SkyTrain Noise Mitigation Study Phase 2 Recommendation Report and Implementation Plan

TransLink

SLR Project No: 201.04644.00007

August 2021

SLR Consulting (Canada) Ltd.
200-1620 West 8th Avenue, Vancouver, BC V6J 1V4

SKYTRAIN NOISE MITIGATION STUDY PHASE 2
RECOMMENDATION REPORT AND IMPLEMENTATION PLAN

VANCOUVER, BC

TransLink Ref No.: Q17-037

SLR Project No: 201.04644.00007

Prepared by
SLR Consulting (Canada) Ltd.
200 – 1620 West 8th Avenue
Vancouver, BC   V6J 1V4

for

South Coast British Columbia Transportation Authority (TransLink)
400 - 287 Nelson's Court
New Westminster, BC   V3L 0E7

August 2021

Prepared by:

19 Aug. 2021

Briony Croft, Ph.D., P.Eng.
Principal Engineer - Acoustics

Reviewed by:

Aug. 26 2021

Arthur Kupper, P.Eng.
Senior Engineer - Acoustics

EXECUTIVE SUMMARY

In 2018, TransLink commissioned a SkyTrain Noise Study in response to noise concerns raised by residents. The Noise Study recommended investigations into the feasibility and effectiveness of six mitigation measures in order of priority:

1. Improvements to switch maintenance practices
2. Investigation of harder rail steel as a measure to improve long-term rail condition
3. Re-introduction of friction modifiers to improve long-term rail condition
4. Improvements to rail grinding practices to improve long-term rail condition
5. Rail dampers to reduce noise radiated from the rails and hence reduce overall noise
6. Guidelines for new noise-sensitive developments near SkyTrain

Pilot studies and investigations to identify the benefit of these noise mitigation options have now been completed, and an Interim Guideline for new developments in noisy areas has been developed. This report summarizes all investigations completed. It provides recommendations for implementation of a noise mitigation program, and describes the requirements for ongoing monitoring and verification of noise mitigation effectiveness as implementation progresses.

SkyTrain noise has historically been highly variable over time with changing track condition between cycles of maintenance interventions. Implementation of the recommendations in this report would not eliminate all SkyTrain noise or all complaints, however the study has demonstrated that significant improvements are feasible. The key factor in this conclusion is that parts of the network are already much quieter than others – the objective of noise mitigation is to achieve the current best-case noise emissions across more of the network, and to keep noise levels as low as possible in between maintenance cycles.

At most locations, people would not experience a sudden reduction in noise. Instead, noise levels would become more consistent, similar to the existing quietest periods. The objective is to optimize maintenance practices to keep train passby noise emissions within 5 dB of the best case (minimum) noise levels at all times in all noise-sensitive areas. This would represent a significant improvement in amenity for people living near the SkyTrain, some of which currently see noise increases on the order of 15 dB or more between maintenance intervals.

CONTENTS

TABLES

FIGURES

APPENDICES

1.0 INTRODUCTION

1.1 NOISE MITIGATION STUDY BACKGROUND

In 2018, TransLink commissioned SLR Consulting (Canada) Ltd. (SLR) to undertake a SkyTrain Noise Study in response to concerns raised by residents. The Noise Study recommended investigation of the feasibility and effectiveness of six mitigation measures in order of priority:

1. Improvements to switch maintenance practices
2. Investigation of harder rail steel as a measure to improve long-term rail condition
3. Re-introduction of top of rail friction modifiers (TORFM) to improve long-term rail condition
4. Improvements to rail grinding practices to improve long-term rail condition
5. Rail dampers to reduce noise radiated from the rails and hence reduce overall noise
6. Guidelines for new residential developments near SkyTrain

These recommended noise mitigation investigations have now been completed. This report documents the investigation outcomes and identifies the expected benefits of implementation of each mitigation measure.

SkyTrain noise emissions at individual locations are not constant. Over time, noise levels increase and decrease with changes in track condition. Noise increases when uneven wear in the wheel/rail interface causes growth in rail roughness. Noise can decrease following maintenance interventions such as rail grinding or switch replacement. The 2018 Noise Study and Noise Maps presented a “snapshot” of noise levels at the time of that study. This mitigation investigation considers normal yearly cycles of wear and maintenance, so that recommendations for implementation of a noise mitigation program are based on the most affected locations over the long term.

Recommendations are also made on methods to verify and monitor the effectiveness of noise mitigation program implementation in the longer term, identifying additional steps to take in the event that progress towards the noise goals is below expectations.

1.2 ACKNOWLEDGEMENTS

Several partners were engaged to assist with various aspects of the investigations. The contributions of these partners working collaboratively with TransLink and SLR are gratefully acknowledged: British Columbia Rapid Transit Corporation (BCRTC); Advanced Rail Management (ARM); Aercoustics; BKL Consultants; and LB Foster.

1.3 NOISE MITIGATION STUDY OUTPUTS

The mitigation measures were investigated in two phases, with both phases now complete. The results of Phase 1 investigations have been reported in detail previously in SLR Report *SkyTrain Noise Mitigation Study Phase 1 Vancouver Recommendation Report and Implementation Plan, April 2020* (the Phase 1 report). This Phase 2 Report integrates all mitigation study investigation outcomes, summarizing the Phase 1 outcomes and reporting the results of the recently completed Phase 2 studies. The outcomes of all investigations (both Phase 1 and Phase 2) have been considered in developing the consolidated set of recommendations for implementation of a noise mitigation program. A Noise Mitigation Program Implementation Plan is provided in Appendix A.

A series of detailed reports and an interim guideline for new developments have been produced in the course of the original 2018 Noise Study and the subsequent phased mitigation investigations. These detailed reports document all the investigations undertaken to date, and are referenced throughout this report:

- SkyTrain Noise Study Vancouver Noise Report and Maps, SLR, November 2018 (the 2018 Noise Report)
- SkyTrain Noise Study Vancouver Next Steps Recommendations Report, SLR, April 2019
- SkyTrain Switch Maintenance Noise and Vibration Study, Aercoustics, 2 December 2019
- Skytrain Noise Mitigation Study: Benefits of Harder Rail for Reducing Noise, British Columbia Rapid Transit Corporation (BCRTC), 28 February 2020
- Rail Damper Workstream – Nanaimo Outbound Trial Site Track Decay Rate Rail Roughness and Noise Results, SLR, 21 August 2019
- Rail Damper Workstream – Broadway Outbound Trial Track Decay Rate Rail Roughness and Noise Results, SLR, 7 March 2020
- Rail Damper Workstream – Broadway Inbound Trial Track Decay Rate Rail Roughness and Noise Results, SLR, 7 March 2020
- Friction Modifier Ecological Toxicity Review Letter, SLR, 20 August 2020
- BCRTC Noise and Corrugation Mitigation Study Friction Readings, LB Foster, 10 December 2020
- Interim Guidelines for New Development Environmental Noise Assessment, BKL Consultants (May 2021) (the Interim Guidelines)
- Acoustic Rail Grinding Investigation and Implementation Recommendations, ARM (June 2021) (the Grinding Study Report)
- BCRTC Friction Management Noise Mitigation Proof of Concept and Implementation Plan, ARM (June 2021) (the TORFM Study Report)

2.0 OBJECTIVES OF NOISE MITIGATION STUDY

2.1 EXTERNAL NOISE GOALS

As identified in the Noise Report, maximum external SkyTrain passby noise levels[1] of 75 dBA are generally considered acceptable inside typical residential façades with windows closed. This level of 75 dBA does not represent "no noise impact"; it is a goal to drive improvement, that aims to find a balance between the adverse effects of noise and the benefits that rail transit systems provide to communities.

Note that when new extensions to the SkyTrain are planned, the noise impacts of these extensions are assessed as part of the environmental impact assessment and detail design process. Specific external noise criteria are applied to the design of new SkyTrain extensions, considering various other parameters in addition to the typical maximum façade noise level goal that is used in this study of the existing network.

[1] The noise parameter is the maximum noise during a train passby, measured using the fast response setting on a sound level meter (LAFmax).

2.2 COMMUNITY EXPECTATIONS FOR EXTERNAL NOISE

Noise is an unwanted effect of all rail transit systems. It is possible to minimize railway noise emissions at source, and that is the main focus of recommendations in this report. It is also possible in some areas to construct noise barriers along the guideway parapet to break the line of sight and hence block noise. However, where noise-sensitive receivers are elevated overlooking the guideway conventional parapet barriers are not effective. Unconventional barrier designs that fully enclose the noise source are not a feasible option to retrofit. Ultimately there is a practical limit to what can be achieved by noise mitigation at source on an existing system. In some areas around the SkyTrain network, reaching the 75 dBA external noise goal may not be feasible or cost-effective.

In particular, there are existing residential buildings that have been constructed close to and overlooking the SkyTrain guideway where it is likely that maximum external SkyTrain passby noise levels will continue to exceed the 75 dBA goal, even if rail is maintained in optimal condition and all recommended mitigation measures are in place.

Implementation of all the recommendations in this report would not eliminate all SkyTrain noise or all complaints, however this study has demonstrated that significant improvements are feasible at many locations. The key factor in this conclusion is that parts of the network are already much quieter than others – the objective of noise mitigation is to achieve the current best-case noise emissions across more of the network, and to keep noise levels as low as possible in between maintenance cycles.

Implementation of the recommendations made in this report would require ongoing effort over several years. At most locations, people would not experience a sudden reduction in noise. Instead, noise levels would become more consistent, similar to the existing quietest periods.

2.3 TRACK CONDITION NOISE GOALS

The Noise Report identified that in some areas maximum SkyTrain passby noise levels at residential façades can exceed 90 dBA. Subsequent studies have identified some areas where residential noise levels can be even higher. Over time, noise levels around the network increase and decrease as the result of changes in track condition and due to maintenance grinding. The Phase 1 noise mitigation studies included an analysis of historical measurements of in-car noise data to investigate the variation in track condition in a typical year, considering wear and maintenance cycles.

Figure 1 and Figure 2 (reproduced from the Phase 1 report) show the difference between the historical measured typical best and worst case track condition and hence noise levels along the length of the Expo and original Millennium lines (excluding the Evergreen Line), both inbound and outbound. Overall, the historical worst case reflects noise levels that are on average 8 to 9 dB higher than the best-case noise level, but in specific locations there can be a difference of 15 to 20 dB or more in noise levels. These locations typically correspond to areas prone to rapid corrugation formation (wavy rough rails), with large variations in track condition occurring over time.

Figure 1 Expo Line historical in-car noise difference between best and worst case

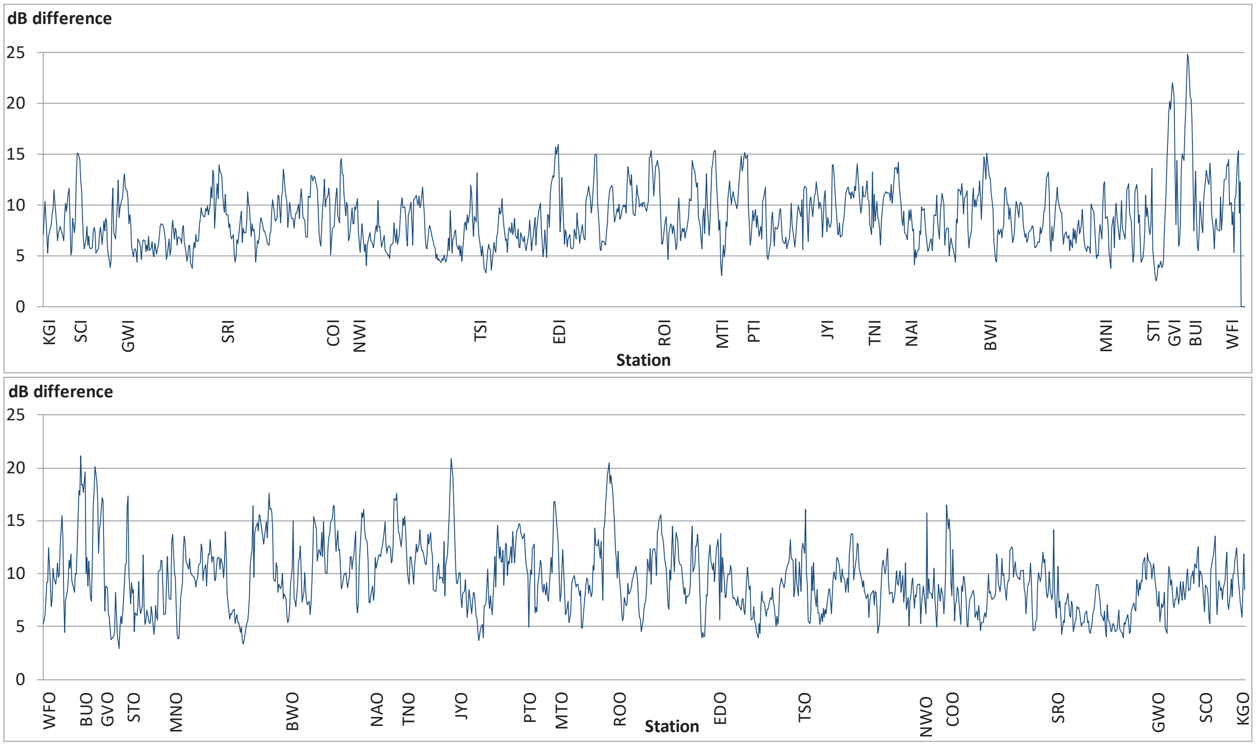


Figure 2 Millennium Line historical in-car noise difference between best and worst case

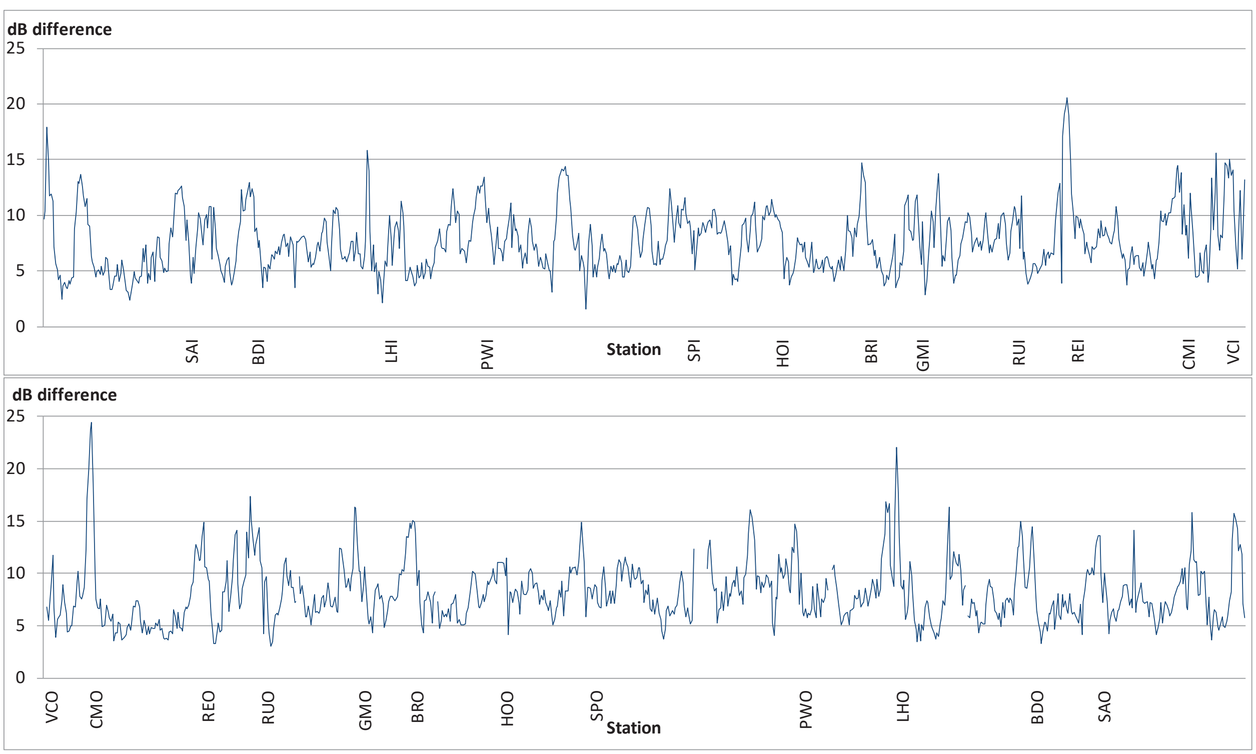


Figure 1 and Figure 2 show that on all lines and in both travel directions, there is a minimum difference between best and worst case noise levels of about 5 dB. These locations correspond to areas where corrugation does not typically appear, and existing maintenance practices result in relatively stable long-term track condition.

Figure 3 illustrates the difference between Skytrain rails that are corrugated, and Skytrain rails that are not corrugated and will therefore generate less noise as a train rolls over them.

Figure 3 Corrugated rail (left) vs normal uncorrugated rail condition (right)

The objective for mitigation implementation is to maintain track condition around the network so that noise levels are maintained within 5 dB of the best case at all noise-sensitive locations long term. Progress towards this objective can be monitored using in-car noise and vibration measurements network-wide, supplemented by spot noise measurements adjacent to the tracks.

2.4 APPROACH TO COMBINATIONS OF MITIGATION MEASURES

A combination of mitigation measures will be required in some areas to maintain noise levels within 5 dB of the best case in noise-sensitive areas and to reduce residential façade passby noise levels. The overall approach to mitigation recommendations considers that some of the mitigation measures have localized benefits while others will be effective network wide or over large extents of the network.

1. Switch maintenance improvements: implementation recommendations apply to all switches
2. Harder rail steels: recommendations will be applied at all locations scheduled for future rail replacement, and for future SkyTrain extensions.

3. Rail grinding improvements and friction modifiers: recommendations apply network wide.
4. Rail dampers: to be installed at specific locations based on the residual noise priority considering the benefit achievable by the other mitigation measures, with consideration of the timeframe required to implement other mitigation measures in high noise areas.

Implementation of noise mitigation will require a staged approach over several years. Factors such as schedules and constraints for implementation are considered. For example, the current original Expo line rail replacement program will take around 10 years to complete. Rail dampers will not be implemented in locations where the rails are due to be replaced within 2 years. Rail dampers are initially recommended only in the highest priority areas but may be added to additional locations in future, if ongoing investigations and mitigation implementation performance monitoring indicates the project noise goals are not met after implementation of other mitigation measures.

2.5 COMMENT ON PARAPET NOISE BARRIERS

As noted in the 2018 Noise Study Next Steps report, parapet noise barriers are an established SkyTrain noise mitigation measure already in use. At locations where residential receivers are located at or below the guideway deck height, adding a parapet barrier can be an effective noise mitigation measure. If the line of sight to the rails can be broken by the parapet, noise reductions on the order of 5 to 10 dB can be achieved. Parapet noise barriers do not provide a benefit to all levels of high-rise buildings overlooking the tracks.

As an already known and established mitigation measure (example shown in Figure 4), the effectiveness of parapet noise barriers have not been investigated as part of this study. However, these remain a mitigation option for SkyTrain particularly for proposed extensions to the network. Retrofitting new noise barriers to existing track locations would only be considered in the event that the measures to reduce noise at source recommended in this report are not successful.

Figure 4 Example of SkyTrain Parapet Noise Barriers

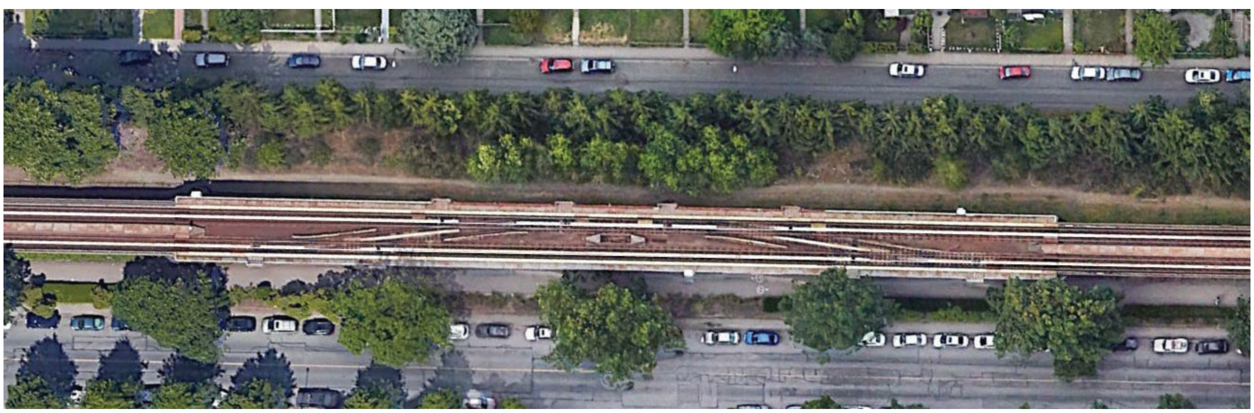
3.0 SUMMARY OF PHASE 1 STUDIES

The Phase 1 report contains full details and results from all Phase 1 studies, including investigation of improvements to switch maintenance, identifying the benefits of harder rail steel, trials of rail dampers on the SkyTrain system and drafting acoustic guidelines for new noise-sensitive developments. This section provides a high-level summary of outcomes and recommendations from these studies. Full recommendations for noise mitigation program implementation are included in Appendix A, which consolidates all outcomes from both Phase 1 and Phase 2.

3.1 SWITCH MAINTENANCE IMPROVEMENTS

Replacement of worn switches on SkyTrain can reduce noise by at least 10 dB and possibly more. Grinding and in-situ maintenance can reduce noise by 3 to 4 dB, but the main benefit is in maintaining switches in their "as-new" quiet state. The noise benefit of remedial grinding work is minimal if the initial switch condition is already severely worn. It is critical to monitor switch condition and to undertake regular maintenance starting from the time of original switch installation. In this way the variation in noise as switches wear can be minimized and the noise benefit of installing a new switch can be maintained for the life of the switch. There are more than 100 switches in total on the SkyTrain system (e.g. Figure 5). Improving switch monitoring and maintenance practices requires increased BCRTC resources.

Figure 5 Switches on the SkyTrain Network



3.2 HARDER RAIL STEEL

Although it was standard at the time, the rail steel originally used for Expo line construction is relatively soft and prone to rapid wear. An investigation was undertaken to quantify the noise benefits and costs of using harder rail steel for SkyTrain rail replacement programs and other projects. Using premium steel for rail replacement is expected to result in annual average noise level reductions of 5 dB on the Expo Line. Areas with harder rail steel require less frequent grinding maintenance, which could free up grinding capacity to address specific problem areas when required.

The Phase 1 study recommendation to specify harder rail steel in all future rail purchases within SkyTrain's rail replacement program was implemented in early 2020. The additional capital cost of harder rail steel represents less than 0.5% of the overall cost of rail replacement and is expected to be balanced by cost savings associated with reduced grinding requirements and longer asset life.

3.3 RAIL DAMPERS

Rail dampers reduce noise levels by up to 6 dB in corrugated track sections with trains operating at 80 km/h, based on trials undertaken on the SkyTrain network. Treatment of a total of 3.2 km of track between Commercial-Broadway Station and Joyce Station with rail dampers has been recommended and implementation of this measure is underway. Rail damper installation targets specific locations where residential receivers close to the tracks are exposed to very high noise levels and trains operate at or close to 80 km/h. Investigations indicate that the other mitigation measures with network wide benefits would not be sufficient to achieve the noise goals in these locations. In locations with operating speeds below about 60 km/h, rail damper effectiveness as a mitigation measure reduces. Skytrain track with rail dampers installed in the proposed configuration is shown in Figure 6.

Figure 6 Nanaimo Outbound Track with Rail Dampers

3.4 INTERIM GUIDELINES FOR NOISE-SENSITIVE DEVELOPMENTS

The minutes of the TransLink Board of Directors public meeting on September 28, 2017 record that the Board discussed the possibility of "region wide construction standards for buildings such as triple glazing on windows, enclosed balconies and air conditioning" to address noise. The Noise Study project has confirmed the utility of such a guideline in consultation with municipal planning staff. To be useful in practice in situations where individual developments are affected by multiple noise sources (roads, rail, aircraft, industry), guidelines must address all environmental noise sources, not only SkyTrain noise.

Interim Guidelines for noise-sensitive developments have been created as part of this project. In addition to typical assessment approaches considering average noise levels, the Interim Guideline recommends consideration of sleep disturbance effects due to short term maximum noise levels, and also that thermal comfort be maintained even if windows need to be kept closed for acoustic amenity. In most buildings adjacent to SkyTrain, closed windows are necessary for indoor acoustic amenity, even when system noise levels are minimised.

Administration of environmental noise guidelines for new developments is outside of TransLink's remit, therefore the Interim Guidelines are published as an example for information and as an optional tool that planning authorities may choose to use. The Guidelines are titled "Interim" since wider consultation with developers, acoustic practitioners and others is recommended. This wider consultation is outside the scope of the TransLink Noise Study.

4.0 FRICTION MODIFIERS TO IMPROVE RAIL CONDITION

A proof-of-concept pilot study has been undertaken to investigate the potential for friction modifiers to improve rail condition and hence to reduce noise on the SkyTrain system. Full details of the pilot study, measurements undertaken, and results are provided in the TORFM Study Report.

4.1 INTRODUCTION TO TOP OF RAIL FRICTION MODIFIERS

Top of Rail Friction Modifier (TORFM) is a railway-specific product that aims to reduce corrugation (roughness) growth rates on wheels and rails. Correctly applied, it adjusts the friction between the rail and the wheel tread to an intermediate level that is lower than dry rail, but significantly higher than lubricated conditions.

TORFM has been in limited use at BCRTC for several decades. In the late 1980's, the Vancouver SkyTrain was the first system in the world to implement vehicle mounted TORFM applicators as a mitigation measure for corrugation and noise. Since that time, TORFM technology has advanced considerably, however usage at SkyTrain has decreased to a point where insufficient TORFM is being applied to be effective. A combination of factors has contributed to the gradual decline in use of TORFM at SkyTrain, including mechanical failures of early applicator designs, the addition of new rolling stock without applicators, and a lack of documented evidence justifying the continued use of TORFM.

A controlled study demonstrating the benefits of TORFM for noise control has not been undertaken previously at SkyTrain.

4.2 DESCRIPTION OF TORFM PILOT STUDY

A trial site was identified to test the effect of application of TORFM on passby noise. The location selected was a segment of Expo Line Inbound track, extending about 400 m west from the switches after Nanaimo Station. This segment of track includes a curve over Hull Street, followed by tangent track over Victoria Drive. This area has historically exhibited high wayside noise and rapid corrugation growth rates.

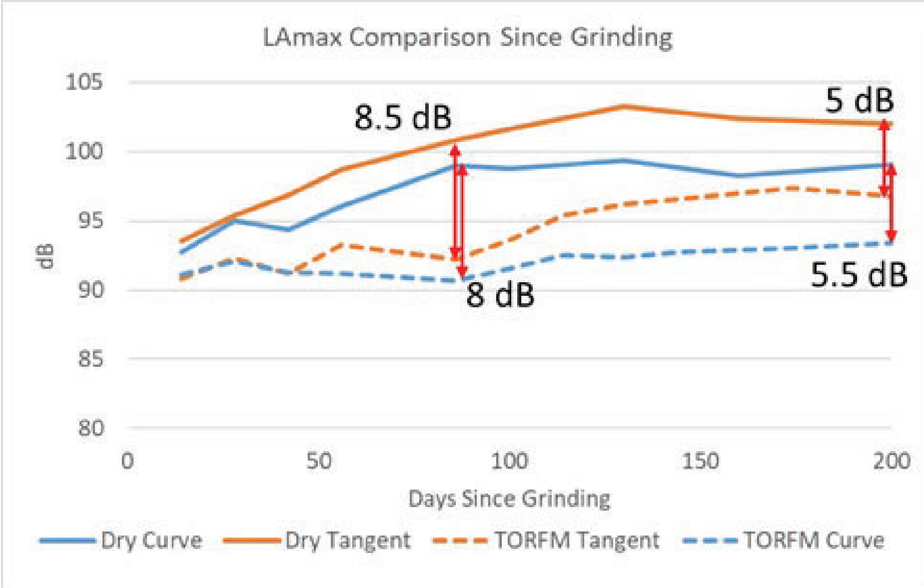
The TORFM pilot study involved an initial "dry rail" data collection period. In this period, measurements were collected between November 2019 and June 2020 to establish the rate of noise increase and roughness growth immediately following maintenance rail grinding, without any TORFM applied. Identical locations were then used to repeat all measurements immediately following another maintenance rail grinding between October 2020 and April 2021 with TORFM applied via a wayside applicator. The TORFM measurements commenced as close as possible to the same time of year of the "dry" measurements, to keep climate effects on the results to a minimum. Measurement data collected in the course of the pilot study included noise, rail roughness (corrugation) and rail friction.

Comparison of the "dry rail" measured noise results to the "TORFM" scenario results was used to quantify the benefits of TORFM in keeping noise levels low in the months after grinding.

4.3 OBSERVED NOISE BENEFIT OF TORFM

Figure 7 provides the comparison of noise results from each study. At 90 days after grinding, passby noise levels with TORFM applied were 8 dB quieter at both the curve and tangent locations than was measured with dry rail. Longer term, noise levels do increase gradually even with TORFM applied, however a clear difference of 5 dB or more is evident after about six months with TORFM compared to the dry rail scenario.

Figure 7 Passby Noise Levels Dry Rail vs TORFM



The study results indicate that TORFM can be used to minimize wayside noise long term, and is particularly beneficial in keeping noise levels to a minimum in the months immediately after grinding. The results suggest that at the trial location with TORFM in place it may be possible to double the grinding interval required to keep noise within 5 dB of the best case. Grinding has historically been required four times a year at the TORFM pilot study location.

In summary, the pilot study shows a direct long-term noise benefit of TORFM, with additional potential benefits in reducing annual grinding costs, maintaining a state of good repair and increasing rail life.

4.4 TORFM IMPLEMENTATION CONSIDERATIONS

This proof-of-concept study trialed friction modifier in liquid form, applied to the rails at a discrete location by a wayside applicator (see Figure 8). However, network-wide application of friction modifier using wayside applicators is not a practical or cost-effective solution for SkyTrain.

On SkyTrain, track condition and noise issues are widespread, a large number of wayside applicators would be needed to treat all problem areas. The elevated guideway on SkyTrain also poses significant engineering challenges for placement and maintenance of wayside application systems. These systems include a tank to hold the product, a power source (wind, solar or grid), wheel sensors, pumps and applicator bars. In many locations space to place a tank is limited, and all inspections, tank re-filling and other maintenance would need to be undertaken outside of revenue service.

Figure 8 Pilot Study Wayside Applicator for Liquid TORFM

Note: Left image shows pilot study TORFM product tank and hose to track. Right image shows hoses leading to applicator bars.

The TORFM Study Report explains why vehicle-mounted "solid stick" applicators are preferred for implementation on SkyTrain, and why it is reasonable to expect similar results from solid stick applicators provided an equivalent quantity of active ingredient is delivered to the wheel/rail interface and distributed appropriately around the network. An example of a solid stick TORFM applicator is shown in Figure 9. Successful implementation of TORFM is expected to require solid stick applicators to be installed and maintained on a minimum of 25 percent of the vehicle fleet wheels.

Figure 9 Vehicle-Mounted Applicator for Solid Stick TORFM

5.0 ACOUSTIC GRINDING TO IMPROVE RAIL CONDITION

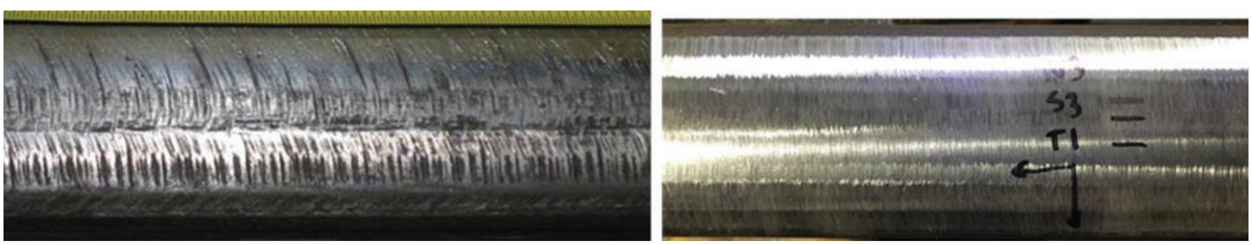
5.1 INTRODUCTION TO ACOUSTIC RAIL GRINDING

BCRTC completes about 130 km of maintenance grinding annually, split about 50/50 between BCRTC's grinder and a contracted grinder. Rail grinding is a critical maintenance practice, required to remove rail defects and correct the rail profile following wear. Even if there are no defects or rail profile corrections required, regular grinding of all rails is a necessary maintenance activity required to avoid rolling contact fatigue. If track is corrugated, rail grinding also reduces roughness, corrugation and noise. Some areas of the network require grinding as frequently as four times a year, others only once every two years.

Grinding requires balancing the amount of material to be removed with the targets for rail surface finish. If a large amount of material removal is required, e.g. to remove corrugation, then coarser grinding stones are used. If only a small amount of material removal is required, finer stones can be used leaving a better surface finish. Using finer stones is not practical for removing corrugation, as it takes too many passes to grind enough material from the rail head to remove the corrugation. Also, the finer stones wear out and must be replaced more frequently than coarser stones. Replacing stones in the middle of a shift is difficult when the grinder is working on elevated guideway. Replacing stones mid-shift is also inefficient when there is only a short night-time window available for rail grinding outside of revenue service.

The residual grinding surface finish (periodic scratches on rail) can possibly initiate corrugation formation and can increase noise directly if the track was not corrugated before grinding. Figure 10 shows examples of grinding surface finish illustrating the rougher, more scratched finish left by coarser grinding stones.

Figure 10 Post-grinding surface finish, coarse stones (left) and fine stones (right)



The objective of acoustic grinding is to improve the surface finish after grinding, with the goal of reducing corrugation growth and limiting noise caused by the residual post-grinding surface finish. Achieving an improved surface finish after grinding is particularly important with harder rail steels, since with harder rail the residual grinding marks do not wear away for some time (months). The importance of acoustic grinding is evident in the number of complaints received from residents along the Evergreen Line after rail grinding in July 2017– this line utilizes harder rail steel than other parts of the network, and grinding with coarse stones to achieve the target rail profiles resulted in increased noise emissions.

5.2 DESCRIPTION OF ACOUSTIC GRINDING PILOT STUDY

The pilot study involved identification of eight different test sites with six of the eight sites split into two zones, a standard grinding zone and an acoustic grinding zone. These sites included areas known for developing corrugation. Another factor in the pilot study site selection was to identify areas with a wide range of rail hardness, since an objective of the trial is to understand which rail hardness categories would benefit from a more stringent acoustic grinding specification. After grinding, all sites were monitored by repeated measurements of rail roughness over a period of approximately nine months. For this study, rail roughness was used as a proxy for noise, since rail roughness and noise are correlated.

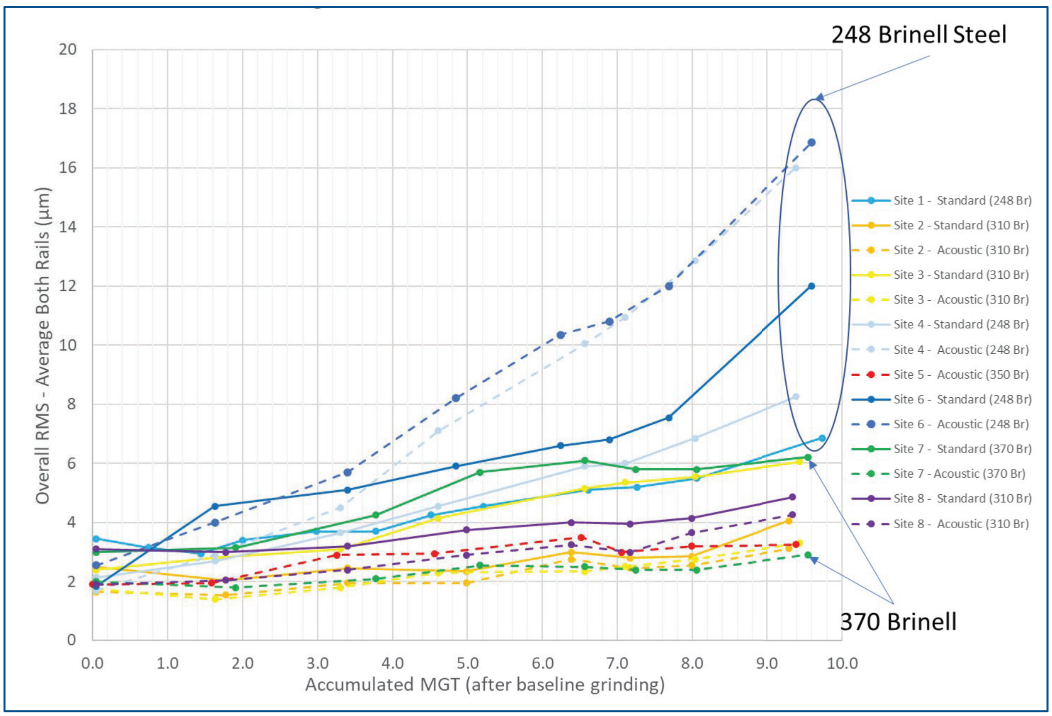
5.3 ACOUSTIC GRINDING STUDY RESULTS

Figure 11 shows the average overall roughness result as measured on both rails for each site and grinding method. Roughness (and hence noise) increases over time as the rails wear under passing rail traffic. Different parts of the SkyTrain network see different train numbers based on operating timetables. To enable direct comparison between sites, the results of the pilot study show traffic volumes accumulated over time expressed as Million Gross Tonnes (MGT). In this way, any differences in wear over time due to different timetabled train numbers at the various sites are normalized.

Roughness growth rates were observed to vary from site to site but in general the following observations were made after review of all measurement results (see the Grinding Study Report for full details):

1. Softer rail steel, e.g. 248 Brinell Hardness, is prone to more rapid increases in corrugation and roughness with accumulated tonnage, regardless of the grinding approach.
2. Harder rail steel, e.g. 370 Brinell Hardness is less prone to increase in corrugation and rail roughness over time than softer rail sites. In all cases, areas with harder rail steel saw reduced roughness growth rates when acoustic grinding was used, relative to standard grinding.

Figure 11 Average rail roughness growth with increasing traffic after grinding for all sites



In summary, the acoustic grinding pilot study identified that acoustic grinding is not beneficial in areas with softer rail steels, since these areas see rapid roughness growth regardless of the grinding technique. Acoustic grinding was found to be beneficial in areas with the hardest rail steel. In areas with medium hardness rail a combination grinding approach is recommended, depending on the initial rail condition and sensitivity of the area to noise.

6.0 RECOMMENDATIONS FOR NOISE MITIGATION PROGRAM

The following sections summarize the recommendations for implementation of a noise mitigation program addressing all six of the identified noise mitigation measures investigated throughout Phase 1 and Phase 2 of the study. In addition to recommendations on individual mitigation measures, Section 6.7 describes a recommendation for BCRTC to create an internal staff role to lead implementation of the noise mitigation program and to be responsible for ongoing monitoring and verification of progress towards the noise goals.

6.1 SWITCH MAINTENANCE IMPROVEMENT RECOMMENDATIONS

It is recommended that SkyTrain implements an ongoing switch monitoring and maintenance program. The basis for this program would be ongoing measurement and analysis of axle-box vibration from regular test train circuits of the network. A dedicated engineering analyst would be required to support implementation of these recommendations.

The data collected would be analysed with a regular report documenting the condition of all switches prepared every two weeks as a minimum. This report would prioritize and direct the efforts of a switch maintenance crew who would undertake preventative maintenance grinding on identified priority switches with the goal of minimizing switch wear and hence noise in the long term.

In the initial year of the program, it is recommended that wayside noise is also measured in conjunction with axle-box vibration, at a minimum sample of twenty switches. This will enable further characterization of the relationship between train speed, axle-box vibration and wayside noise. In subsequent years, it is expected that it will be possible to rely on the axle-box vibration data in isolation to assess switch condition.

For each switch around the network a baseline condition indicator would be developed based on an understanding of the axle-box vibration level through a switch in good condition (generating minimal noise) for the typical operating speed through that switch. Monitoring this condition indicator for each switch will indicate when and where maintenance attention is required to minimize noise.

Planning is underway for budgets to be allocated for implementation commencing in 2022.

6.2 HARDER RAIL STEEL RECOMMENDATIONS

The recommendation for use of harder rail steel arising from this study have already been implemented. SkyTrain have committed that future rail replacement and build projects will specify AREMA High Strength rail (370HB+), in place of the previously specified AREMA Standard grade hardness (310+HB).

6.3 FRICTION MODIFIER RECOMMENDATIONS

Implementation of TORFM network wide is recommended. TORFM should be applied to the wheel-rail interface using vehicle-mounted solid stick applicators, since widespread use of wayside applicators is not a practicable approach for SkyTrain.

Successful implementation of TORFM will require stick applicators to be installed and maintained on a minimum of 25 percent of the existing Mk2 and Mk3 fleet wheels, and on all future new vehicles. Installation of applicators is not recommended on Mk1 trains since they are being phased out of service. In the transition period until Mk1 vehicles are phased out it may be necessary to adjust applicator settings (increase spring force) on Mk2 and Mk3 trains, to compensate for the lack of applicators on Mk1 trains.

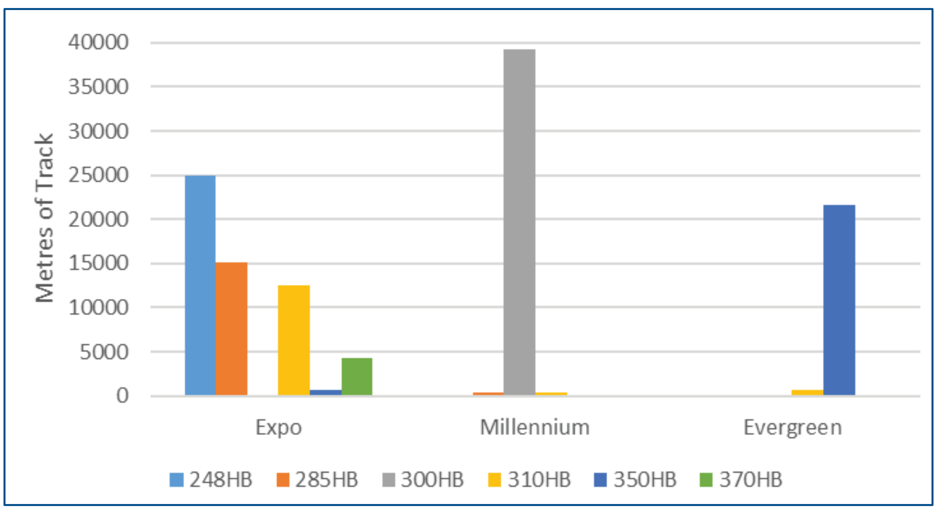
A procurement process is required to identify and select a candidate supplier for vehicle-mounted TORFM applicator equipment and materials. BCRTC should also determine if they will require the supplier of new vehicles to design and install the applicators, or if applicators would be retrofitted independently of new vehicle procurement. The recommended approach is for BCRTC to work directly with suppliers of TORFM stick applicators, who would likely complete the design as part of the supply cost resulting in the fastest and most cost-effective route forward for full system implementation.

TORFM implementation would be expected to require at least a year encompassing procurement processes followed by progressive installation of applicators on existing vehicles. During this period and for at least another year, BCRTC would need to actively monitor system performance including verifying that rail friction is maintained within the target ranges and that noise objectives are met. TORFM is expected to provide benefits network-wide, however some particularly challenging locations may require supplementary mitigation or more frequent grinding than typical to reach noise targets.

6.4 ACOUSTIC GRINDING RECOMMENDATIONS

SkyTrain has approximately 120 kilometres of track split between the Expo, Millennium, and Evergreen lines. Figure 12 provides a breakdown of rail hardness used on each line. The Millennium line is predominantly moderate hardness 300 HB steel. The Evergreen extension is predominantly harder 350 HB steel. The Expo line is about a 70/30 split between softer steels and harder steels with nearly 45 percent (25 kilometres) of the line still comprising the originally installed 248 HB steel. The rail replacement program is progressively upgrading Expo Line rail, with track sections from Waterfront to Main Street / Science World Stations and from New Westminster to 22nd Street Stations completed at the time of this study.

Figure 12 Rail hardness breakdown by SkyTrain line



Based on the results of this study, the following grinding approaches are recommended:

- Evergreen line: Acoustic grinding.
- Millennium line: A combination of standard and acoustic grinding, to be determined based on maintenance objectives, rail condition before grinding and available grinding capacity.

- Expo line: Standard grinding for softer steels < 300 HB, and acoustic grinding where original rails have already been replaced with harder rail steel.

Note that harder steels not developing corrugation or seeing significant rail wear still require regular grinding to prevent rolling contact fatigue conditions. Rail should be monitored for initiation of surface damage like head checking or gauge corner cracking as SkyTrain looks to extend grinding intervals and achieve an optimized preventative maintenance grinding program.

6.5 RAIL DAMPER IMPLEMENTATION RECOMMENDATIONS

The Phase 1 study recommended that rail dampers be installed at several locations on the Expo Line identified as being of highest priority for noise control. Locations selected for implementation of rail dampers met the following criteria:

1. Multiple residential properties with maximum passby façade noise level of 90 dBA or more, calculated in worst-case baseline noise model.
2. Train speed 60 km/h or more (rail dampers are increasingly less effective at lower speeds)
3. Tangent track with fastener spacing of 1000 mm, to fit the best performing rail dampers.

The locations recommended for rail damper installation are expected to have maximum (worst case) train passby noise levels at some residential façades above 80 dBA even after implementation of all other mitigation measures. The elevation of the receiving residences relative to the guideway also means that parapet noise barriers (if not already present) would not provide more noise benefit than rail dampers.

The resulting recommended initial rail damper implementation locations are summarized in Table 1. The total recommended extent of rail dampers is 3.2 km. A contract has been signed to procure rail dampers and installation on track is scheduled throughout 2022.

Table 1 Rail Damper Implementation Locations

LOCATION	NOTES
Commercial-Broadway to Nanaimo	Specific locations targeted for maximum effect in high noise areas, excluding curves and switches.
Nanaimo to 29th Avenue	Majority of full speed track sections treated (at grade tangent track, high noise areas).
29th Avenue to Joyce Collingwood	Majority of full speed tangent track sections west of Rupert Street to be treated (at grade track, high noise areas).

Rail replacement has also been scheduled for 2022 between Commercial-Broadway and Nanaimo Stations. In this area, rail dampers will not be installed until after the rail replacement has been completed. In the other areas, future rail replacement has not yet been scheduled and is likely to be at least 5 years away. When rail replacement does occur in these locations, the rail dampers should be removed prior to rail replacement and reinstated on the new rails.

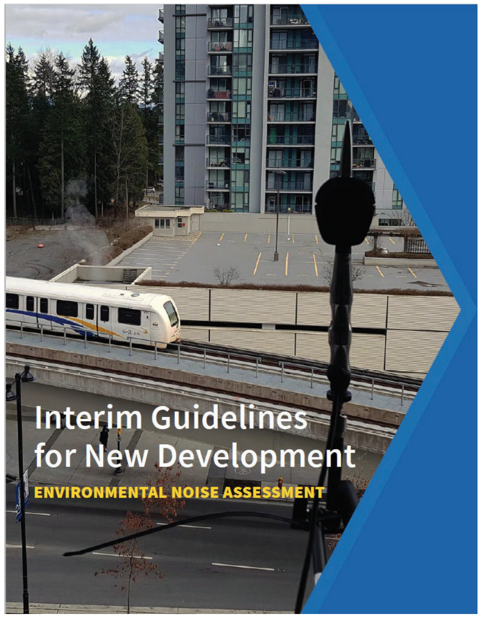
It is possible that additional rail damper implementation locations may be recommended in future, subject to ongoing monitoring of progress towards the identified noise goals.

6.6 NOISE SENSITIVE DEVELOPMENT GUIDELINES RECOMMENDATIONS

An interim environmental noise guideline for new noise-sensitive developments has been prepared and has been published to TransLink's website.

It is noted that administration of environmental noise guidelines for new developments is outside of TransLink's remit. The Interim Guidelines are provided as-is, for information, and as an optional tool that planning authorities may choose to use. The Guidelines are titled "Interim" since wider consultation with developers, acoustic practitioners and others is recommended, and also to reflect that TransLink is not a planning authority. It is hoped that appropriate residential amenity in future development projects would be facilitated by adoption of the Interim Guidelines by developers and by municipal planning authorities.

Figure 13 Interim Guidelines for New Development



6.7 RESOURCE TO LEAD NOISE MITIGATION PROGRAM IMPLEMENTATION

An in-house BCRTC staff resource is required to lead the implementation of the ongoing SkyTrain Noise Mitigation Program. Success in achieving the SkyTrain noise goals will require coordinated implementation of all mitigation measures, appropriate prioritization of noise mitigation program activities within BCRTC, and ongoing long-term efforts monitoring progress towards the noise goals. These objectives would be best achieved by identifying an internal program lead.

The responsibilities of the Noise Mitigation Program Lead would include:

1. Ongoing network wide data analysis and performance monitoring (in-car noise, test train axle vibration, rail friction, network noise condition monitoring)
2. Coordinating rail grinding programs, scheduling grinding, rail grinding quality management
3. Liaising with the dedicated switch maintenance analyst
4. Technical support for friction modifier implementation project
5. Monitoring effectiveness of friction modifier implementation as it progresses
6. Responsible for coordinating or conducting annual noise compliance measurements and preparing public reports on program progress and effectiveness
7. Ongoing analysis of trends in complaints received and response to complaints
8. Point of contact for developers / those working with the Interim Guidelines for new developments.

7.0 RECOMMENDATIONS FOR ONGOING MONITORING

Successful long-term implementation of a noise mitigation program will require ongoing monitoring and verification of effectiveness. There are five key aspects to be monitored: test train in-car noise levels; test train axle vibration levels; switch condition; train passby noise at representative locations; and friction. Monitoring the first three of these components will be data-intensive and it is recommended that cloud and/or network-based data analysis and visualization tools be identified or developed to assist with ongoing assessments and business decisions related to the noise mitigation program.

7.1 ONGOING MEASUREMENT OF TEST TRAIN IN-CAR NOISE LEVELS

Ongoing monitoring of in-car noise levels each week is recommended. This data should be presented visually as the noise level difference above the best case rail condition for each location. In this way the proportion of the network with noise levels within 5 dB of the best case can be visualized, this is an overall Key Performance Indicator for the noise mitigation program. This “difference from best case” approach also removes the effects of train speed and tunnels on the data presented.

Test train in-car noise data has been a useful tool historically to monitor trends in track condition. However, there are limitations to using noise measured inside the train as an indicator of external noise levels. In particular, the severity of noisy switches is not easily determined from noise measurements inside the train. In addition, measurements outside the train adjacent to plain track sections have exhibited higher variability in passby noise levels (after correcting for speed and distance from the track) than is typically observed inside the train (see Appendix B).

7.2 ONGOING MEASUREMENT OF TEST TRAIN AXLE VIBRATION

Ongoing weekly measurement of test train axle vibration is required to support the switch maintenance recommendations. It is likely that axle vibration will also provide information on general rail condition including corrugation growth over time network wide. This data would be used by the Noise Mitigation Program Lead to prioritise rail grinding and assess the overall success of the Noise Mitigation Program.

7.3 ONGOING MONITORING OF SWITCH CONDITION

Ongoing monitoring of switch condition long term is a critical component of successful implementation of the recommendations for improvements to switch maintenance. In the initial year of the program, it is recommended that wayside noise is measured at twenty representative switches, with the data analyzed alongside the corresponding text train axle vibration data. This will enable further characterization of the relationship between train speed, measured axle-box vibration and wayside noise. Locations for switch noise measurement would be selected by BCRTC to capture switches in a range of ages and conditions, with various train operating speeds and with reference to axle vibration data.

7.4 PASSBY NOISE MEASUREMENTS AT REPRESENTATIVE LOCATIONS

Undertaking an ongoing annual series of measurements of train passby noise at representative trackside locations around the network is recommended to enable direct reporting of the effectiveness of the noise mitigation program in the long term. This data also provides a point of comparison for the use of in-car noise data and axle-box vibration data to monitor track condition network-wide. The key requirements of these measurement locations are as follows:

1. All measurement locations should be publicly accessible and reproducible in future years.
2. Wherever possible, all measurements should utilize a microphone elevated above rail height. If noise barriers are present, then the microphone should be located above the top of the barrier.
3. The preferred horizontal offset distance for measurements is approximately 15 m from the near track centreline. Other offset distances are acceptable if measuring at 15 m is not feasible.
4. All measurement locations should enable measurement of train passby maximum noise level without excessive influence from road traffic noise.

A total of 14 representative measurement locations have been identified around the network as shown in Figure 14. Table 2 provides details of why these locations were selected. The majority are in or near residential areas, and many locations correspond to noise complaint hotspot areas identified in the 2018 Noise Report. Other locations have been selected to ensure a geographic spread across the network, from the original Expo line to the more recently constructed Evergreen Line, and including Surrey. Another objective was to include measurement points that will facilitate a review of the effectiveness of mitigation implementation, including areas where rail replacements or rail dampers are planned. Locations with switches are excluded since switch noise and condition monitoring is recommended as a separate task.

Appendix B provides full details of all locations with results from an initial set of passby noise measurements conducted in November 2020.

Although the initial measurements in Appendix B were collected in November, it is recommended that going forward measurements should generally be completed in spring or summer. While the timing of the measurements is somewhat arbitrary, SkyTrain noise complaints are sometimes linked to weather that is conducive to open windows. Scheduling of measurement campaigns should also consider timing of contracted rail grinding programs which can strongly influence the results. A minimum of 10 train passby events should be measured at each location in each direction at locations where only a single train type operates (Millennium and Evergreen Lines). At locations with all train types, measurement of 15 to 20 train passby events each way is recommended.

Figure 14 Representative external noise measurement locations

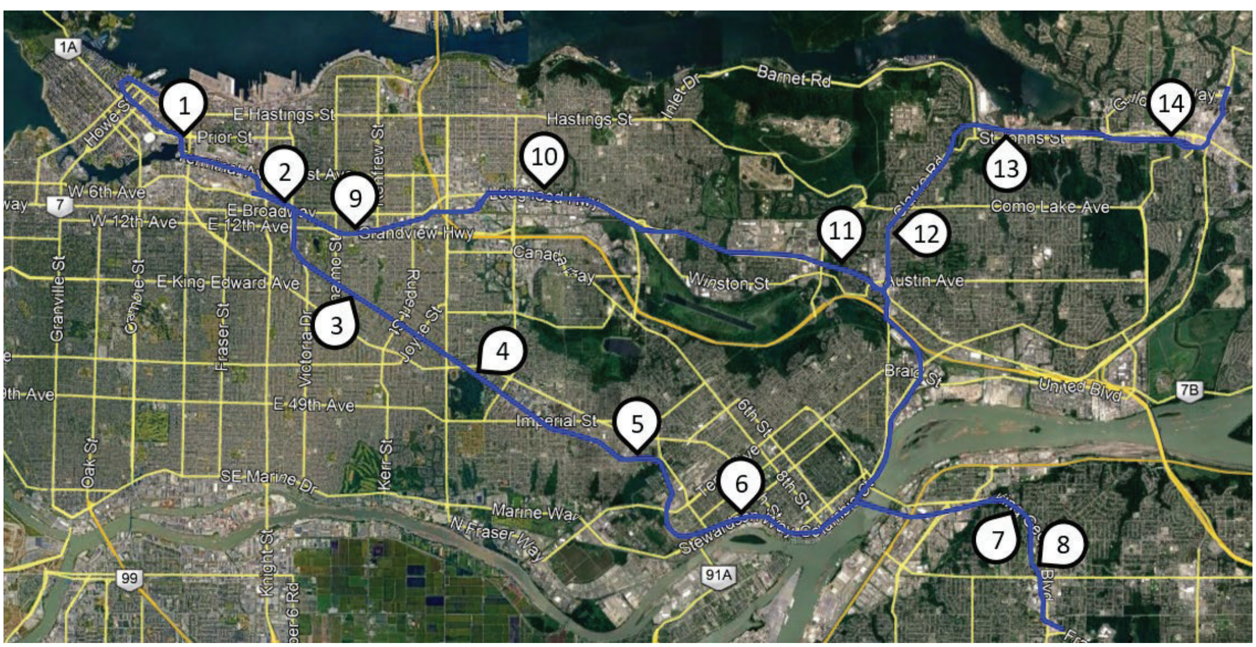


Table 2 Representative external noise measurement locations

REF.	LOCATION	NOTES
1	Quebec Street at Expo Blvd.	Expo Line, residential, noise complaint hotspot, 2018 Noise Study area, speeds 50-65 km/h, curved track, rails have been replaced (248 HB rails installed 2003 were replaced with 330 HB rails in 2020).
2	N Grandview Hwy at McLean Drive	Expo Line, preschool, residential, 2018 Noise Study area, speeds 80 km/h, history of corrugation. Original rails (248 HB installed 1986), rail replacement is scheduled for late 2021 / early 2022.
3	East 27th Avenue at Penticton Avenue	Expo Line, residential, track at grade, speeds 70-80 km/h, history of corrugation and high noise. Original rails (248HB installed 1986) not scheduled for replacement, recommended location for rail damper installation.
4	Central Park / South Burnaby Lawn Bowling Club	Expo Line, public park, speeds 80 km/h. Original rails (248HB installed 1986) not scheduled for replacement.
5	Prenter St at Hawthorne St	Expo Line, residential, speeds 80 km/h, history of corrugation and high noise. Original rails (248HB installed 1986) not scheduled for replacement
6	Stewardson Way – Lookout Green Space	Expo Line, park and residential, noise complaint hotspot, 2018 Noise Study area, speeds 80 km/h, history of corrugation and high noise. Original rails (248HB installed 1986) were replaced in early 2020 outbound (330 HB) and late 2020 inbound (370 HB).
7	132 St at 112 Ave	Expo Surrey, residential, speeds 80 km/h, curved track, 285 HB rail in service since 1994.
8	105 Ave at 134a St	Expo Surrey, residential, speeds 70 km/h, large radius curved track, 285 HB rail in service since 1994.
9	N Grandview Hwy west of Slocan St	Millennium, park and residential, speeds 80 km/h, 300 HB rail in service since 2002.
10	Lougheed Hwy at Gamma Ave	Millennium, residential, 2018 Noise Study area, speeds 80 km/h, 300 HB rail in service since 2002
11	Lougheed Hwy at Bell Avenue	Millennium, residential, 2018 Noise Study area, speeds 80 km/h, 300 HB rail in service since 2002
12	North Rd at Foster Avenue	Evergreen, residential, 2018 Noise Study area, speeds 80 km/h, 350 HB rail in service since 2016
13	Clarke St at Queens St	Evergreen, commercial area, track at grade, speeds 65 km/h, 350 HB rail in service since 2016
14	Aberdeen Avenue at Lansdowne	Evergreen, residential/industrial, 2018 Noise Study area, speeds 80 km/h, 350 HB rail in service since 2016

7.5 TORFM IMPLEMENTATION FRICTION MONITORING

An ongoing series of supplementary measurements and data collection is recommended specifically for the purpose of monitoring the effective implementation of TORFM. Collection and/or review of the following data sets is recommended every two months for the duration of the implementation process, until it is clear that target friction conditions around the network are being achieved and maintained. It is expected that this data will need to be monitored for a period of the order of 12-18 months starting when applicators begin to be installed on existing trains and are being refilled with sticks as part of regular vehicle maintenance:

- Review of stick consumption rates
- Rail roughness / corrugation measurements at a minimum of four locations (both tracks)
- Friction measurements at the same four locations (both tracks)
- Review of in-car noise data corresponding to the four locations (collected weekly)
- Review of axle-box vibration data corresponding to the four locations (optional)
- Wayside noise data (additional measurements every two months at the four locations)

Suggested locations for monitoring are a subset of the annual noise monitoring locations, e.g. locations 3, 7, 10 and 12. These locations include a mix of curve and tangent track and cover the main operating traffic patterns (mixed train types on the Expo line, and Mk2 trains only on Millennium and Evergreen. The TORFM monitoring locations would be confirmed in consultation with the selected TORFM supplier.

When it is clear that target friction conditions around the network are being achieved and maintained, the monitoring requirements can be reduced. In the longer term and it would be sufficient to track TORFM stick consumption rates to verify that product is consistently being applied. Ongoing monitoring requirements will then align with regular ongoing noise data reviews and annual reporting on overall mitigation program effectiveness.

7.6 ANNUAL REPORTING ON MITIGATION PROGRAM EFFECTIVENESS

The final component of ongoing monitoring and verification of effectiveness is annual reporting. This annual reporting should include assessment of overall track condition variation (90th percentile vs 10th percentile) using the in-car noise and vibration data. Monitoring these parameters is recommended to track progress towards the noise goals. The objective is to see that over time, the difference between the best case and worst case noise and vibration levels decrease, indicating track condition and hence noise levels are stable over time and are maintained close to best case condition.

Annual reporting would also document the results of the passby noise measurements at representative trackside locations and provide direct feedback on SkyTrain noise emissions and trends over time. Annual reporting provides a mechanism to review trends in complaints received, assess overall mitigation program effectiveness and make recommendations for additional mitigation at specific locations if required.

8.0 POTENTIAL RESULTS OF NOISE MITIGATION PROGRAM

There is considerable variation in SkyTrain noise emissions around the network depending on the rail condition and cyclical maintenance interventions. A key objective for the noise mitigation program is to reduce this variation and keep noise consistently close to the minimum feasible. The following sections illustrate the potential noise benefits of implementation of the recommended mitigation program.

8.1 INDICATIVE SKYTRAIN NOISE SCENARIOS

A series of four indicative scenarios have been calculated to illustrate the potential benefits of implementation of the recommended noise mitigation program. Each scenario has been calculated with and without parapet noise barriers. While not specifically investigated in this study, parapet noise barriers remain an established noise mitigation measure for SkyTrain, in situations where the noise sensitive floors of buildings are at a similar height or lower than the guideway deck. Parapet barriers are not effective if building windows overlook barriers with a clear line of sight to the tracks.

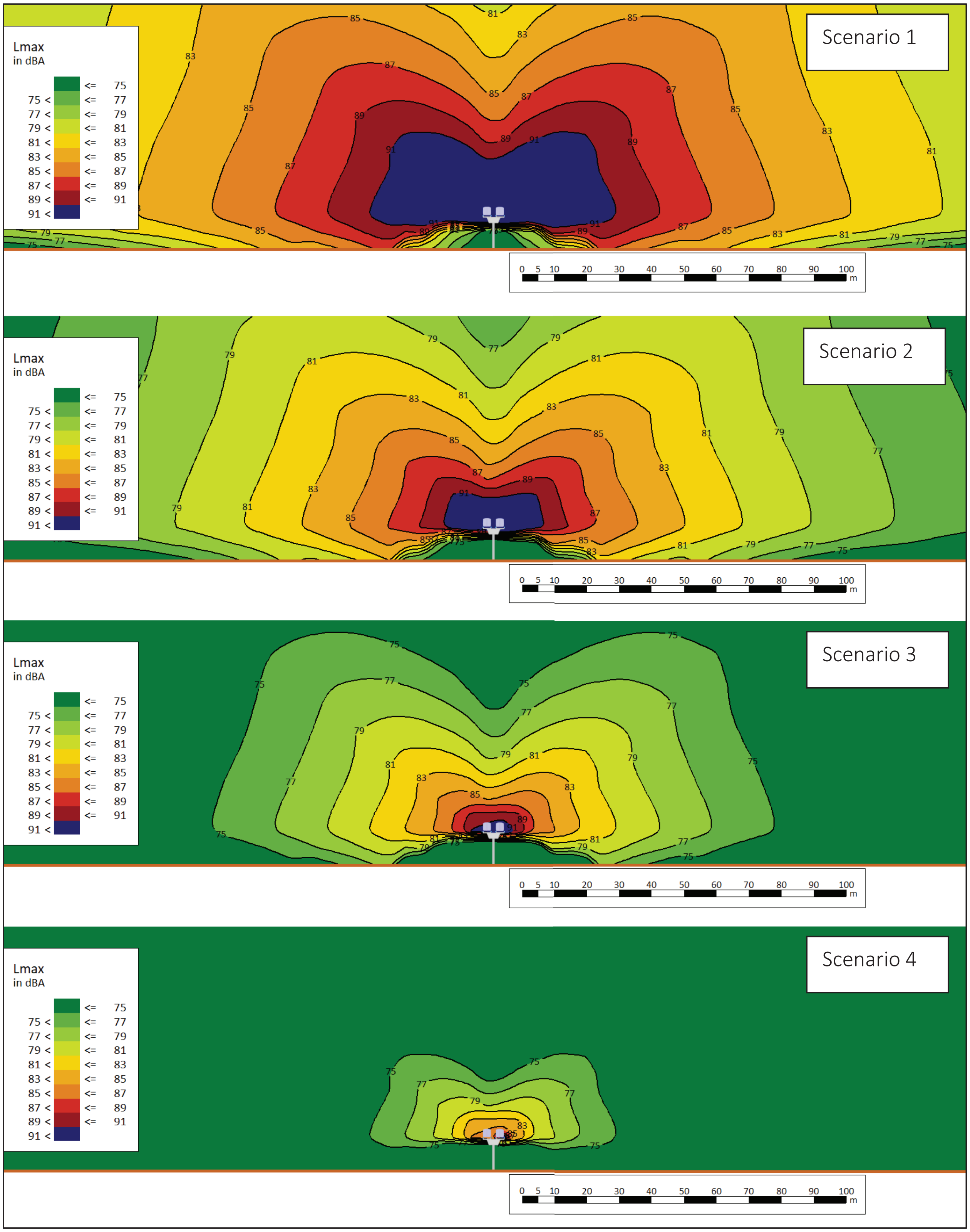
Recognizing that noise emissions are variable with track condition over time, these scenarios are not specific to any individual location. All scenarios have been calculated using a flat ground model, with the guideway deck 10 m above ground. Noise has been calculated out to 150 m from the track centreline, and up to an elevation of 75 m above ground level (approximately the height of a 25 storey building).

In all cases, the noise levels shown are indicative of the typical worst case passby noise levels, at the noisiest point in the maintenance cycle. At many locations, the train passby noise level for much of the year will be less than shown. There are also a small number of exceptions where noise levels may sometimes be higher than shown.

The four scenarios calculated and shown in Figure 15 and Figure 16 are:

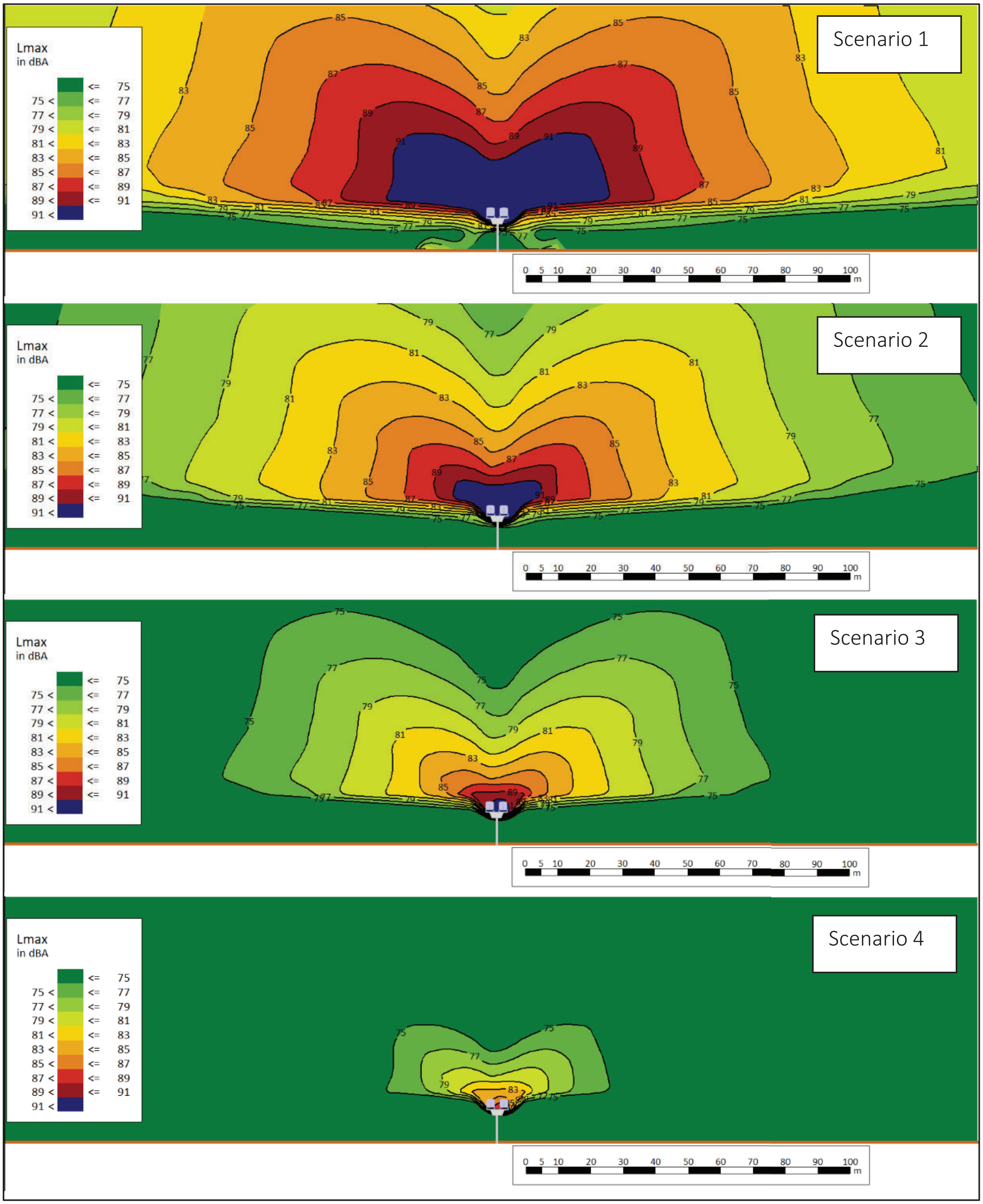
1. Baseline with softer rail or rail/switch surface condition giving noise levels 10 dB higher than track in good condition. Some residential façades located within about 30 m from the guideway are in the 90 dBA LAmax zone (or higher). This scenario is indicatively representative of some areas of the original Expo Line.
2. Harder rail steels giving typically improved surface condition, about a 5 dB benefit on average over the baseline scenario. This scenario is indicatively representative of areas adjacent to the Millennium Line, and some areas where newer rail has already been installed on the Expo Line.
3. Target with implementation of harder rail steel, friction modifiers and improved grinding (maintaining good condition), about a 10 dB benefit over the baseline. This scenario is representative of all areas of the network with successful implementation of these noise mitigation measures. Much of the Evergreen extension has noise levels close to this scenario already, primarily due to the use of harder rail steel, and resulting in minimal grinding requirements.
4. Full implementation of harder rail steel, friction modifiers and improved grinding, plus rail dampers giving an additional 6 dB benefit, i.e. a 16 dB improvement over the baseline. Rail dampers will be installed only at particular locations. Additional rail dampers and parapet barriers may be considered in future, if long term noise issues remain following implementation of all other recommended mitigation measures in areas where rail dampers or barriers would be effective.

Figure 15 SkyTrain Maximum Noise Cross Sections Without Parapet Barriers



Note: See preceding paragraphs for descriptions of Scenario 1 to 4

Figure 16 SkyTrain Maximum Noise Cross Sections With Parapet Barriers



Note: See preceding paragraphs for descriptions of Scenario 1 to 4

8.2 EXAMPLE NOISE MAPS

The original Expo line (being the track sections from Waterfront to Columbia) generally has the highest noise emissions of the network as a whole, in particular in areas where the relatively soft original 1986 rails have not yet been renewed. The following figures provide examples from several areas on the original Expo Line of the difference in noise emissions between the historic typical worst case (noisiest point in the maintenance cycle) and the best case potentially achievable through successful implementation of all recommended noise mitigation measures.

The example locations chosen for illustrative purposes are as follows:

- False Creek (Stadium-Chinatown to Main Street – Science World). This area is lower speed than many parts of the network, with historical noise issues related to switches, rail defects and traction noise.
- Commercial-Broadway to Nanaimo. This area includes switches, curves and tangent track, with historical noise issues at switches and corrugation linked to relatively soft rail steel.
- Nanaimo to 29th Avenue. This area is tangent track with historical noise issues due to corrugation with relatively soft rail steel.
- Joyce-Collingwood – historical noise issues at switches.
- Metrotown to Royal Oak – historical noise issues at switches and corrugation linked to relatively soft rail steel.
- 22nd Street to New Westminster – historical noise issues due to due to corrugation with relatively soft rail steel.

Although not shown in these indicative examples, other parts of the network would also benefit from the recommended network-wide noise mitigation measures. However, harder rail steel is already used on the newer parts of the network in particular on the Millennium Line and Evergreen Extension. In those areas noise variation between maintenance interventions is typically less that has been observed on parts of the original Expo line.

These figures are intended to assist with visualization of noise mitigation benefits. They have been generated by adapting the 2018 noise study model, calculating noise at a grid of points 10 m above ground level, and interpolating the results to generate noise maps. Noise at specific locations will vary depending on receiver elevation; noise levels on lower floors are considerably less than noise experienced above the guideway deck and 10 m above ground.

The best-case scenario shown is the minimum noise feasibly possible at any point in the maintenance cycle. With normal variation over time, actual noise levels would be expected to be between 0 dB and 5 dB higher than the best-case shown in these examples.

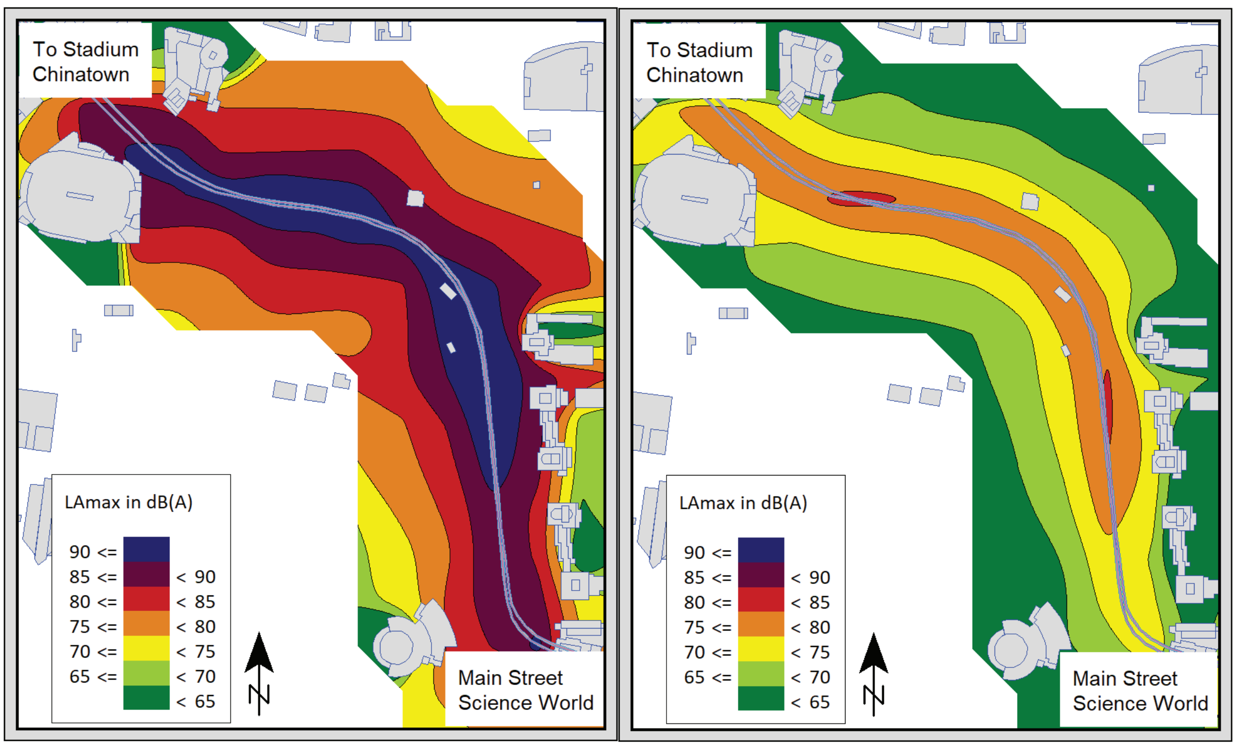
Noise may change over time with operational changes. At some locations, it may not be feasible to meet the program noise goals even after implementation of all recommendations.

8.2.1 EXAMPLE NOISE MAPS – FALSE CREEK

Figure 17 shows rail noise in the False Creek area. Historically, noise issues in this area have been related to noise from trains passing over worn switches, and also to spalling (rail surface defects) near the north end of Quebec Street. In this area there is also distinctive traction noise as trains accelerate, particularly Mk1 type trains. Noise has varied historically when temporary operational speed reductions have been in place.

At the time of the 2018 noise study, train passby noise levels around 80 dBA were measured in this area on an upper level balcony opposite the switch. The switch was subsequently replaced in 2019. Rails in this area were replaced in 2020. Additional location-specific track-based noise mitigation is not recommended in this area, noting that relatively low train speeds even without temporary speed reductions mean rail dampers would not be effective. In this area, the goal moving forward is to maintain long-term noise levels within 5 dB of the best-case shown, relying on monitoring to inform track maintenance as required.

Figure 17 Modelled Historical Worst Case vs Potential Best Case, False Creek



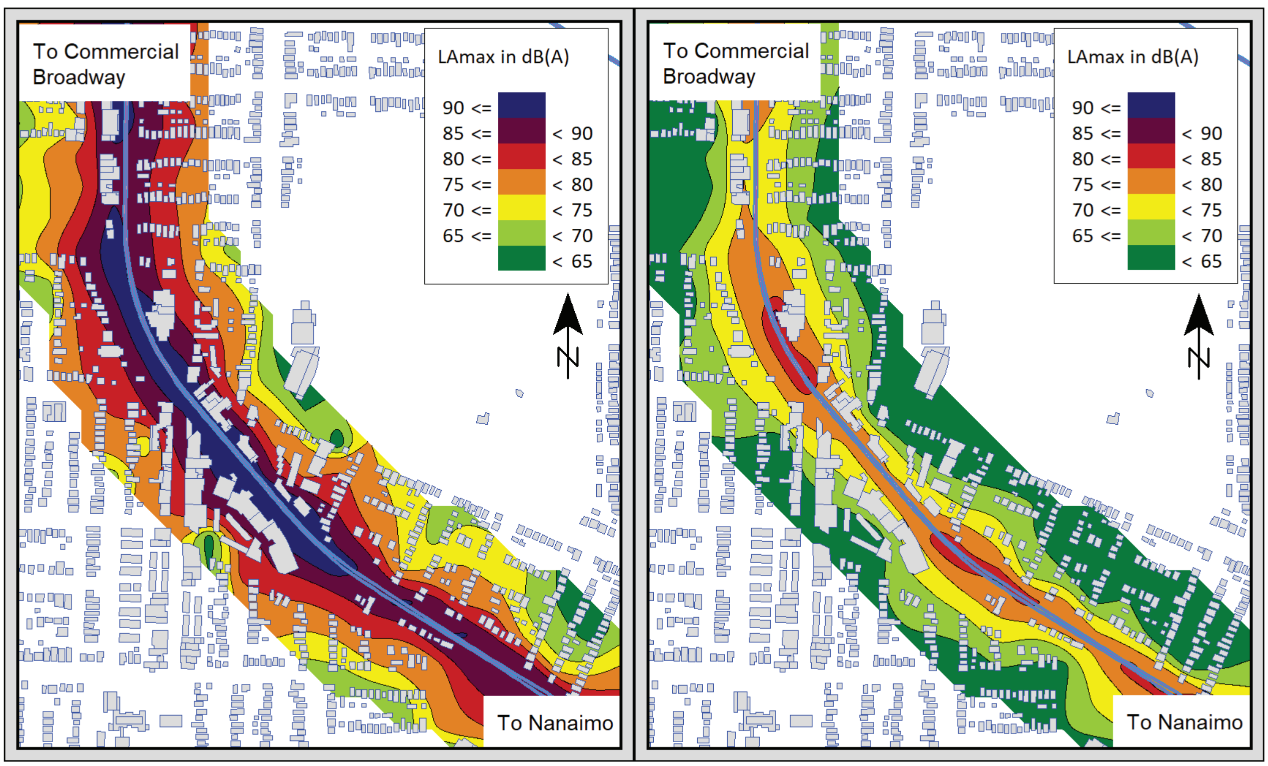
Note: Indicative noise levels 10 m above ground level. Noise often less than shown at building levels below 10 m height. The best-case scenario shown is the minimum noise feasibly possible at any point in the maintenance cycle. With normal variation over time, long term noise levels would be expected to be between 0 dB and 5 dB higher than the best-case shown.

8.2.2 EXAMPLE NOISE MAPS – COMMERCIAL TO NANAIMO

Figure 18 shows noise levels in the Commercial-Broadway to Nanaimo Station area. Historical noise issues in this area have been switch noise west of Nanaimo Station and severe rail corrugation on both curves and tangents, linked to the relatively soft original rail steel. High wear rates and rapid corrugation growth rates have historically required grinding as frequently as 4 times a year, with noise levels increasing again almost immediately after grinding. Trains operate at maximum speeds through this area and many residential buildings (some constructed prior to SkyTrain) are very close to the tracks.

Measurements undertaken as part of this noise study during TORFM and rail damper trials in this area indicate noise levels can sometimes be as high as 90 to 100 dBA at severely impacted residential façades. In this area one switch was replaced in 2021 and rail replacement is scheduled for 2022. Although these measures will result in some improvements in noise levels, additional location specific noise mitigation is recommended in this area, in the form of rail dampers in tangent track sections where they can feasibly be installed. Figure 18 (right panel) shows the best-case noise levels with implementation of all mitigation measures, including rail dampers. In this area, rail dampers would be installed after rail replacement, the goal would then be to maintain long-term noise levels within 5 dB of the best-case shown, relying on monitoring to inform track maintenance.

Figure 18 Modelled Historical Worst Case vs Potential Best Case, Commercial to Nanaimo



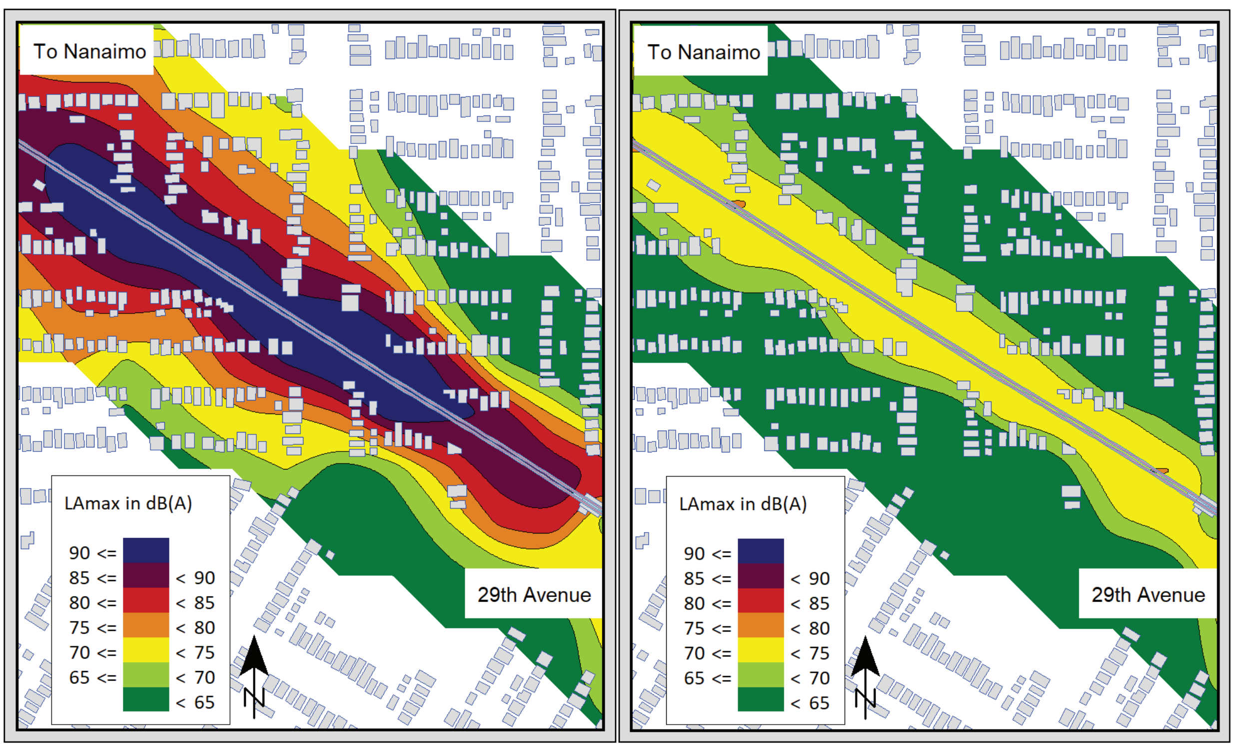
Note: Indicative noise levels 10 m above ground level. Noise often less than shown at building levels below 10 m height. The best-case scenario shown is the minimum noise feasibly possible at any point in the maintenance cycle. With normal variation over time, long term noise levels would be expected to be between 0 dB and 5 dB higher than the best-case shown.

8.2.3 EXAMPLE NOISE MAPS – NANAIMO TO 29TH AVENUE

Figure 19 shows noise levels in the Nanaimo Station to 29th Avenue Station area. Historical noise issues in this area have been severe rail corrugation, linked to the relatively soft original rail steel. High wear rates and rapid corrugation growth rates have historically required grinding as frequently as 4 times a year, with noise levels increasing again almost immediately after grinding. Trains operate at close to maximum speeds through this area and many residential buildings (some constructed prior to SkyTrain) are relatively close to the tracks. The tracks are not elevated in this area, so even low rise residential buildings are exposed to relatively high noise levels.

Noise measurements undertaken in this area (Appendix B) confirm noise levels can be as high as 90 dBA at some severely impacted residential façades. In this area rail replacement has not yet been scheduled. Location specific noise mitigation in the form of rail dampers is recommended. Figure 19 (right panel) shows the best-case noise levels with implementation of all mitigation measures, including rail dampers. In this area, this best case noise level is unlikely to be achieved until after rail replacement which is likely to be at least 5 years away, however rail dampers and TORFM would improve things in the interim, keeping noise down for as long as possible after each grinding intervention. The recommended ongoing monitoring would be used to inform track maintenance requirements.

Figure 19 Modelled Historical Worst Case vs Potential Best Case, Nanaimo to 29th Avenue



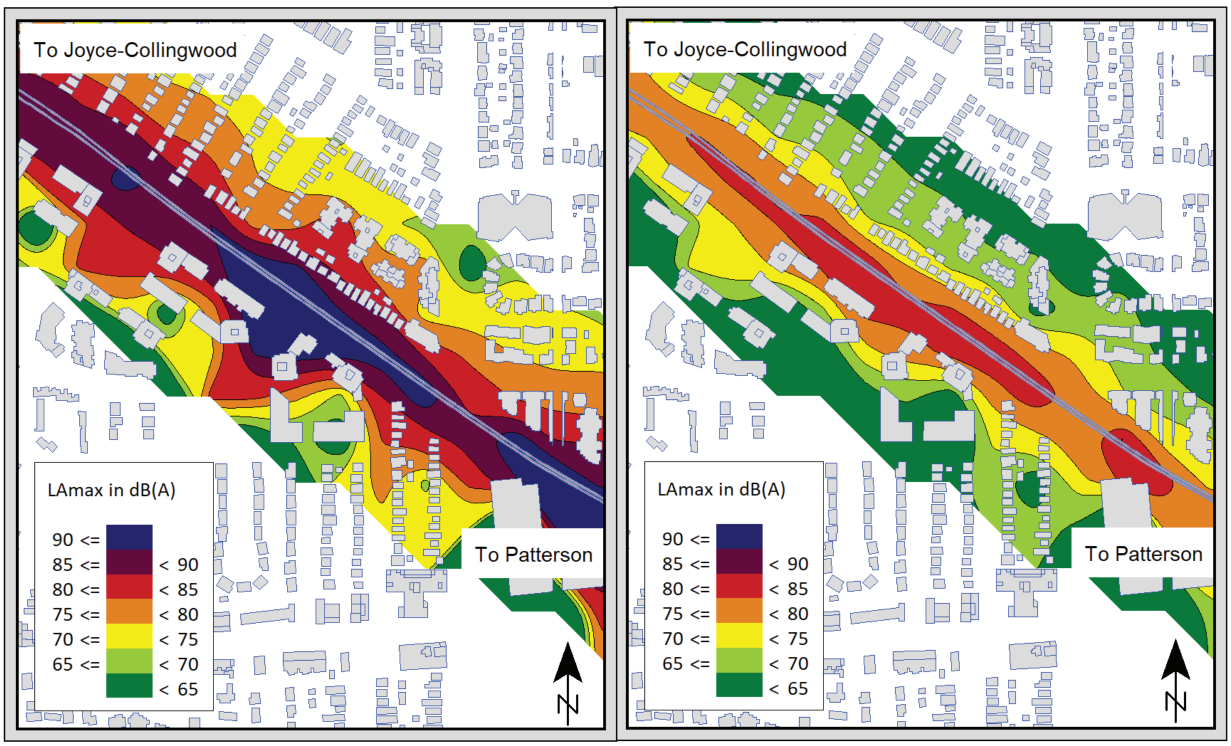
Note: Indicative noise levels 10 m above ground level. Noise often less than shown at building levels below 10 m height. The best-case scenario shown is the minimum noise feasibly possible at any point in the maintenance cycle. With normal variation over time, long term noise levels would be expected to be between 0 dB and 5 dB higher than the best-case shown.

8.2.4 EXAMPLE NOISE MAPS – JOYCE-COLLINGWOOD SWITCHES

Figure 20 shows noise levels centred on the switches east of Joyce-Collingwood Station. At the time of the 2018 noise study measurements, the switches on the inbound track were worn resulting in maximum train passby noise levels around 90 dBA at residential facades around 70 m from the tracks (noise from trains on the outbound track were 10 dB lower). Trains normally operate at maximum speeds through this area. Two high noise switches in this set were replaced in 2018 and 2019.

Figure 20 left panel shows the historical worst-case noise levels with the worn switches, while the right panel shows the best-case noise levels with implementation of all mitigation measures in particular monitoring of switch condition and targeting switch maintenance to minimize noise. In this area, TORFM will also assist in keeping noise down for as long as possible after each grinding intervention on regular track either side of the switches. The goal in this area is to maintain long-term noise levels within 5 dB of the best-case shown, relying on monitoring to inform track maintenance.

Figure 20 Modelled Historical Worst Case vs Potential Best Case, Joyce-Collingwood Switches



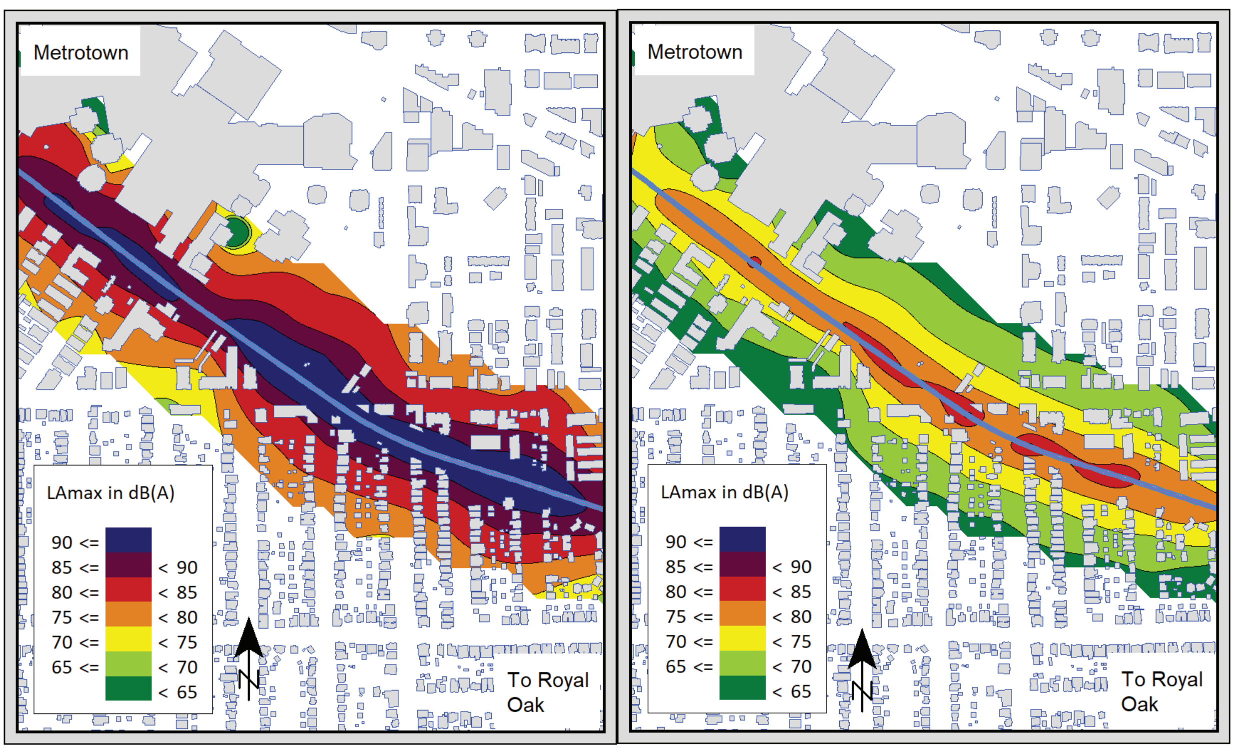
Note: Indicative noise levels 10 m above ground level. Noise often less than shown at building levels below 10 m height. The best-case scenario shown is the minimum noise feasibly possible at any point in the maintenance cycle. With normal variation over time, long term noise levels would be expected to be between 0 dB and 5 dB higher than the best-case shown.

8.2.5 EXAMPLE NOISE MAPS – METROTOWN TO ROYAL OAK

Figure 21 shows indicative noise levels in the area east of Metrotown Station, towards Royal Oak. Trains normally operate at maximum speeds through this area outside of station approaches. Residences in this area are a mix of newer and older properties, including some high-rise towers constructed before the Expo line opened. There are also blocks of older and newer lower rise buildings, and new high-rise developments. Noise issues in this area have historically been a combination of switch noise east of Metrotown Station, in addition to corrugation and high noise linked to the relatively soft original rail steel. One of the four switches in this area was replaced in 2018.

Figure 21 left panel shows the historical worst-case noise levels, while the right panel shows the best-case noise levels with implementation of all recommended mitigation measures in particular monitoring of switch condition and targeting switch maintenance to minimize noise. In this area, TORFM will also assist in keeping noise down for as long as possible after each grinding intervention on regular track either side of the switches. Replacement of the original soft rail steel is not yet scheduled so is likely to be at least several years away. The goal in this area is to maintain long-term noise levels within 5 dB of the best-case shown, relying on monitoring to inform track maintenance.

Figure 21 Modelled Historical Worst Case vs Potential Best Case, Metrotown to Royal Oak



Note: Indicative noise levels 10 m above ground level. Noise often less than shown at building levels below 10 m height. The best-case scenario shown is the minimum noise feasibly possible at any point in the maintenance cycle. With normal variation over time, long term noise levels would be expected to be between 0 dB and 5 dB higher than the best-case shown.

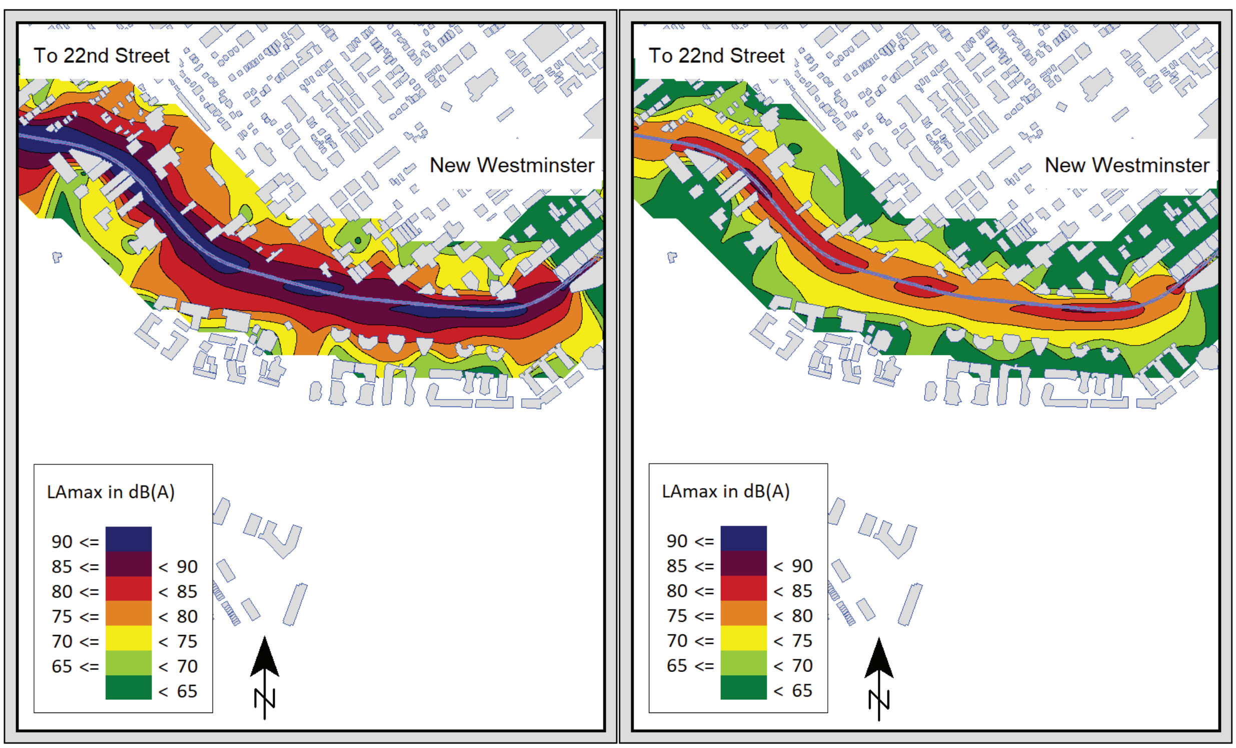
8.2.6 EXAMPLE NOISE MAPS – 22ND STREET TO NEW WESTMINSTER

Figure 22 shows indicative noise levels in the area east of 22nd Street Station, to New Westminster. Trains normally operate at maximum speeds through this area outside of station approaches. Residences in this area are a mix of new condominium towers and low-rise apartments or detached houses on rising ground north of the Skytrain lines. Noise issues in this area have historically been corrugation and high noise linked to the relatively soft original rail steel, with terrain in the area meaning some one or two storey buildings overlook the guideway, albeit at some distance.

Rail replacement has been taking place progressively in this area throughout 2020 and 2021. Measurements near this area completed immediately before rail replacement indicated noise at residences from inbound trains were of the order of 90 to 100 dBA (Appendix B, location 6), whereas noise from outbound trains (where rails had already been replaced) was 20 dBA quieter.

Figure 22 left panel shows the historical worst-case noise levels with the original rail steel, while the right panel shows the best-case noise levels with implementation of all recommended mitigation measures in particular rail replacement with harder rail steel, improvements to grinding practices and TORFM. These measures should assist in keeping noise levels as low as possible after each grinding intervention on regular track either side of the switches. Replacement of the original soft rail steel is not yet scheduled so is likely to be at least several years away. The goal in this area is to maintain long-term noise levels within 5 dB of the best-case shown, relying on monitoring to inform track maintenance.

Figure 22 Modelled Historical Worst Case vs Potential Best Case, 22nd Street to New Westminster



Note: Indicative noise levels 10 m above ground level. Noise often less than shown at building levels below 10 m height. The best-case scenario shown is the minimum noise feasibly possible at any point in the maintenance cycle. With normal variation over time, long term noise levels would be expected to be between 0 dB and 5 dB higher than the best-case shown.

8.3 NOVEMBER 2020 NOISE LEVELS AT REPRESENTATIVE LOCATIONS

A series of train passby noise measurements at 14 representative locations around the network were completed in November 2020 as a template for future representative annual measurements (see Appendix B for full details and measurement results). The measured maximum train passby noise levels were corrected to a standard reference 15 m distance and 80 km/h speed, to enable direct comparison of the variability in SkyTrain noise emissions around the network. The measured passby noise levels ranged from 75 dBA up to 101 dBA with a median value of 83 dBA.

The location with the lowest measured noise levels was on the Evergreen Line, while the location with the highest measured noise levels was on the Expo Line, in a location where rail was in extremely poor condition immediately prior to being replaced.

These measurements confirm that there can be a very large (25 dBA) difference in SkyTrain noise emissions due to maintenance state and rail condition. The long term objective of the noise mitigation program is to progressively address the variability in noise emissions so all track is maintained with noise emissions within 5 dB of the minimum possible, at all times.

8.4 DISCUSSION OF OUTCOMES AND TIMEFRAMES FOR IMPLEMENTATION

The recommended plan for mitigation implementation is expected to result in the following outcomes and timeframes:

1. Switch monitoring – implementation of a switch monitoring and maintenance program is expected to result in a reduction in noise from switches network wide, with benefits beginning to be seen within approximately one year from commencement of implementation. Success for this measure relies on adequate resourcing i.e. a dedicated engineering analyst working with a switch maintenance crew. The approximate one year ramp up period to see benefits includes the initial detailed characterization of the relationship between train speed, axle-box vibration and wayside noise at 20 switches, and time required to procure necessary equipment.
2. Expo Line Rail replacement – rail replacement with harder rail steel is expected to result in reduced noise levels at specific rail replacement locations. Rail replacement has occurred or is scheduled to occur in the following locations:
    a. Stadium / Chinatown to Main Street / Science World (completed)
    b. 22nd Street to New Westminster (completion scheduled by end 2021)
    c. Main Street to Broadway scheduled in 2021-2022

   Rail replacement in other Expo line locations would follow through to about 2030, with no specific schedule available at this time.
3. Friction Modifier – implementation is expected to commence in 2022 with network-wide benefits being realized from 2023 onward.
4. Improvements to rail grinding – implementation of these mitigation measures is expected to commence in late 2021 with benefits primarily in areas with harder rail steel.
5. Rail dampers – implementation of this mitigation measure at the identified highest priority locations is expected to reduce noise levels between Commercial / Broadway station and Joyce Station with installation throughout 2022.

At some locations, it may not be feasible to meet the program noise goals even after implementation of all recommendations. Ultimately there is a practical limit to what can be achieved by noise mitigation at source on an existing system. In some areas around the SkyTrain network, reaching the 75 dBA external noise goal may not be feasible or cost-effective. In particular, there are existing residential buildings that have been constructed close to and overlooking the SkyTrain guideway where it is likely that maximum external SkyTrain passby noise levels will sometimes exceed the 75 dBA goal, even if rail is maintained in close to optimal condition and all recommended mitigation measures are in place.

Implementation of the recommendations in this report would not eliminate all SkyTrain noise or all complaints, however the study has demonstrated that significant improvements are feasible. The recommended mitigation measures prioritize reducing noise at the most affected residential locations.

9.0 CONCLUSIONS

This report describes the results of investigations of the feasibility and effectiveness of six noise mitigation measures. Recommendations are provided for implementation of a Noise Mitigation Program for SkyTrain, considering the interactions between the various mitigation measures.

The primary conclusion of the study is that reducing noise from SkyTrain is feasible in the long term. The key factor in this conclusion is that parts of the network are already much quieter than others – the objective of noise mitigation is to achieve the current best-case noise emissions across more of the network, and to keep noise levels as low as possible in between maintenance cycles.

Achieving a meaningful noise reduction in a cost-effective way will require a combination of different noise mitigation measures. Progressing the implementation of all six mitigation measures as described in this report and the attached preliminary implementation plan is recommended. A coordinated approach to implement all mitigation measures and monitor effectiveness long term is required to maximize the noise benefit. Many of the mitigation measures are inherently linked and the full benefit may not be achieved if only some measures are progressed.

10.0 STATEMENT OF LIMITATIONS

This report has been prepared and the work referred to in this report has been undertaken by SLR Consulting (Canada) Ltd. (SLR) for TransLink, hereafter referred to as the “Client”. It is intended for the sole and exclusive use of TransLink. The report has been prepared in accordance with the Scope of Work and agreement between SLR and the Client. Other than by the Client and as set out herein, copying or distribution of this report or use of or reliance on the information contained herein, in whole or in part, is not permitted unless payment for the work has been made in full and express written permission has been obtained from SLR.

This report has been prepared in a manner generally accepted by professional consulting principles and practices for the same locality and under similar conditions. No other representations or warranties, expressed or implied, are made.

Opinions and recommendations contained in this report are based on conditions that existed at the time the services were performed and are intended only for the client, purposes, locations, time frames and project parameters as outlined in the Scope or Work and agreement between SLR and the Client. The data reported, findings, observations and conclusions expressed are limited by the Scope of Work. SLR is not responsible for the impacts of any changes in environmental standards, practices, or regulations subsequent to performance of services. SLR does not warrant the accuracy of information provided by third party sources.

BC/ijk

N:\Vancouver\Projects\Translink\201.04644 Acoustics\201.04644.00007 Skytrain Noise Mit\Deliverables\Ph2 Rec Report\Final\1. 201.04644.07 Skytrain Noise Mitigation Ph2 20210819.docx