Acoustic Research Group
Department of Mechanical Engineering
University of Canterbury
Christchurch

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Noise Attenuation by Roof Cladding Systems - Phase 1

Prepared by: Jeffrey Mahn

For: Peter Atkinson
Executive Officer
New Zealand Metal Roofing Manufacturers Association Inc.
Private Bag 92-066
Auckland 1142

Issued by: John Pearse
Mechanical Engineering Department
University of Canterbury
Private Bag 4800
Christchurch 8140
Ph: (+64) (3) 364-2987 ext 7252
Fax: (+64) (3) 364-2078
Email: jeffrey.mahn@canterbury.ac.nz

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Summary

The findings in this report were commissioned as the first phase of an investigation of the noise attenuated by roof cladding systems. The purpose of the first phase was to determine the requirements of a research and development project which would identify and assess the parameters affecting noise through the roofs of domestic dwellings. To this end, a literature review of prior work was conducted resulting in a list of significant parameters for the attenuation of noise through roof systems as well as a proposal for further phases of the investigation.

Summary of Parameters which Affect the Attenuation of Noise through Roof Systems

Prior studies have found that the specification of the noise attenuation of just the roof or of just the ceiling was inadequate to express the noise attenuation of the complete roof system inclusive of the roof, the trusses and the ceiling. The trusses act as a transmission path for structure-borne noise between the roof and the ceiling and therefore the system must be considered as a whole.

The addition of fibreglass or mineral wool insulation between the joists above the ceiling has been reported to result in a greater improvement to the noise attenuation of the roof system than adding sarking (sheets of lead or aluminium in the prior studies) between the roof and the trusses. Therefore the requirement that plywood sarking be added under the roof may not be the most effective means of improving the noise attenuation of the roof system.

The noise level in the room of a dwelling is affected by the noise attenuation of all of the building elements including the window (frame and the glazing), the roof and the walls. The attenuation of the elements must be known and ranked before improvements can be made. Attempts to improve the sound insulation of a dwelling must focus on the element with the lowest noise attenuation. Further improvements made to the elements which do not have the lowest noise attenuation will have little effect on the overall noise level in the room.

Prior studies have suggested that the windows of the dwelling may be the primary transmission path of traffic noise into the dwelling, depending on the thickness and configuration of the glazing. If this is the case, increasing the noise attenuation of the roof system will have little effect if the sound reduction index of the windows is not addressed by sealing the windows or by specifying thicker glazing or double glazed windows.

The height of a dwelling and the pitch of the roof can affect the level of the traffic noise incident on the façade. A microphone positioned 2m from the façade and 1.5 m from the ground may measure a higher level of traffic noise than a microphone located higher on the façade or on the roof. The lower noise level incident on the roof may result in less noise transmitted through the roof system.

Further Work

The following activities have been identified as subsequent phases for the investigation of the noise attenuated by roof cladding systems:

Phase 2: Laboratory testing of complete roof systems to quantify the effect of sarking under the roof or insulation between the ceiling joists.
Phase 3: Field testing of different roof system configurations and the evaluation of the source noise across the face of the façade and the roof.
Phase 4: Models to predict the noise attenuation of the roof system and to predict the source noise level across the face of the façade and the roof.
Phase 5: System design to improve the noise attenuation of the roof system.

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1. Literature Review

It is surprising how little has been published regarding the noise attenuation of roofs. Furthermore, there is very little acoustical test information available for roof-ceiling structures [1]. The studies which are available point to three issues particular to noise transmitted through the roof system including the noise attenuation of the roof system as a whole versus the noise attenuation of the other roof elements, the effect of diffraction on the sound incident on the roof and the effect of other paths of transmitted noise into the dwelling.

1.1. Sound reduction index of the Roof System

The most extensive published study of noise attenuation of roofs was conducted by Cook [2-4] at what is now RMIT University in Melbourne, Australia. Part one of the study was a laboratory investigation of the sound reduction index of just the ceiling. The ceiling was tested both by itself and with different configurations of fibreglass infill between the ceiling joists as well as sarking of 0.23mm thick aluminium which was laid across the ceiling joists. Part two of the study investigated the sound reduction index of the roof. The pitched roofs tested in the laboratory included concrete tiles and galvanized steel sheeting. The roofing materials were tested with and without aluminium sarking between the roof and the trusses. Part three of the study investigated the sound reduction index of the combined roof and ceiling components.

One of the conclusions of the study was that the trusses between the roof and the ceiling act as pathways for structure-borne sound. It was found that the sound reduction index of the roof system inclusive of the roof, ceiling and the connections between them could not be predicted from the sound reduction index of the roof or ceiling measured separately from the roof system. Specifying a higher sound reduction index rating for one part of the roof system without considering the system as a whole may not be effective.

Cook used a single number rating called the sound transmission class (STC) to quickly identify improvements in the sound reduction index of modified roof systems. The STC rating is calculated by fitting a standard reference curve to the sound reduction index according to ASTM E413-04 [5]. Cook found that the addition of fibreglass insulation between the ceiling joists increased the STC rating of the roof system by a greater amount than the addition of a 0.23 mm aluminium foil sarking between the roof and the trusses. For example, a concrete tile pitched roof alone had an STC rating of 33. Adding 50 mm glass fibre blanket between the ceiling joists increased the STC rating by 7 whereas the addition of a 0.23 mm double sided aluminium foil sarking under the roof increased the STC rating by only 3.

Cook found that the increase in the sound reduction index was achieved regardless of whether the fibreglass insulation was added between the joists above the ceiling or between the trusses. The greatest increases in the sound reduction index of the roof system were achieved by also sealing the sound leaks at the perimeter of the roof. However, the sealing of all of the sound leaks may not be permissible under the Compliance Document for New Zealand Building Code Clause E2 - External Moisture [6].

A separate study by Scholes [7] regarding the transmission of aircraft noise into dwellings near Heathrow also found that the addition of mineral wool insulation between the ceiling joists to be more effective at reducing the noise in the dwelling than the addition of sheets of lead under the roof. It is important to note is that the study by Scholes differed from that by Cook in that the measurements were made in actual houses and therefore included the effect of flanking transmission. Cook made his measurements in the laboratory and so the sound reduction index of only the roof system was measured.

Therefore, any suggestion to improve the sound insulation in a dwelling must consider the roofing system as a whole including the roof, the trusses, the ceiling, openings for ventilation and any insulation between the ceiling joists. NZS 4218:2009 [8] and the Compliance Document for New Zealand Building Code Clause H1 - Energy Efficiency [9] both require that buildings with any wall type has a roof with a R value between 2.9 and 3.3, depending on the climate zone. It is not unreasonable to expect that a dwelling built in compliance with Clause H1 will include fibreglass or mineral wool insulation between the ceiling joists to achieve the required R value. However, it can not necessarily be assumed that the insulation added to comply with the thermal requirements will also yield the required acoustic benefits [10]. Testing or modelling must be done to ensure that the roof system with the insulation will meet the acoustic requirements for the dwelling.

1.2. Angle of Incidence and the Diffraction around the Roof Edge

In a theoretical and experimental study of the field performance of skylights installed in roofs, Villot [11] found that roofs are less exposed to the noise from road traffic than are the vertical facades of the building. Even a roof with a slope as steep as 60^o still resulted in a 5 dB difference between the sound pressure level measured at the ground level of the building and at positions on the roof.

The implication of the possible attenuation is that the roof system will be exposed to a lower level of noise than the façade of the dwelling. For example, the Norman Disney and Young report of April 2008 [12] found that the external sound level was L_{A10} = 63 dBA. Based on a hypothetical 5 dB attenuation in the traffic noise measured on the roof, the averaged external sound L_{A10} at the roof could be 63 - 5 = 58 dBA. If the roof system had an average level difference of 27 dBA then the contribution of the roof system to the sound pressure in the bedroom would be 31 dBA. The actual L_{A10} measured in the bedroom was 34 dBA which would suggest that the roof was not the primary transmission path in this hypothetical case.

Experiments [13] have shown differences between the sound pressure level measured at 1.5 m from the ground and at different heights along the façade and the roof. The façade and roof construction specified in the Marshall Day report of November 2006 [14] appears to be based on the predicted noise levels at ground level without taking into account the attenuation due to the façade. The measurements reported in the Norman Disney and Young report of April 2008 [12] also do not account for the possible attenuation due to the façade. The measurement of the external noise was made at a height of 1.5 m from the ground to calculate the level difference of the elements in the second storey bedroom. The measurement height was reported to be in accordance NZS 6801:2008 [15] and NZS 6802:2008 [16]. However, NZ 6801 states that the measurement of sound received inside the building is not recommended if the sound source is outside the building. Therefore, the measurements specified in NZ 6801 and NZ 6802 should not have been used to determine the level difference or the sound reduction index of building elements when traffic noise is the source.

Alternatively, the standard, ISO 140-5 [17] gives specific instructions for the measurement of the sound reduction index and the level difference of a façade due to traffic noise. ISO 140-5 specifies that the external sound pressure level be measured at the middle of the façade at a height of 1.5 m above the floor of the receiving room. Therefore, if the external sound pressure level for two story houses such as those included in the Mt. Wellington Quarry were measured according to ISO 140-5, the level would have been measured at a height that would be 1.5 m above the floor of the bedroom. The differences between the New Zealand standards and the ISO standards are explained further in Appendix B.

Villot also found that due to the diffraction on the lower edge of the roof, the sound exposure of roofs has the particularity of being at grazing incidence. Since sound transmission is strongly affected by the angle of incidence of incoming waves [18], Villot questioned the acoustic field performances of skylights as opposed to their laboratory performances since ISO140-3 [19] and ISO15186-1 [20] which are used to measure the sound reduction index of elements in the laboratory assume that the source sound field is diffuse. Laboratory experiments confirmed that the sound reduction index of the glazing was different for different angles of incidence. However, Villot found that the roof insulation was little affected by grazing incidence in terms of single number ratings.

1.3. Other Transmission Paths

External noise enters a dwelling by many paths, the most obvious of which is through the windows [21]. By reviewing the sound reduction index values for various components of the external building envelope, Cook [4] found that the weakest link in the dwellings evaluated was the windows. A simple, openable window has an over-riding influence on the dwelling envelope sound insulation, even when of minimum regulatory area and kept closed. This effect was so pronounced that attempts to achieve a roofing system of high insulation properties was largely negated by the window component.

However, as the sound reduction index of windows is increased, it becomes increasingly important to take other possible sound paths into account [7] such as through the roof, through the walls and through gaps around external doors. For example, Cook found that the STC rating of the metal roof that he tested was 34 without sarking or insulation between the ceiling joists. The 6 mm thick windows of the dwelling had a STC rating of 31 making them the primary source of noise in the dwelling. However, replacing the 6 mm glass with 13 mm glass increased the STC rating of the windows to 36 [22]. The STC rating of the roof system then needed to be improved by adding insulation between the ceiling joists to prevent the roof from being the primary source of noise in the dwelling. This was also the case in a separate study by Walker [23] where fibreglass insulation was added between the ceiling joists and a layer of gypsum board was placed above the ceiling joists to increase the STC rating of the roof after double glazed windows were installed in the dwelling.

When comparing the sound reduction index of windows to that of other elements of the external building envelop, it is important to differentiate between measured data for glazing and measured data for windows. The sound reduction index of a window may be lower than that of the glazing since the performance of a window is affected by the window frame and the sealing as well as the glazing [24]. Steps to increase the sound reduction index of windows should include sealing the window to eliminate small gaps through which noise can penetrate and increasing the thickness of the glass.

2. Proposed Future Work

2.1. Measurements

Based on the findings by Cook, it is proposed that a complete roof system be tested to evaluate the sound reduction index of the roof system. The configurations of the complete roof systems which are tested should include:

- Metal roof without sarking, no fibreglass insulation between ceiling joists
- Metal roof without sarking, fibreglass insulation between ceiling joists as specified in the Marshall Day report of 2006 [14].
- Metal roof with 17.5 mm plywood sarking, no fibreglass insulation between ceiling joists
- Metal roof with 17.5 mm plywood sarking, fibreglass insulation between ceiling joists as specified in the Marshall Day report of 2006 [14].

To be representative, the testing must include the ventilation and air gaps which would be common in an actual construction [10]. It is also proposed to measure the sound reduction index and the STC rating of typical windows including 10.8 mm and 6.4 mm laminated glazing as specified in the Marshall Day report of 2006 [14].

The purpose of the proposed measurements is to determine the sound reduction index and the STC rating of the different configurations. If the STC rating of the roof system is lower than that of the other transmission paths of traffic noise into the bedroom of the dwelling, then further improvements in the STC rating of the roof system would not be effective without the improvement of the STC rating of the other elements. If the additional measurements including the roof systems with plywood sarking or insulation between the ceiling joists show that the insulation is more effective than the addition of the sarking at improving the STC rating of the roof system, the argument can be made that a requirement for insulation is preferable to a requirement for plywood sarking. Furthermore, it can be argued that the insulation between the ceiling joists will have the added benefit of increasing the thermal insulation of the dwelling in accordance with the New Zealand Building Code Clause H1.

In addition, measurement of the mean square velocity on the element surfaces according to ISO10848 is also proposed. The velocity data will be required for the prediction of the sound reduction index of the roof system using Statistical Energy Analysis (SEA) as described in Section 2.2.

2.1.1. Laboratory versus Field Measurements

The measurements could be made either in the laboratory or in the field. Each measurement location has advantages and disadvantages. In a dwelling, the roof is attached not only to the ceiling but also the surrounding walls of the room through the joists. Therefore, the structure-borne noise due to the exposure of the roof to airborne noise is transmitted into the room not only through the ceiling, but also through paths including the walls of the room as shown in Figure 1.

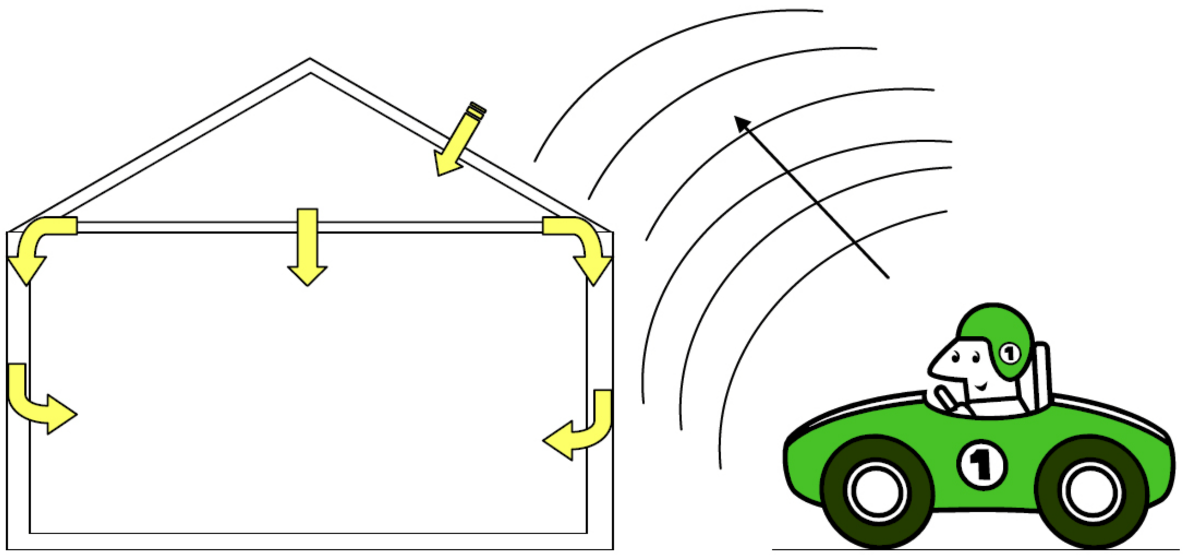

Figure 1: Flanking transmission paths from the roof.

Laboratory measurements would not include the contribution of the flanking transmission through the walls of the dwelling. Therefore, the laboratory measurements would be useful to quantify the effect of the addition of the sarking or the fibreglass insulation on the sound reduction index of only the roof system without the effect of flanking transmission. The measurements would also provide data for the SEA models.

Field measurements in either a dedicated test house or real houses have the advantage of testing the a full roof system plus the contributions of flanking paths. By using sound intensity measurements made according to 15186-2:2003 [25] the *in-situ* sound insulation of the ceiling, walls and windows can be determined. The intensity measurements can be made in the presence of flanking transmission and would allow the contribution of each element to be assessed. The use of intensity offers a significant advantage over the measurement of the level difference due to traffic noise reported in the Norman Disney and Young report of April 2008 [12] or made according to ISO 140-5 which only report the total contribution of all of the transmission paths to the sound pressure in the room.

A dedicated test house where the roof system can be modified to include sarking or insulation between the ceiling joists would offer more reliable measurement data than testing actual houses with different roof system constructions. If actual houses are used, the orientation of the roofs and the noise (ideally traffic noise but a loudspeaker could be used), the height of the buildings relative to the source of the noise, and the relative contributions of the noise source to the total noise must be the same for all of the dwellings [24]. Furthermore, there could be differences in the construction of the houses due to workmanship or differences in the designs. These requirements may present a challenge to finding actual houses for the testing unless the houses are all adjacent to each other in the same complex.

In either case, using traffic noise as the source is preferable to using a loudspeaker as a source. In the case of traffic noise, the sound is from different directions and with varying intensity whereas the noise from a loudspeaker is direct sound. Due to the differences in the nature of the incident sound, the results of measurements made using a loudspeaker can not be expected to fully agree with measurements made using traffic noise as the source [17].

2.1.2. Laboratory Measurements

The laboratory measurements would involve the measurement of the sound reduction index of the building elements according to ISO 15186-1. In addition, the velocity level difference between the roof and the ceiling could be measured according to ISO 10848-1 [26]. A sample of the roof system would need to be constructed and mounted between the reverberation room and a semi-anechoic chamber at the University of Canterbury. The roof sample would be approximately 2 m x 2 m as shown in Figure 2.

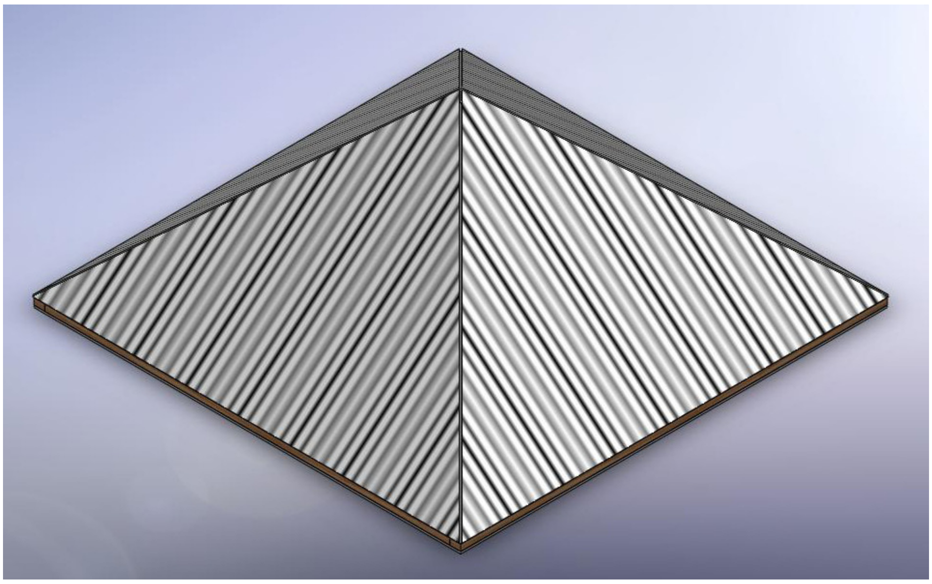

Figure 2: Test roof system for laboratory measurements.

The test roof system would be mounted horizontally to an opening in the concrete wall between the rooms as shown in Figure 3.

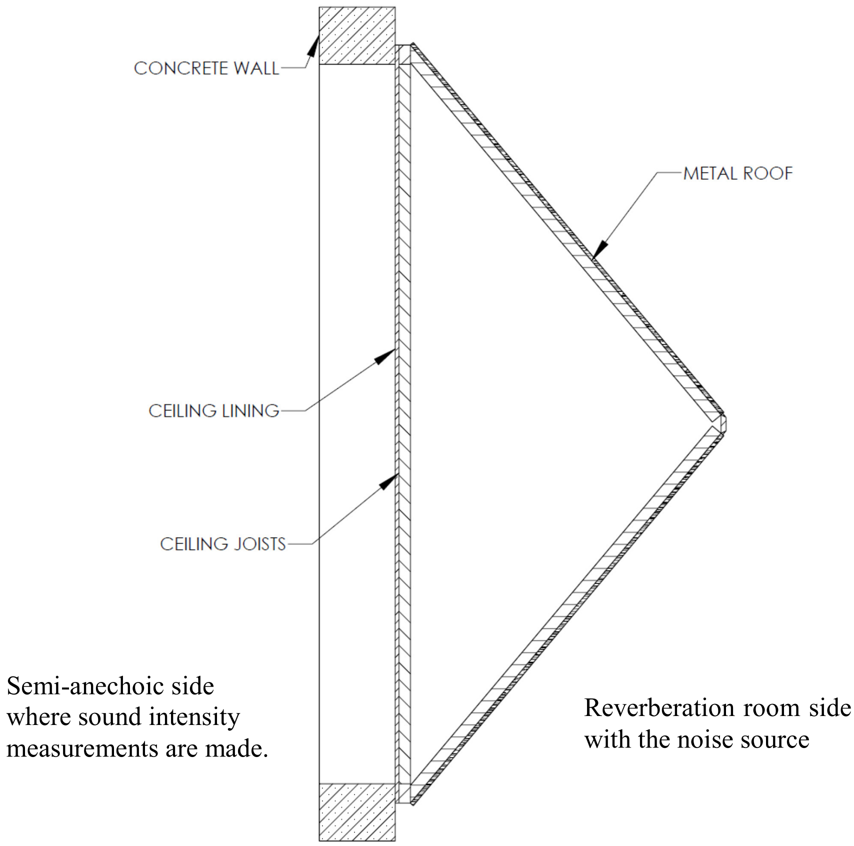

Figure 3: Simplified cross section of test roof system mounted to the concrete wall of the reverberation room. The trusses of the roof are not shown.

The test roof can be modified between tests to allow for the configurations with sarking and with fibreglass insulation between the ceiling joists to be tested. Since the test roof would be mounted vertically, the fibreglass insulation between the ceiling joists would need to be secured with wire or nylon mesh.

Deliverables of the Laboratory Measurements

- A library of test data for each roof system configuration including the sound reduction index measured according to ISO 15816-1 and the STC rating calculated according to ASTM E413-04.
- Data for the prediction models measured according to ISO 10848-1.

The library of test data can be used to choose the roof system designs for future construction projects. If, for example the addition of the plywood sarking under the roof is shown to have less effect on the sound reduction index than the addition of the insulation between the ceiling joists, the measured data can be used to justify the omission of the plywood sarking in future construction projects. Furthermore, the STC ratings can be compared to the STC ratings of other elements in the dwellings to indicate which element represents the dominant transmission path for noise in the dwelling. The STC rating of the dominant transmission path must be improved first before the other elements should be considered for improvement.

If the roof system without plywood sarking is shown to have a higher STC rating than other elements, then the addition of the sarking will not be effective at reducing the noise in the dwelling.

2.1.3. Field Measurements

The field testing can be conducted in houses with different roof systems or in a dedicated test house where the roof system can be modified. If different houses are to be used, the orientation of the roofs and the noise (ideally traffic noise), the height of the buildings relative to the source of the noise, and the relative contributions of the road traffic must be the same for all of the dwellings [24]. In order to meet the requirements of the location of the microphones in the dwelling according to NZS 6802 or ISO 140-5, the rooms where the measurements are made will need to be free of furniture.

The testing will be conducted according to ISO 140-5:1988 and ISO 15186-2 [25]. If the traffic noise is not sufficiently loud enough to measure levels in the receiving room that are above the background noise level, then a loudspeaker will be used. The intensity sound reduction index of the ceiling, walls and the windows will be measured using sound intensity. The apparent sound reduction index of the room (inclusive of all sources) will be measured by averaging the sound pressure from several microphone positions. A comparison of the results will allow the relative contribution of each element to the total sound reduction index of the room. However, if one element, for example the window has a much lower sound reduction index than the other elements so that it is the dominant source of noise in the room, it may not be possible to measure the sound intensity of the other elements without adding a sound barrier over the window.

Deliverables of the Field Measurements

- For each roof system configuration, the following will be measured:
    - The standardized level difference of the complete façade according to ISO 140-5.
    - The apparent sound reduction index of the roof system and the windows according to ISO 140-5.
    - The sound reduction index of the roof system, the walls and the windows according to ISO 15186-2.
- Measurements made according to ISO 1996-2 to show the attenuation of the traffic noise across the façade and on the roof for use in the models.

The proposed field testing represents a novel study of the noise transmitted into dwellings. Although similar measurements have been made in the past [27] by the Acoustics Research Group, a study which includes the measurement of the sound reduction index of the roof system and of the other elements in a room according to ISO 15186-2 has not been published in New Zealand or in the major international journals.

2.2. Prediction Models

It would be advantageous to develop a mathematical model to predict the level difference of a roof system due to traffic noise. The model would allow for the design of the roof system to be chosen to meet the façade specifications of dwellings. However, the development of a mathematical model is not straightforward and there is some risk associated with this activity.

A simple prediction model for the roof system may not be feasible since the model must account for the sound reduction index of the roof and ceiling, inclusive of any additional sound absorbing material as well as the sound reduction index of the structure-borne noise through the trusses. However, a more complex model based on SEA using either a model developed for this program or according to ISO 15712-3:2005 [28] may be possible.

The accuracy of applying SEA to the roof system may be limited due to the incorporation of lightweight elements such as the metal roof and the ceiling lining. SEA requires that the elements support a uniform energy density and contain resonant modes. Furthermore, the elements must be weakly coupled. It has been found that [27] lightweight elements may not meet these requirements of an ideal SEA subsystem which can lead to large uncertainty in the predictions. Alternatively, classical models or finite element models may be used.

Any prediction models should also include a method of calculating the difference in the level of the traffic noise measured at the ground level and measured at different heights along the façade and at positions at the roof level. The difference in the level of the traffic noise could be calculated using a mathematical model or using a commercial ray tracing package such as ODEON.

Once the model has been created and validated using experimental data, the uncertainty of the predictions can be estimated using the ISO Guide to the Expression of Uncertainty (GUM) [29] and Monte Carlo simulations [30].

Deliverables of the Prediction Models

The goal is to deliver a prediction model which can estimate the level difference of the roof system based on the construction of the roof system, the height of the dwelling, the pitch of the roof and the location of the traffic noise relative to the dwelling. The model will include the attenuation of the traffic noise by the façade and the roof.

2.3. System Design

Opportunities would be expected to arise during the measurement of the sound reduction index and the modelling of the roof system to determine the effect of modifications to the roof system design. For example, insulation materials of different composition or thickness can be added between the ceiling joists to determine the effect on the sound reduction index of the roof system.

The objective of the system design would be to identify and to evaluate change to the roof system which could enhance the acoustic performance of the roof system. The experimental measurements and the mathematical model would enable the evaluation of any identified changes to the roof system.

3. Execution of the Proposed Future Work

The proposed future work which has been identified may be executed in four subsequent phases as described below.

Phase 2: Laboratory testing

Laboratory measurements as described in Section 2.1.2 of the sound reduction index of various roof system configurations including roof systems with and without plywood sarking and with and without insulation between the ceiling joists. In addition, the sound reduction index of complete windows inclusive of the frame and glazing as specified in the Marshal Day November 2006 report may be measured.

Deliverables:
A detailed report which would include a description of the test facilities, measurement procedures and the results. The results would include the sound reduction index measured according to ISO 15816-1 and the STC rating calculated according to ASTM E413-04. In addition, data for the prediction models measured according to ISO 10848-1 will also be measured.

Duration:
Eight weeks to evaluate four roof system configurations, not inclusive of the time required to construct the roof systems.

Cost:
$8000 not inclusive of the cost of the roof system samples.

Phase 3: Field testing

Measurements made *in-situ* in a dedicated test house or in several houses with different roof system designs as described in Section 2.1.3.

Deliverables:
A detailed report which would include a description of the test houses, measurement procedures and the results. The results would include the standardized level difference according to ISO 140-5, the apparent sound reduction index of the roof system according to ISO 140-5 and the sound reduction index of the roof system, the walls and the windows according to ISO 15186-2. In addition measurements of the traffic noise will be made according to ISO 1996-2.

Duration:
Six weeks not inclusive of the time required to modify a dedicated test house or to locate other test houses. Additional time may be required if more than four roof system configurations or measurement locations are requested.

Cost:
$8000 not inclusive of the cost of modifications to the test houses or travel costs.

Phase 4: Prediction model

Development of models to predict the sound reduction index of the roof system inclusive of the roof, joists and ceiling as well as insulation between the joists as described in Section 2.2. Additional models will predict the attenuation in the traffic noise across the façade and the roof.

Deliverables:
A prediction model which when given a distance and height of the traffic noise relative to the dwelling can estimate the level difference of the roof system.

Duration:
Six weeks.

Cost:
$8000

Phase 5: System design

Propose enhancements to the roof system design to further reduce the STC rating. The proposed enhancements will be based on the laboratory and field measurement findings as well as the prediction model.

Deliverables:
A report of the estimated sound reduction index and STC rating of proposed enhancements to the roof system.

Duration:
Four weeks.

Cost:
$6000

Appendix A: Summary of Acoustic Terms

Airborne Sound Transmission	Sound transmission through the air.
Apparent Sound Reduction Index R'	Ten times the logarithm to the base 10 of the ratio of the sound power W_1 which is incident on the test specimen to the total sound power transmitted into the receiving room, if, in addition to the sound power W_2 radiated by the specimen, sound power W_3 radiated by flanking elements or by other components is significant: $R' = 10 \log \left(\frac{W_1}{W_2 + W_3} \right)$ (dB)
Average Sound Pressure Level	The average of the sound pressure level measured in multiple locations in a room. The number of measurement locations is specified in the relevant standards. For example, ISO140-5 requires a minimum of five measurement positions.
Average Sound Pressure Level on a Test Surface $L_{1,s}$	Ten times the logarithm to the base 10 of the ratio of the surface and time average of the sound pressure squared to the square of the reference sound pressure, the surface average being taken over the entire test surface including reflecting effects from the test specimen and the façade.
Average Sound Pressure Level in a Room L_2	Ten times the logarithm to the base 10 of the ratio of the space and time average of the sound pressure squared to the square of the reference sound pressure, the space average being taken over the entire room with the exception of those parts where the direct radiation of a sound source or the near field of the boundaries (wall, window, etc.) is of significant influence.
Decibel	The term used to identify 10 times the logarithm to the base 10 of the ratio of two like quantities proportional to intensity, power or energy.
Level Difference	The difference between the sound pressure level measured on each side of an element such that: $D = L_{p1} - L_{p2}$ (dB) where L_{p1} and L_{p2} are the sound pressure levels on each side of the element. If traffic noise is used as the sound source, the notation is D_{tr}. If a loudspeaker is used, it is D_{ls}.

L_{10}	The level in decibels equalled or exceeded for 10% of the measurement interval.
Equivalent Continuous Sound Pressure Level L_{EQ}	Value of the sound pressure level of a continuous steady sound that, within the measurement time interval, has the same mean square sound pressure as the sound under consideration, the level of which varies with time; it is expressed in decibels.
Measurement Time Interval	The duration of a single measurement
Sound Intensity	Time averaged rate of flow of sound energy per unit area oriented normal to the local particle velocity. Measured using a intensity probe according to ISO15186-1.
Sound Pressure Level	Ten times the logarithm, to the base 10, of the ratio of the square of the sound pressure to the square of the reference value. $L_p = 10 \log \left(\frac{p^2}{p_o^2}\right)$ (dB) where p_o= 2 x 10^{-5} Pa.
Sound Reduction Index	Also referred to as the transmission loss. Ten times the logarithm to the base 10 of the ratio of the sound power incident on the test specimen W_1 to the sound power transmitted through the specimen W_2 such that: $R = 10 \log \frac{W_1}{W_2}$ (dB) The sound reduction index is measured in the laboratory according to ISO140-3 or ISO15186-1 or in the dwelling according to ISO140-5 or ISO15816-2.
STC Rating	Single number quantity used to express the airborne sound insulation in buildings and of building elements such as walls, floors, roofs and windows. The STC rating is calculated from the sound reduction index of the element according to ASTM E 413 - 04.
Structure-borne Sound Transmission	Sound transmission through the structure in the form of mechanical energy.

Appendix B: Comparison between NZS and ISO Standards

The New Zealand standard, NZS 6802:2008 references both ISO 140-5:1998 *Measurement of sound insulation in buildings and of building elements -- Part 5: Field measurements of airborne sound insulation of façade elements and façades* [17] and ISO 1996-2:2007 *Description, Measurement and Assessment of Environmental Noise -- Part 2: Determination of Environmental Noise Levels* [31]. However, the measurements specified by NZS 6802 are different than those specified in the ISO standards.

Furthermore, NZS 6801 clause 6.2.1 states that *the measurement of sound received inside a building is not recommended if the sound source is outside the building* whereas the purpose of ISO 140-5 is *to measure the sound insulation properties of a facade with respect to outside noise such as traffic noise, thus making it possible to ensure that the constructions meet the desired acoustical conditions inside the building*. Therefore, the New Zealand standards should not be used to determine the level difference or the apparent sound reduction index of a façade.

B.1. Measurements outside the Building

NZS 6802 clause 5 and NZS 6801:2008 [15] clause 6 state that the measurement of environmental noise should be made 3.5 m from any reflecting surface and 1.2 m to 1.5 m above the ground. However, in cases when a measurement is needed close to a building, the preferred measurement positions are 1 m to 2 m from the external wall of the building. In these cases, the effect of the building reflection may be removed to give an approximation of the free field incident level by subtracting 3 dB from the measured value.

ISO 1996-2 specifies that in the case of outdoor measurements near buildings, the preferred measurement positions are 1 to 2 m from the façade and 1.2 to 1.5 m above each floor level of interest. ISO1996-2 notes that the incident sound pressure level may be obtained by subtracting 3 dB from the measured value. ISO 140-5 describes several measurement positions depending on the purpose of the measurement and the nature of the noise source. If the purpose of the measurement it to measure the standardized level difference of the whole façade with traffic noise as the source, the microphone is to be located 1.5 m above the floor of the receiving room and 2 m from the plane of the façade or 1 m from a balustrade or similar protrusion. No correction for the reflections is made in the source sound pressure level.

Therefore, the difference between the measurement locations is that the ISO standard requires that the measurement position is 1.5 m above each floor level. Furthermore, if the measurement is to be used to determine the standardized level difference of the whole façade due to traffic noise, no subtraction of the source sound pressure level is made.

B.2. Measurements inside the Building

The New Zealand standards were not developed as a method of measuring the apparent sound reduction index of the façade. NZS 6802 clause 5 and NZS 6801:2008 clause 6 states that *the measurement of sound inside a building is not recommended if the sound source is outside the building*. In circumstances where there is no other practical option, measurements shall be made at a height of 1.2 m to 1.5 m above the floor and at least 1.5 m from windows. The preferred measurement positions are at least 1 m from the walls or other major reflecting surfaces, and of a sufficient number to capture the spatial variation of the sound field. The average level for the room shall be found from an energy average of the measurements. This may be undertaken using the 'sweep' method.

Alternatively, ISO 140-5 states that a minimum of five measurement positions are required in the receiving room if stationary microphones are used. The distance between the microphones is to be 0.7 m and there is to be 0.5 m between the microphone positions and the boundaries and or objects in the room and 1.0 m between any microphone position and the sound source. If a moving microphone is used, the sweep radius shall be at least 0.7 m and the plane of the sweep shall be inclined.

ISO 140-5 also requires a correction for background noise in the source room and the measurement of the reverberation time in the source room.

B.3. Level Difference

For field measurements, the airborne sound insulation can be described in terms of the sound pressure level difference, D between the source and the receiving measurement positions. This can cause problems when setting sound insulation requirements for regulatory purposes because adding or removing sound absorptive materials from the receiving room will change the measured sound pressure level and hence change the level difference. In some situations the reverberation time in the receiving room may be fixed by other requirements and it may be appropriate just to use the level difference. Otherwise, it is necessary to measure the reverberation time in the receiving room and to 'standardize' or to 'normalize' the level difference. This provides a fairer basis on which to set performance standards for sound insulation. The level difference is standardized by using a reference value for the reverberation time and the level difference is normalized using a reference value for the absorption area [32].

3.1.2. Standardized Level Difference

ISO 140-5 gives the standardized level difference in cases where it is required to measure the protection afforded by the façade irrespective of its construction and surface area or its position relative to the noise source such that:

$$D_{tr,2m,nT} = L_{1,2m} - L_2 + 10 \log \frac{T}{T_o} \tag{1}$$

where $D_{tr,2m,nT}$ is the standardized level difference due to traffic noise, T is the reverberation time measured in the receiving room and T_o is the reference reverberation time which is 0.5 s for dwellings. When the standardized level difference is used, there will not usually be significant differences between the results made using road traffic noise or a loudspeaker as the sound source [32].

3.1.3. Normalized Level Difference

ISO 140-5 gives the normalized level difference which corresponds to the reference absorption area in the receiving room such that:

$$D_{tr,2m,n} = L_{1,2m} - L_2 + 10\log\frac{A}{A_o} \quad (2)$$

where A is the equivalent absorption area in the receiving room and A_o = 10 m^2.

3.1.4. Level Difference in the Norman Disney and Young Report April 2008

NZS 6801 clause 6.2.1 states that *the measurement of sound received inside a building is not recommended if the sound source is outside the building*. Therefore, there is no provision in NZS 6801 to assess the level difference of the complete façade or one of the building elements. However, the report by Norman Disney and Young dated April 2008 uses the measurements made according to NZS 6801 and NZS 6802 to assess the logarithmically averaged level difference across the façade and roof according to the equation:

$$D_{tr,1m} = L_{1,1m} - L_2 \quad (3)$$

where D_{1m} is the level difference, $L_{1,1m}$ is sound pressure level measured 1 m in front of the test specimen and L_2 is the sound pressure level in the receiving room averaged over the room. However, if the value of $L_{1,1m}$ used in the calculation was measured according to NZS 6801, then 3 dB would have been subtracted from the measurement to correct for the reflection from the façade. ISO 140-5 does not include this provision. Therefore, if the level difference had been measured the level difference reported in the Norman Disney and Young report would have been higher. However, since the measurement position was 1.5 m from the ground and not 1.5 m from the floor of the bedroom, the measured data is incorrect according to ISO 140-5. Therefore, the level difference calculated by Norman Disney and Young and as shown in Table 7 of the April 2008 report is not correct.

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