and E).

Some basic relationship patterns between insulation values and architectural dimensions discussed in literature review are evident; these are summarized in Table 21 and listed in bullet form below.

Table 21: Dimensional ratios and TL rating

Dimensional relationship to TL rating						
Bold = maximum; <u>underline</u>= minimum						
Case study facade	**A**	**B**	**C**	**D**	**E**	**F**
Fenestration/facade ratio	12%	24%	22%	<u>0%</u>	**51%**	19%
Façade/floor ratio	**106%**	<u>41%</u>	96%	67%	52%	74%
Architectural notes		Open plan	Open plan, high ceiling		Open plan, open loft bed space, high ceiling	Open plan, semi-loft high ceiling
OITC (80-4000Hz): outdoor-indoor transmission class						
AFOITC (apparent field OITC)	26	**30**	27	27	<u>24</u>	27
MOITC (modelled OITC)	29	29	<u>27</u>	**35**	<u>27</u>	30
STC (125-4000Hz): sound transmission class						
AFSTC (apparent field STC)	30	**35**	30	34	<u>26</u>	28
MSTC (modelled STC)	33	36	<u>31</u>	**37**	32	33

- The lowest facade insulation values (AFOITC 24, AFSTC 27 and MOITC 27) have the highest fenestration/facade ratio (51% at E).
- The lowest modelled insulation value MSTC 31 has higher fenestration/facade ratio (22% at C).
- The second lowest OITC 26 has the highest facade/floor ratio (106% at A).
- Lower insulation values generally have higher facade/floor ratios.
- The highest modelled insulation values MOITC 35 and MSTC 37 and second highest field measured insulation rating AFSTC 34 have the lowest fenestration/facade ratio (0% at D).

- The highest field measured insulation ratings AFOITC 30 and AFSTC 35 and second highest modelled insulation rating MSTC 36 have the lowest facade/floor ratio (41% at B).

These patterns are discernable even in modelled results, where room absorption and facade size are not included in calculations. It is also worth noting that all case study facades have high to very high facade/floor ratios ranging from 41% to 106% with an average of 73%; high facade/floor ratio relates to low facade insulation values.

All case study facades are on the lower end for acoustical insulation rating. Partition walls between apartments or next to service spaces are required to be STC 55 to 65 [24] [26][7]. STC 55 is at least 25dB more insulating than the highest field-rated case study LWH facade.

4.5.1.2 Discussion of individual case study results

Facade A appears compliant by the standard CMHC model (Table 20 item No. 2). However, its LWH model STC and FSTC are non-compliant (Table 20 item No. 5 and 7) or barely compliant (items No. 4 and 6). The primary factor for A's non-compliance is architectural layout or room designation, with the placement of a relatively sensitive living space (study with bedroom potential, criteria 35-40 LAeq) at a location with the highest predicted outdoor level (61 LAeq). Although this is the yard-side facade typically shielded by the main house, in A's case it faces a high traffic volume road (W. King Edward). On the other hand, CMHC does not take into consideration lane side noise sources. Lane side noise potential and high predicted noise level on the yard-side compromise placement of sensitive spaces like bedrooms, dens, and studies. A

[7] These partition criteria were specified to insulate activity and impact noises and to improve acoustical privacy.

also has the highest facade/floor area ratio (106%, Table 21) and the smallest room size (7.2m^2, Table 21). The small room size offers minimal absorption and sound reduction must be provided by the facade. A will need to increase facade insulation to meet indoor space criteria.

Facade B has the highest field tested insulation rating and complies with room criteria by an ample margin. B performs well for several reasons. One, it is rated for the least sensitive indoor use (the kitchen with criteria 45LAeq) at the predicted quietest side of the building (54LAeq in Table 16). This is opposite to facade A. Two, B has the lowest surface-to-room-floor-area ratio out of all case study facades (41%, see Table 21), which means that the room will play a bigger role in absorbing sound to help "alleviate" the sound reduction load of the facade. This is also opposite to facade A. Three, B's adjoining facade enclosing the room has higher insulation (with cupboards and without windows), thereby reducing facade B's sound insulation requirement. Given these three factors, B complies with CMHC criteria by a large margin (see Figure 95, Figure 96 and Figure 97). This margin can accommodate lane side noises, non-road traffic noises, and more sensitive room use. This is appropriate as B is on the lane side, and is open to the living space (criteria 40LAeq). In terms of insulation, despite using the same wall construction as A, C and E, B has interior-side cupboards, refrigerator and counter storage which all contribute to TL.

Facade C meets criteria by field test and LWH model results but does not meet criteria by CMHC model results for component AIF. Facade C's insulation values are on the low end across different methods and rating systems. Despite having low insulation values (comparable to A and E), C is subject to lower predicted outdoor road traffic noise levels and is thus compliant by field test and LWH model results. Facade C is non-compliant because of low CMHC component AIF rating for glazed double patio doors. In addition, this type of fenestration is designed to be open from time to time for enjoyment of outdoor living. Because of C's high room volume and high room absorption, open fenestration would not affect C's living space as drastically as it would for a much smaller space like A; nevertheless, outdoor living-oriented fenestration should use acoustical strategies.

Facade D is the second highest insulating facade and like facade B is compliant by a significant margin due to very low criteria. Facade D has high TL because it is 100% wall with no fenestration (lowest fenestration/facade ratio). It was built during a time when the street layout, traffic patterns and building technologies were likely very different; today's LWHs are less likely to be completely windowless on the lane side, particularly given current LWH Guidelines encouraging fenestration on the lane side [18]. In the Soundflow model, D's presumed full 100mm size wood stud has higher TL than both 89mm and 140mm studs in frequencies below 400Hz, which gives it higher OITC (Figure 85). On site, a low height storage sits on the loud side (Kingsway side) of the building and helps to insulate it. What is of concern is the high indoor levels measured on-site, assumed to be contributed by indoor equipment.

Facade E is consistently the lowest performer across all rating scales and by different investigation methods, being either non-compliant or at-risk. One cause for facade E's low insulation value is the high fenestration/facade ratio (51%). This deserves attention because using high fenestration/facade ratio is an anticipated trend in LWH, as discussed previously. Facade E is also on the lane side and one of the noisier sides of the lot, directed towards a high traffic arterial road two blocks to the south. This location measured high in the outdoor ambient sound level check, yet it is designed to anticipate outdoor-oriented living. Like facade C, this facade uses glazed double patio doors and has a small patio fenced in for private outdoor living. Found at two out of the four LWHs, this type of ground-level patio access appears to be a popular LWH feature. It will require noise insulation improvement such as extra attention to weather-stripping and closing of any wide gaps. Leaving the patio doors open depends on outdoor levels during the time frame and the resident's tolerance for outdoor noise.

A possible contribution to facade E's low field-tested insulation value is flanking by the lofted ceiling. The sloped roof over this double height ceiling space was a significant flanking sound path but its area was not included into calculations. There may also be significant flanking from the adjoining south west facade which also has a window in it. However, flanking is not an issue in modelling, by which E still ranks low. This means that the fenestration/facade ratio and glazed door construction are more relevant causes for low insulation values.

E has a completely open plan with double-height ceilings and a lofted sleeping area. Open plans and lofted spaces are common in LWH. Three out of six case studies have lofts or double height ceilings and five have some form of open plan living space. In E the open loft sleeping area will be affected by louder adjacent spaces.

In predicted quieter areas, as in the case for F, low facade insulation is not a problem. Despite low facade insulation (lowest TL curve and mid-low OITC and STC ratings), facade F is compliant by a healthy margin. F also has the lowest indoor ambient sound level checks that may meet more stringent standards. In Soundflow-modelled exterior wall comparisons without fenestration (Figure 85), the F exterior wall has the highest TL, OITC and STC.

In all case studies, LWH model TL and insulation values are higher than empirical values. The real facades may have air leak paths, flanking paths, lower construction quality, or a combination of the above which are not reflected by the LWH model. The above findings highlight some acoustical problems found in LWH.

4.5.2 Increasing OITC of LWH facades

Strategies for improving OITC are useful for LWH facades with excessive outdoor levels or sensitive indoor use, especially when other strategies, such as conventional acoustical barriers, are impractical in the laneway setting.

Supposing that air leakage is minimized and that ventilation and mechanical systems are acoustically optimized, improving fenestration insulation is one of the most effective strategies to improving overall facade insulation. For example, C and E can benefit significantly from improvements to the glazed doors. Some strategies below have been distilled from the NRC lab tests and CMHC AIF rating tables that may help improve LWH window and glazed door insulation against outdoor traffic noise. Improving window OITC beyond those listed and improving open window insulation are beyond scope.

Figure 101: Improving fenestration insulation

Fenestration insulation strategy	OITC or AIF improvement
Weather-strip and seal all gaps. Seals will degrade over time with use so this needs periodical replacement.	High importance
Use storm windows spaced 25mm or wider for significant effects on weaker windows like aluminum windows. Use storm doors over patio doors [107].	+2 – 7
Increase inter-pane spacing between double glazing, from 13mm to 25mm or more [14, p. 57].	+3 or more
Increase glass thickness of at least one pane to 6mm [14, p. 57].	+2
Casement type is more insulating than double-slider type windows; vinyl-clad wood, wood and vinyl frame windows are more insulating than aluminum frame windows [107].	+2
Taping seals helps improve OITC in some types of windows [107].	+1
Consider using laminated glass or acoustical windows for very noisy locations.	

For exterior walls, strategies for improving OITC without adding too much to wall thickness are listed below. Some of these are easier to plan from the beginning than to retrofit later. These suggestions are distilled from the laboratory test result analysis by NRC-Bradley and Birta, in order of effectiveness.

Figure 102: Improving exterior wall insulation

Exterior wall insulation strategy	OITC improvement
Use staggered studs + RC construction. These work best for 406mm OC walls, especially to protect against noise below 200Hz [107, pp. 15,23,30]	+19
Use staggered stud construction [ibid]	+8 – 14
Use resilient channels between the stud frame and the interior gypsum wall board [107, pp. 25, 48]	+7
Use cement stucco siding [107, p. 15]	+4
Space studs wider apart, such as at 610mm or wider +3 dB OITC [107, pp. 22, 23]	+3
Use an extra layer of gypsum board on the inside [107, p. 25]	+2
Using cellulose or rock fiber insulation [107, p. 24]	+1, +2 respectively

As an example of applying the above strategies, facade A can be helped by adding storm windows at a 25mm-or-wider airspace over the current windows, or by adding one layer of gypsum to the interior of all exterior walls for the room. Interior strategies include placing chests or furniture against the wall, furnishing with very absorptive furniture, and using heavy fabric curtains and carpets. For E, storm windows and storm doors and increasing indoor absorption will help. Also, the thin wood fence just outside this facade around the patio can be converted to living walls for more barrier effect (Figure 103).

Figure 103: Case study E outdoor living space
A living wall installation in place of the current wooden fence may benefit outdoor living space and reduce outdoor noise levels.

Keep in mind that increasing overall sound insulation may not be just about one facade component or one facade. It may require comprehensive consideration for the architecture and construction of the whole building. Design of facades and selection of facade components need to anticipate outdoor noise level, other building elements (fenestration, floors, and roofs), and room information, including adjoined rooms and related room furnishing.

4.5.3 Methods evaluation

In this section, each research method is evaluated. The research limits and uncertainties contained in the results are discussed below.

4.5.3.1 CMHC (traffic noise model Part 3, 5 and 6)

CMHC Part 3 predicts that more than half of the LWH under study are at risk of higher outdoor levels from road traffic noise, which can degrade outdoor living quality and disadvantage the opening of windows and patio doors. These levels do not include bus stops, canyon effects, and lane traffic. CMHC Part 6 is essential by providing an overall insulation criteria (facade AIF). CMHC compliance is not solely based on construction type, but also the relationship between the unique outdoor level and the noise-sensitivity of the indoor space. CMHC does not provide a whole-facade estimate for users; more practically, it rates components individually for users to focus attention on insufficient facade components, and does not estimate the whole facade. Users need additional methods to estimate their effective facade insulation value. CMHC predicted that two of six facades require additional acoustical insulation.

Uncertainties and limitations in the CMHC model are listed below:

- Limited data in estimating traffic volume and percentage of heavy traffic.
- Generalization in determining shielding and barrier effects of neighboring buildings.
- Lacks application to complex and decoupled room volumes and floor areas (open lofts, double-height or vaulted ceiling designs, interconnected spaces and open plan designs).
- Uncertainties in determining room designation for mixed-use or open plan layouts.
- Flanking, ventilation, air leaks and roof contribution are not included in model.
- Lack of data for current construction assemblies and special components common in Vancouver LWHs, such as the rainscreen wall, doors with glazing inset larger than 20%, and glazed double patio doors.

Despite the above limitations requiring special user discretion, CMHC is the most holistic investigation method taking the widest array of major factors into account, and is the most accessible and practical for common users. When used in conjunction with an on-site acoustical evaluation, CMHC is recommended for application to all LWH developments.

4.5.3.2 ASTM E966 (field test)

Field tests best reflect real in-situ performance, revealing that three of six case studies need acoustical improvement. However, there are practical limitations in field testing. It is disruptive for several hours (3-6 hours), requires industry equipment, labor, aptitude with test procedures and field instrumentation, extensive data processing, and sometimes manufacture of custom structures (for flanking tests). Field testing also requires important contextual data, such as detailed architectural information that are sometimes unavailable. Uncertainties and limitations inherent in field measurements include:

- Excessive flanking in smaller structures
- Site dimensions limiting procedural compliance; incident angle and distance of source from test facade in very space-limited conditions may be compromised. Some angles were closer to grazing and may have lowered test outcome. At F, landscaping was not yet complete; at C and E, there was fencing in the way.
- Room absorption; reverberation in small spaces can be difficult to take accurately, especially for lower frequencies.
- Room volumes for irregular and inter-connected interior spaces
- Field measurement is for full facade; additional tests are required for component analysis

In literature, field ratings are expected to be around five points below laboratory ratings [17]. Thus the positive error range for insulation ratings is five points. This value may be higher for facades with strong flanking influence such as at A and E. Negative error range is estimated at two points and attributed to possible overestimation of room absorption and other sources of errors listed. For TL data, E966 estimates uncertainty to be 2 to 4dB depending on frequency, including room absorption in small rooms [99] [129]. The results are only valid for the tested angles of incidence, and are unique to the facade and non-transferrable.

The field test method is recommended as it provides more realistic in-situ assessment than models and is very valuable for contextual information. It is highly recommended for locations with high traffic noise exposure to verify CMHC evaluation. However, users are advised to include data for 5000Hz.

4.5.3.3 Soundflow

Soundflow is based entirely on TL theory, which is complex. For its ease of use and low learning curve, it is quite powerful and sensitive. Soundflow assesses a multitude of acoustically-important physical phenomena that range from properties at the microscopic level such as fiber diameter, porosity, interlayer air gap differences that are invisible to the human eye (less than 0.1mm), to larger influences like incident angle and facade size. With the high number of possible variables, Soundflow TL data can be unreliable in some modelling scenarios. Also, due to high adherence to TL theory, Soundflow is unrealistic in certain frequency ranges and needs cross-checking with lab and field data. For example, in frequencies above 2500Hz, Soundflow adheres to stiffness-controlled TL theory and overestimates TL in comparison to the field data where the higher frequencies are affected by sound leaks and flanking. The LWH model (using NRC data and Soundflow) predicted that only one case study facade needs acoustical improvement. This is the most relaxed assessment out of all the evaluation methods. Soundflow does not include complexity and geometry of actual envelope details; the user must perform additional composite calculations to account for realistic construction.

Uncertainties and limits in Soundflow modelling include:

- Accuracy of input material properties data (e.g. mass density, Young's modulus, Poisson's ratio, porosity, etc.)
- Air leaks
- Cladding surface shape
- Inter-layer air gap width—a <0.01mm air gap width difference between layers of assembly materials can attribute to +/-1 in STC

In this study, Soundflow data was successfully combined with lab-tested data for a more realistic approximation of multi-component TL. In general, Soundflow is a handy supplemental tool to quickly estimate single-number ratings (STC) of a construction cross-section and the relative performance of different building materials. For example, a builder may benefit from Soundflow in selecting materials or evaluating construction widths. However, relying on this software to check criteria compliance is not recommended.

4.5.3.4 Insulation rating systems AIF, OITC, and STC

Unlike indoor standards using STC rating, outdoor standards are not specified in OITC. In Canadian outdoor noise standards, the AIF is used. There is a gap between common use of OITC and standard use of AIF that needs to be addressed. The ASTM E966 does not include results for the 5000Hz frequency band so that an AIF value could be computed from empirical results for comparison to criteria.

Error bars are not displayed in the graphs as it is uncommon for TL data presentation. For STC, industry uses a unique format to display deficiencies where necessary, and is not included in this paper [118]. Errors attributed to data processing and conversion between TL data and OITC, AIF and STC is ±1.5.

CHAPTER 5: Conclusion

In conclusion, this study fulfills the goals of examining the acoustics of Vancouver's laneways and LWH construction, and evaluating various tools that can be used to assess acoustical conditions in laneways and LWH. The hypothesis and predictions regarding urban canyon effects in higher density laneways, and on various architectural traits of LWH being problematic in terms of acoustics, are confirmed. Unhealthy acoustical conditions for LWHs include excessive outdoor levels (particularly on the lane side and on the street side for corner block LWH), open plan layout, size-related disadvantages, and inadequate facade insulation to meet CMHC indoor criteria, particularly where facades have heavily glazed areas. These research findings are translated into recommendations for design and construction strategies for Vancouver LWH.

The investigation of the potential for laneways to behave as urban canyons (Chapter 2) confirms that noise levels can remain higher inside laneways. The magnitude of canyon effect in a laneway increases with building density, building height, extensive laneway pavement and reduced laneway vegetation. Results confirm the hypothesis that in reflective built-up laneways, point source sound levels remain audibly higher at farther distances down the laneway. In comparison to the absorptive and highly vegetated case study laneway, the built-up laneways can have as much as 9dB to 17dB higher SPL at distances down the lane, translating to a difference of two to four times louder for LWH residents in terms of their immediate outdoor sound environment. This compromises outdoor living for laneway residents, such as gardening, enjoyment of patio (and/or deck), outdoor play and other uses of outdoor space.

Receiver-side strategies to reduce noise buildup within laneways include wider separation between lane side building facades and lower building heights. Additionally, sound absorbent and diffusive building surfaces, increased laneway vegetation including the use of vertical greenery systems, and absorptive laneway pavement such as gravel, dirt and grasscrete can reduce the canyon effect. The CMHC model predicts three out of four case study laneways having excessive outdoor levels, indicating the need for acoustical measures at facades and for outdoor living spaces.

Figure 104: Lane side vegetation on a laneway house in Toronto [130].

In the preliminary investigation of sounds in laneways (Chapter 3), it is readily apparent that laneways have a different balance of sounds than the associated street. It is discovered that more than half and up to three-quarters of sounds (by duration) heard inside laneways are transportation/works sounds from outside the laneway. When these sounds are maintained at higher levels by laneway canyon effects, total noise level may exceed CMHC criteria and negatively affect outdoor living and indoor living with open windows. Based on literature findings, green roofs and living walls placed at strategic positions on the main houses and the laneway houses can help lower noise levels from sources outside laneways.

Sounds originating inside the laneway are generally more balanced and less dominated by transportation/works. The exception is noise distribution in the high density, mixed-use laneway at E. Hastings. E. Hastings is a dramatic example of the future effect of increasing residential density inside laneways. As more people move into laneways, noise increases should be anticipated.

Another phenomenon needing attention is the high amplitude close approach vehicle noise in laneways. This does not only apply to large special vehicles like garbage trucks, but to all motor vehicles and sometimes even non-motorized wheeled carts. Because laneways are so narrow, vehicles moving through them are very close to the facades and to any people in the laneway, such as pedestrians, exposing them to very high sound levels.

(A) Street vehicle approach (regular house on right)

(B) Laneway vehicle approach (LWH on left)

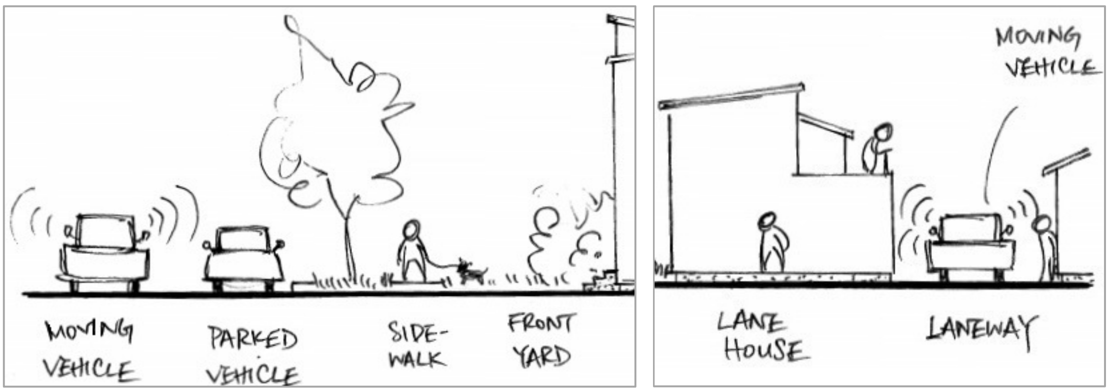


Figure 105: Vehicle approach distance from pedestrian (A) on street and (B) in laneway.

Upon closer examination of LWH architecture and facade insulation (Chapter 4), at-risk LWH planning and design features that require better acoustical strategy and extra noise insulation are identified. These include placement of sensitive spaces such as bedrooms and studies on noisier sides, excessive fenestration/facade ratio on specific facades in accordance with LWH Design Guide recommendations, relatively higher facade/floor-area ratios, and open plan and loft layouts that expose bedroom and living spaces (criteria 35 and 40 LAeq, respectively) to areas of higher noise-tolerance. In addition, higher outdoor noise levels are found at facades on the second floor (usually where bedrooms and decks are located), facades facing the lane and facades facing the street on a corner block LWH. LWH Design Guide recommends placing windows on street- and lane-facing facades, which have higher noise levels and thus require additional acoustical strategies. Investigation also reveals a significant number of cases of outdoor levels exceeding criteria. In these cases, outdoor living and open windows may be problematic, and facades need to provide higher noise insulation.

Figure 106: Corner lot LWH with very high fenestration/facade ratio facing street.

The case study LWH facades were tested and modelled to have low to mid-low insulation ratings. Depending on the specific method of assessment (CMHC or the LWH model), model predictions show that as many as three of six case study facades are insufficient for achieving indoor level criteria. CMHC predicted two non-compliant facades, both using glazed double-doors for patio access, again bringing concern to outdoor-oriented living in these LWHs. The LWH model (using software and lab test data) reveals one non-compliant facade enclosing a small and non-absorptive study room placed at a location with high predicted outdoor noise level. Empirical field measurements reveal half of the case studies being non-compliant, with one on the borderline and vulnerable to any additional noises not included in the CMHC road noise predictions, such as transit node noises, laneway noises, community noises and elevated laneway levels by the urban canyon effect. Together, the evidence showed that LWH is not free from excessive outdoor levels. This study demonstrates a greater need for good acoustical design and construction to achieve health and comfort, especially in ways such that the benefits of LWH-unique architectural features (such as smaller size, high fenestration/facade ratio, and lofted and/or open floor plans) can be maintained while their acoustical disadvantages reduced.

Figure 107: Very high fenestration/facade ratio on the lane side with high noise level

Many methods are used in this study. The field tests, despite the number of variables in field conditions, produce results that best reflect realistic in-situ behavior or performance. Empirical data (including lab data from government tests) are critical in this study, providing standard values for other investigative methods to compare to. More testing is required to build acoustical information on current envelope design.

The CMHC TNM is found to be a comprehensive and accessible tool for prediction and assessment, providing reasonable results for outdoor levels and for facade insulation. Its outdoor line source sound propagation results are conservative and thus do accommodate urban canyon effects in laneways. When used to specify and to estimate specific facade insulation performance, an acoustical site evaluation is recommended to augment CMH TNM results. Some of CMHC's tabulated information is in need of updating and gaps need to be filled to improve user experience and quality of results. It will be beneficial for the City of Vancouver to make this tool more widely known to citizens, to encourage its use, and to provide some guidance on its use (including updated information and addressing gaps in the tool), so that local home builders can more tangibly and effectively improve the acoustical quality of LWH and other single family residential zone construction in Vancouver.

Odeon is an acceptable professional planning tool to help predict sound propagation through a regular laneway (such as William and W34th), and to check for general trends and patterns existing between taller versus shorter and closed versus open theoretical laneways. However, Odeon is inadequate to predict accurate magnitude for (1) the degree of urban canyon effects in very built-up laneways like Charles and E. Hastings, and (2) noise mitigation effects of vegetated facade, roof and pavement installations through laneways. Odeon requires careful data-alignment and cross-referencing against field data for reliability, and requires considerable computing resources and aptitude in software troubleshooting.

Soundflow is an acceptable tool to quickly estimate partition insulation performance through a cross-section and to check for trends between different types of material, different sized air gaps, and permutations on multi-layer assemblies. Soundflow TL data is sometimes highly unreliable in certain frequency ranges. The software requires correct material and assembly input data, and works best when combined with laboratory fenestration data and/or when cross-referenced with lab test results for accuracy. Notwithstanding non-reasonable results, Soundflow is useful for providing TL data for calculating single-number insulation ratings AIF, OITC and STC.

Many issues relevant specifically to LWH discovered over the course of this research were beyond scope and resource limits but warrant further study. These include:

- Roof transmission loss for small open plan or lofted bedroom spaces
- Excessive flanking transmission for small wood frame structures
- HVAC, ventilation and indoor equipment in small open plan residential spaces
- Noise mitigation in laneways by vegetated architectural systems
- Long term criteria compliance due to increasing urban density and envelope degradation
- Further exploration of acoustical modelling tools for LWH applications

As more people take up residence in Vancouver laneway homes, noise exposure and acoustical environmental quality in these spaces need careful attention to comply with recommendations and criteria for healthy living. The findings of this study are presented to inform policy makers, stakeholders, the real estate industry, the construction industry, and future residents to consider acoustics early in long-term community planning, in designing and building laneway houses, and in making real estate decisions. This research calls attention to the specific acoustical needs of laneway housing and uncovers at-risk acoustical conditions that are harmful to residential health. It also presents existing tools that the public can use to plan and assess acoustics for their laneway house. Laneway homebuilders are strongly encouraged to take advantage of government resources available for residential acoustics—CMHC and NRC publications—to ensure that their best efforts to design a comfortable and healthy laneway home would not be compromised by poor acoustics. This research also provides real data and snapshots of current acoustical conditions of real LWH for learning and reference. Lastly, this study provides practical recommendations, strategies and warnings for acoustical planning, design, construction and retrofit that can help improve LWH in the future. This information can also benefit residential settings beyond the laneway to help maintain the prized serenity of Vancouver's RS neighborhoods.

Figure 108: One of Vancouver's three 'country lanes.'
Photograph by Ben Nelms for National Post [131]. This is a past laneway greening initiative by the City of Vancouver called "Country Lane," which was successful in achieving a lovely laneway environment [131]

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Appendices

Appendix 1: Acoustical criteria for residential spaces

WHO, CMHC and NRC noise level guidelines for residential spaces are presented below [8] [1] [15].

Table 22: Acoustical criteria for residential spaces

Residential Noise Level Limits					
		Bedroom	Living Room	Kitchen/Bath	Outdoor Living Space
WHO	Community noise, including all sources that affect domestic space.	30dbA night 35dbA day			55dBA; 57dBA is deemed "high annoyance)
CMHC	Exterior traffic noise source, measured indoors in 24 hour noise level	35LAeq(24)	40 LAeq(24)	45 LAeq(24)	55LAeq(24)
NRC	Road and rail noise. Author J.D. Quirt recommends lower value due to LAeq.[8] Events should be no higher than 5dB over the steady-state background level.	30-40 LAeq	35-45 LAeq	40-45 LAeq	55LAeq

[8] These values do not guarantee optimal acoustical environment or health but merely serve as a guideline.

Appendix 2: Categorized laneway sound types and component details

Table 23: Sound type categories with itemized contents and more description

OUT		IN	
Transportation/works			
Sound type	Contents	Sound type	Contents
Aircraft	many types and patterns: propeller jets, helicopters	Close vehicle incident	Loud vehicle noise including drive-throughs, idle engines at close range, and non-garbage truck operations
Special vehicle signals	boat horns, train horns, ambulance sirens, car alarms, backup signals, bus beeps	Garage and car	garage door motors and operation, domestic in-out movements like cars entering and exiting garages, lock/unlock open/close of car doors and related horn and beeps and slams, starting, idling, and shutting off of engines, domestic vehicle loading/unloading (like parents and kids arriving home from school or moving groceries) and related interaction with buildings
Loud road traffic		Garbage truck	garbage trucks or similar loud truck operating with rhythmic pattern, including beeping, air-release “tss-“ sounds, metal racks clanking, volumes of objects being

			hurled, impact noises, etc.
Normal road traffic	Includes buses and motorcycles in normal volume range.	Equipment	equipment, motors, power tools, and other machine sounds not including garage doors, includes vacuums, drills, mechanical like heat pumps or A/Cs, and any other mechanical/machinery noises sounding near
Low road traffic	Faint traffic noise	Work	work type sounds in the laneway: bottles, hammering, thuds, gardening, yard work, cleaning, dragging and moving things, cleaning out garbage cans, unidentifiable heavy-sounding activity including related interaction with building
Breaks/screeches	high pitch screech or skidding	Miscellaneous	electronics beeping or faint bell
Work	People-present work-related noises, including construction, rhythmic hammering, moving, loading/unloading, mowing, vacuuming, etc.	Cyclist	
Equipment	mechanical and equipment noise: drills, mower, power tools (these may be within the laneway just further off, but sound distant and		

	not from within the laneway)		

OUT		IN	
People presence			
Lively			
Sound type	Contents	Sound type	Contents
Domestic	kitchen sounds: making coffee or boiling water, bottle and dishes clanking, opening of blinds, dining	Human voice	Conversations in 4-5 different languages, talking, whistling, yelling, coughing, etc. includes times of silence mid-conversation between sentences or pause between answers
Music	not from within the laneway)	Human activity	moving around, walking, shifting sounds, unidentifiable activity sounds made by people
		Children	infants, toddlers or children's voices (includes periods of silence mid conversation)
		Dog bark	bark, growls, roofs and yelps mostly in response to human stimuli
		Dog-walking	Dog pants with distance-based volume change
		Music	from inside cars
		Miscellaneous	phone rings, electronic beeps
Relaxing			
Church bells	Musical sound mark		
Natural			
Crows	Large variety of crow sounds: “gah… gah… gah…,” craws, calls, conversations,	Bird calls	Father range communication, steady and repeating, such as “jiu… jiu… jiu…”

	loud/soft, distant/close, cacophony/singular, various temporal patterns		
Seagulls	Craws, crying and wailing	Bird song	chirps, tweets, musical sounds; more intimate and closer range, various temporal patterns
Bird calls	Far range calls	Bird movement	Fluttering of wings, shaking and dusting things off, landing, etc.
Environmental	Meteorology sounds: ambient whooshing, air, wind, thunder, rain	Bugs	Crickets or other insect buzz and sounds.
		Environmental	Trees and leaves rustling
		Quiet	notable phases of no sound activities except very low ambient level that's unidentifiable for content

Appendix 3: Chapter 4 research components summary

Table 24: Transmission loss of LWH research components

LWH Transmission Loss Study			
Research Module	**Method**	**Data to collect for calculations**	**Outcome**
Traffic Noise Model (Part 3, 5, 6)	CMHC (see Appendix 5 for more details)	**Traffic Noise Source** Identify all major road noise sources Daily traffic volumes (from CoV Vanmap) Posted speeds % heavy vehicles Intersections **Traffic Noise Path** Distance (between source, receiver, and barriers) Ground effects Elevation (source, receiver, and barrier heights) Barriers and obstacles (quantity, length, and form) Shielding/exposure effect **Receiver** Room use Facade surface area Facade construction and elements (exterior wall, windows and doors types) Room floor area or room volume Room absorption (furnishing) Assess need for building correction	Criteria (based on space usage); outdoor road traffic noise levels at facade and outdoor living spaces; criteria compliance; and Unique insulation requirement for each facade
TL field test	ASTM E966	**Construction properties**	Facade surface area
		Facade Transmission Loss Source and receiver levels Source and receiver positions (angles distances and spatial average) Flanking* (beyond scope)	OITL
Room absorption A field test	ASTM C423	Indoor materials and furnishing Room volume Air condition (temperature and humidity)	Reverberation time Room absorption
Ambient levels	Field measurement	**Ambient sound levels (indoor and outdoor)**	Indoor levels Outdoor levels
Model constructi on for TL	AFMG Soundflow	**Envelope component details (walls)** Material mass density, stiffness/elasticity, porosity, fiber size, airflow permeability etc. for impedance and absorptivity. Layer material thickness and size Air cavity spacing between material layers Angle of incidence/sound field	OITL STC

LWH Transmission Loss Study			
Research Module	**Method**	**Data to collect for calculations**	**Outcome**
		Wall stud and cavity composition Facade surface dimensions Thermopanes, rigid foam insulation and SIPs	
Facade insulation rating	ASTM E1332	TL data for 80-4000Hz	OITC
	ASTM E413	TL data for 125Hz to 4000Hz	STC
	CMHC TNM NRC BRN 172	Receiver room properties and use designation Number and type of elements in facade Room layout, size and volume Facade to floor area ratio, or TL data for 100Hz to 5000Hz	AIF AIF to STC
Compariso n and supplemen tal	NRC and CMHC lab test results, Manufacturer lab test results, AFMG	IRC-Bradley and Birta lab test results for the closest approximate element type. Manufacturer lab test results for SIPs and rigid foam AFMG model results for exterior walls, rigid foam insulation and SIPs	Comparison results; Soundflow software validation; field vs lab measurement validation
Design and layout	Architectural review	Exposure to direct or reflected sounds Siting and surrounding noise sources Size and placement of fenestration Open floor plans and lofts	Design impacts and analysis

Appendix 4: Soundflow testing

For a standard NRC test wall ("TLA-99-019a"[9]), the NRC data is compared with Soundflow modelled data [107, p. 82]. Soundflow adheres to TL theory, showing TL increasing with frequency. However, when juxtaposed for comparison to empirical values, this TL is significantly overestimated at frequencies above 2500Hz, by approximately ±10dB and increasing to +48dB at 5000Hz. In this case Soundflow yields STC 4 points higher and OITC 8 points higher than laboratory ratings, a significant difference.

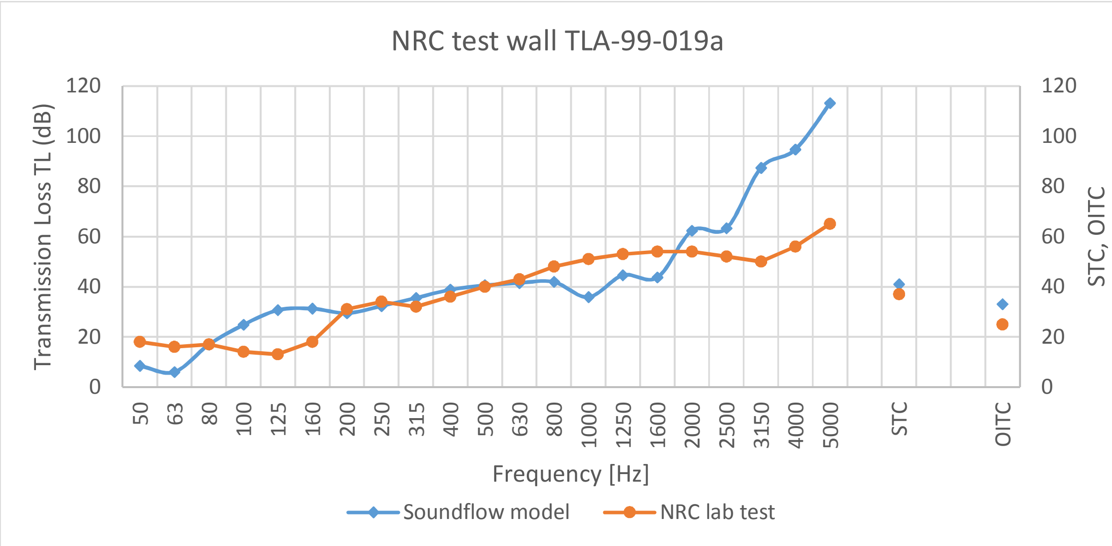

Figure 109: Basic NRC rainscreen test wall TL comparison

LWH D was modelled in Soundflow to check for degree of cavity insulation. Figure 110 shows that insulation in cavity improves exterior wall TL performance but neither Soundflow model

[9] Consisting of vinyl siding attached on 19mm wood furring to 11 mm OSB on 140 mm wood studs spaced at 406 mm with glass fibre insulation in the cavity and a single 13 mm layer of gypsum board as the interior surface.

matches field results better. Field results are included for this comparison shows Soundflow differing from empirical data in highest frequencies above 2000Hz.

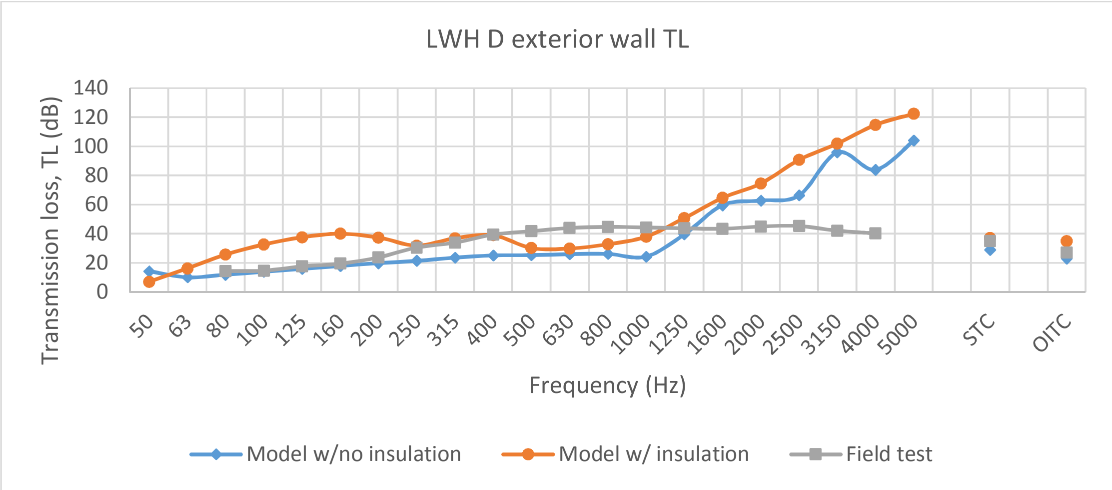

Figure 110: Case study D exterior wall comparisons

Appendix 5: The CMHC Traffic Noise Model

Table below shows a simplified scheme of modelling laneway house traffic noise levels using CMHC.

Traffic Noise Model Overview (Part 3, 5, 6)	
Input data	**Outcome**
Traffic Noise Source Identify all major road noise sources Daily traffic volumes (from CoV Vanmap) Posted speeds % heavy vehicles Intersections and distance from each intersection **Traffic Noise Path** Distance (between source, receiver, and barriers) Ground effects Elevation (source, receiver, and barrier heights) Barriers and obstacle corrections (simplified) Shielding/exposure effect **Receiver** Room use Facade surface area Flanking/neighboring facades and total number of components on neighboring facades Facade construction and elements (exterior wall assembly components, windows and doors types and details such as glazing widths and number of panes) Component areas Room floor area	Room criteria outdoor road traffic noise levels at facade and outdoor living spaces such as decks, patios and gardens criteria compliance unique insulation requirement for each facade

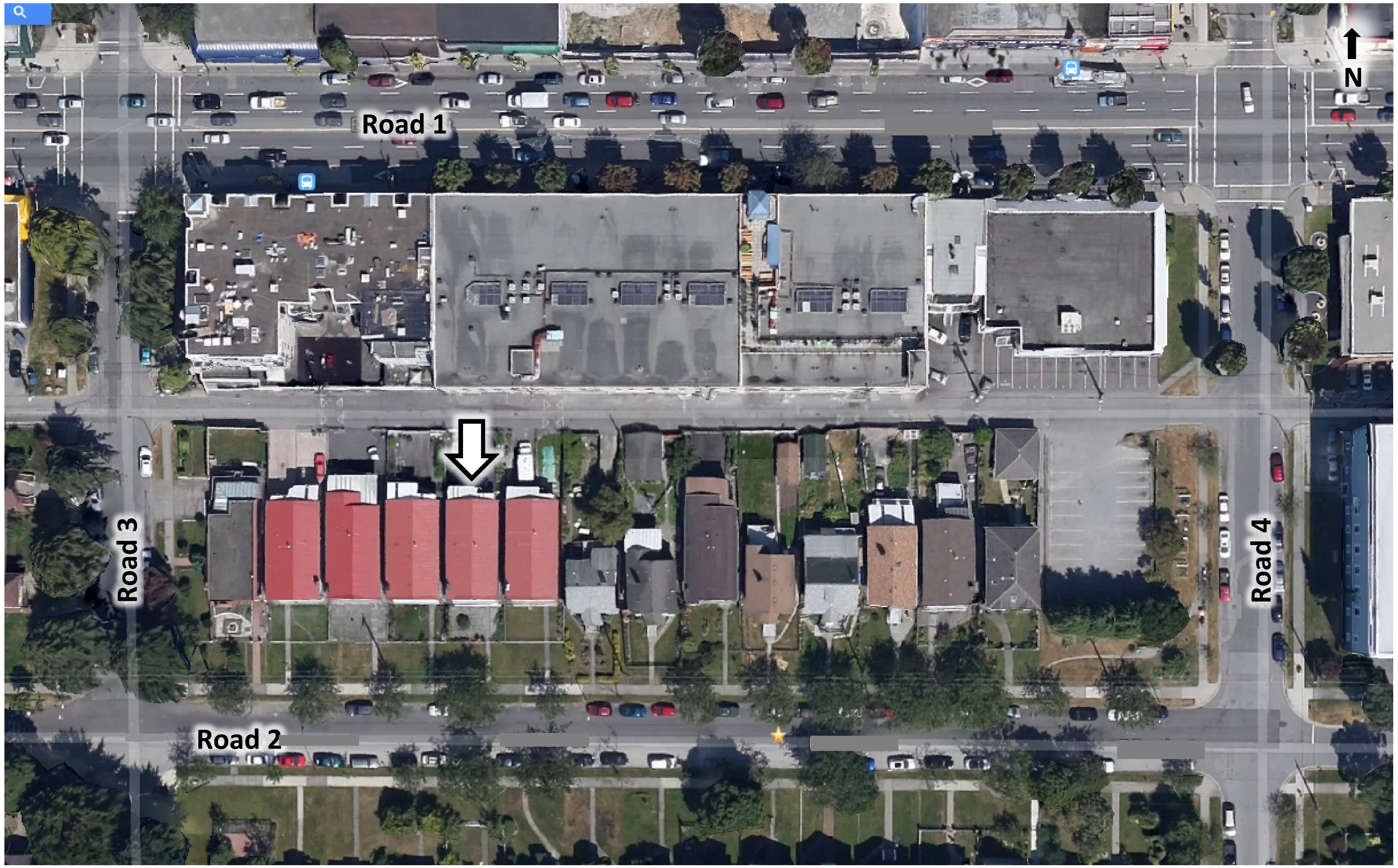

Figure 111: Case study aerial map for CMHC modelling

Receiver/Source	Posted Speed (km/hr)	Traffic volume per day (24)	% Heavy Vehicle* (+bus)	3.1.2 Noise level (dBA) over hard surface	distance (m) to INTERSECTIONS (VANMAP)		Table 3.3 Interrupted flow (dB correction)	Horizontal distance S-R (m) (to center of wall) VANMAP	G map Soft surface (m)	Soft surface % (if over 50 then SOFT)	Van Map Table 3.5 Step 6	4-2-2 pg 20 Obstacles	Path length difference	v/g	u/g (same for values over 9.5)	Table 3.6 Barrier length ratio	Table 3.7 Continuous barrier correction	Exposure/Shielding pp51-53	dBA (Leq)	10^(L/10)	
SOUTH WEST HOUSE #5																					
Ground level																					
NORTH façade																					
Road 1	50	52132	10	68	61	123	2	40	0	0%	-1	-4	16	9	7	7		0	65	3162277.7	
Road 2	40	1000	0	45	61	124	2	39	0	0%	-1	-4						-10	32	1584.9	
Road 3	40	1000	0	45	47		2	48	0	0%	-2	0						-3	42	15848.9	
Road 4	40	1000	0	45	117		1	117	0	0%	-6	0						-3	37	5011.9	
													North Wall, Level G							65.0	dBA

Figure 112: CMHC Model Part 3 and 5, worksheet for the one facade marked by an arrow in Figure 111

CMHC Part 6

Step 1	Results from Parts 3-5 above)							
	Ground floor							
	West	51.4						
	South	54.4						
Step 2	Room Category							
	West	Kitchen/dining/living						
	South	Living/dining/recreation						
Step 3	Omit shielded wall under 55dB				West			
		# components						
	West	3	say this wall is "shielded from noise sources" and omitted from calculations					
	South	3						
Step 4	AIF per Table 6.1							
	# of Components per façade							
	West		3					
	South		3					
	North		2					
	Total components		8	if reduce to 7 (see note on pg 55 of CMHC Part 6), AIF req is still same, 26.)				
	lowest dB on chart		55dB					
	AIF Requirement		**26**					
Step 5	Determin floor area ratios							
			ft2	m2	area as % of floor size	Table 6.2-4	Corres pondin g AIF	
	Room floor size		241.512	22.43722	100%			
	Surface Areas							
	South	Window	20	1.858063	8%	2,2,6mm	32	
		Door	35	3.25161	14%	80% glazed dou	22	D1 is 24. -2 to account for double and glazed door.
		Wall	53.16	4.93873	22%	EW1	37	2x6 studs not in CMHC. Per Bradley and Birta NRC O
		Façade	108.16	10.0484	45%	2,2,6mm	24	using glass because the huge window and glazed dc

Figure 113: CMHC Model Part 6: facade insulation rating requirement and estimated component ratings

Appendix 6: Proposed CMHC improvements for LWH application

Below is a list of suggested improvements to the CMHC TNM for application in LWH development.

1) Include the laneway as a noise source, including near field effects.
2) Include effects of bus stops and light rail transit.
3) Include effects of vertical vegetation.
4) Include effects of vertical reflective surfaces.
5) City to provide more accurate data for heavy traffic composition along arterial roads.
6) Amend obstacle and barrier correction calculations for clarity, ease of application and improved accuracy for LWH conditions. These include:
    a. Improve attenuation values for rows of detached housing with minor gaps between buildings (e.g. -4dB for the first row and -2dB for the second row) to reflect difference between small and large buildings. Smaller buildings such as garages, tool sheds and other laneway houses are common obstacles around laneway houses and should not be treated the same as larger buildings.
    b. Improve instructions and values for barrier calculations (including CMHC Tables 3.6 and 3.7 [14]) to reduce overestimation of barrier attenuation and to streamline process for multiple barriers.
    c. Depending on the outcome of barrier/obstacle attenuation improvements, it may be necessary to add reflection factors that increase resulting sound levels.
7) Improve soft ground/hard ground evaluation procedures as distances for LWH application can be very short.

8) Update data to include new architectural components, such as:
    a. 140mm (2x6”) wood stud walls
    b. Rainscreen wall construction
    c. Glazed double patio doors and other types of glazed doors commonly used in LWH
    d. New insulation material and wall types such as EPS and SIPs
9) Include consideration of roofs, which is important for bedroom spaces on second levels.
10) Clearly specify that open floor plans and spaces connected to lofted areas should meet most stringent criteria for the quietest function.
11) Include consideration for irregular architectural volumes, such as over-height ceilings and lofted spaces.
12) Provide procedures to convert AIF into OITC for ease of field application and/or for evaluating market-ready wall and fenestration components.
13) Provide clearer instructions and computerize the entire model into a software program to encourage wider application.