LIGHT RAIL VEHICLE NOISE: EVALUATION OF RAIL ROUGHNESS
AND NOISE FROM WHEEL RAIL INTERFACE

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ABSTRACT

Sound Transit opened its first light rail line, the Central Link, in 2009. There were a number of community noise issues that arose immediately after the line went into revenue service that were generally attributed to poor quality rail grinding when the initial mill-scale grinding was performed. As a result of that experience, Sound Transit has been cautious when predicting noise and designing noise mitigation for new alignments. The future alignments include the University, Northgate, and Lynnwood Links to the north, the Federal Way and South 200th Links to the south, and East Link to the east. In all, over the next 15 years the system will be expanded from the current 16 miles to over 50 miles. Detailed noise data collected as part of final design of East Link suggests that measures could be taken to reduce the need for substantial noise mitigation on future Sound Transit extensions. This paper summarizes the measurements and key observations from that noise study. A key observation suggests that through implementation of “acoustic” rail grinding and maintaining the current wheel truing program, there is potential for minimizing the amount of sound walls that would be required to achieve the community noise goals. The results also suggest that through a detailed, information-based investigation, reference noise levels used to determine the need for noise mitigation could be reduced by approximately 4 decibels. However, the results of this study combined with experience from rail roughness studies in general suggests that achieving a true “acoustic” rail grinding that leaves no artifacts is not straightforward, as it requires careful monitoring by the rail grinder operator as well as quality control measurements by the grinding company or the transit system.
INTRODUCTION

The noise emissions from modern light rail vehicles (LRVs) moving at cruise speed are dominated by the noise of steel wheels rolling on the steel rails. This noise is directly related to the condition of the rail and wheel running surface. When rail corrugations occur, which is a common problem on steel wheel/steel rail systems, noise levels can be up to 20 decibels higher than on smooth rail surface. Proper rail grinding will result in a smooth rail surface and, assuming the wheel surface is smooth, can substantially reduce noise levels. However, if the rails on a rail transit system are ground in the same manner as for a freight rail system where rail is ground to remove surface cracks and smoothness to reduce noise is only a minor concern, noise levels can be increased instead of decreased. In this paper we use the term acoustic grinding for rail grinding on a transit system where a primary goal is to minimize community and in-car noise levels.

To obtain good quality acoustic rail grinding it is important to prepare an objective and achievable specification for the grinding and measure the rail roughness before, during and after the grinding is performed (Ref 1-3). Experience is that poor quality grinding can increase noise levels by up to 10 decibels and, on a typical rail transit system, the adverse effects of poor quality rail grinding will not be “rolled out” even after several years. At the same time, smooth rails with roughness levels below the ISO roughness limits have shown to result in substantially lower noise levels at the San Diego Trolley light rail transit (LRT) system compared to other similar LRT systems (Ref. 4, 5).

The initial segment of the Sound Transit light rail system, the Central Link, opened in 2009. There were immediate and strident complaints about high noise levels from the community. Part of the problem was flanging and wheel squeal on some curves. These problems were largely resolved through implementing rail lubrication and adjusting the rail and wheel profiles to improve curving performance. A wheel profile maintenance program was implemented which showed remarkable improvement in noise and vibration management. A number of different noise studies were performed to resolve these issues (Ref. 6 - 11). The key points from the studies were:

- A study in 2010 that showed noise levels to be 4 decibels higher than the reference noise levels recommended by the FTA Guidance Manual (Ref. 6).
- A follow up study in August 2011 showed that the noise emissions from the Sound Transit fleet had been reduced by 2 decibels after acoustic grinding of the rails in July 2010 and implementing new wheel truing procedures (Ref. 7).
- A study in 2011 of the wheel/rail interface and rolling noise using a panel of international experts to identify ways to improve the wheel/rail interface for existing and future alignments. The study recommended preferred rail profiles based on the wheel profiles that would minimize noise and vibration emissions (Ref. 8). Sound Transit developed a rail reprofiling grinding specification in December 2012 based on recommendations from that study.

In 2013 as part of final design for the East Link project, detailed noise and vibration measurements were performed on the Central Link to characterize the noise and vibration emissions (Ref. 12). This paper summarizes the results that are presented in Ref. 12. For more details, see the full report. Vibration measurements were performed at three locations. These
results are summarized in an earlier TRB paper (Ref. 13). Noise measurements were performed at two of the three test locations. The noise measurements provided important insights on how to minimize noise levels on future projects and demonstrated that there is the potential to reduce the amount of sound wall substantially. A key question in 2013 was whether the Central Link reference noise levels had changed since 2011 and whether a lower reference level could be used to assess noise mitigation for the East Link project. In addition, the noise test program was designed to evaluate the effects of track structure, speed, and rail roughness on rolling noise.

MEASUREMENT APPROACH

The two Central Link locations where detailed noise measurements were performed in 2013 were Site 2, Direct Fixation (DF) track on aerial structure, and Site 3, At-grade ballast and tie track (B&T). Site 1 was in cut and was used for vibration measurements only and is not discussed in this paper. The measurements at Sites 2 and 3 included train noise and rail roughness. Both sites were close enough to relatively busy roadways so that measurements were affected by the traffic noise. All the WAV files were listened to and the results were carefully inspected to exclude traffic noise from the train data wherever possible, although this process was challenging for some of the train passbys at Site 3.

Rail roughness was measured with a Rail Measurement Ltd. Corrugation Analysis Trolley (CAT) that basically moves an accelerometer along the head of the rail to measure the longitudinal roughness. The acceleration signal is integrated twice to calculate displacement as a function of rail position. It is considered to provide an accurate measure of rail head roughness over wavelengths ranging from 2mm to approximately 1m. In addition, train speed was measured with a handheld radar speedometer located either at the wayside or in the operator’s cab.

The measurements included a three-car test train and revenue service trains. It was not possible to measure the roughness of the wheel surfaces on the test train; however, the wheels of the test train were visually inspected. Most of the wheels appeared to have been recently trued and only minor irregularities on the wheel surfaces were observed.

SITE 2 TEST RESULTS (DF ON AERIAL STRUCTURE)

Site 2 was located where the Central Link is on an aerial structure adjacent to SR599. Following are the details of the measurements at this site:

- A *trackside microphone* was located 3.3 ft from the edge of the left rail of Track 2S (the outbound track) at a height of 1 ft above the top of rail. This microphone was 7.5 ft from the left rail of Track 1S.

- Another microphone was located at the top of a pole that extended to the height of the top of rail. This microphone (*the top of rail microphone*) was 25 ft from the centerline of Track 2S.

- Test Train: There were 31 passbys on Track 2S; 13 at 54 mph, and 6 each at speeds of 45 mph, 35 mph, and 25 mph.
• Revenue Service Trains: There were 24 train passbys on Track 2S and 26 train passbys on Track 1S (far track).

• Rail roughness was measured on all four rails.

**Site 2 Noise Results**

The average A-weighted SEL and \( \text{L}_\text{max} \) at the top of rail microphone normalized for a two-car train at 25 ft are shown in Figure 1. Figure 1 also shows a curve for the FTA suggested reference level as a function of train speed and the best fit line of sound level vs. speed derived from the measurements (Ref. 14). The figures show that the noise levels at the aerial structure site are 1 to 2 decibels higher than the reference level provided in the FTA manual. The results in Figure 1 also show that the measured SEL has a speed dependence close to \( 20 \times \log(\text{Speed}) \) and the \( \text{L}_\text{max} \) has a speed dependence close to \( 30 \times \log(\text{Speed}) \), which are consistent with the assumed speed dependence in the FTA Guidance Manual.

Some general observations from the noise measurements at Site 2 are:

• The noise levels are 1 to 2 decibels higher than the FTA reference (Figure 1).

• The overall sound levels and the 1/3 octave band spectra were consistent and the standard deviations were less than 1 decibel.

• The sound level change with increasing speed is frequency dependent. The peak frequency tends to increase with speed (Figure 2).

• The 1/3 octave band spectra indicate broadband noise potentially from general roughness rather than the pure tones that characterize corrugation (Figure 2).

• The average \( \text{L}_\text{max} \) at the trackside microphone was about 103 dBA for the test trains and 106 dBA for the revenue service trains. However, the difference between Track 1S and Track 2S for revenue train passbys was less than 1 decibel and therefore insignificant.

![Figure 1: Site 2, Measured Noise Levels Normalized to 2-car Trains, 50 feet](image-url)
Figure 2: Average 1/3 Octave Band Spectra, Site 2, Test Train

**Site 2 Roughness Results**

The average rail roughness measurements for each rail are shown in terms of 1/12 octave band spectra in Figure 3. The plots show that:

- The roughness at wavelengths less than 50mm for the Track 1S rails is about 10 decibels above the ISO 3095 curve (Ref. 5), which corresponds to 500 Hz noise at 55 mph.

- For the Track 2S rails, the roughness at wavelengths shorter than 50mm tend to be equal to or slightly higher than the ISO curve. The primary exceptions are the peaks at wavelengths of 40mm, 20mm, 13mm, and 10mm that could all be related to the lower peak at 80mm. There are some minor peaks on Track 1S that are at similar frequencies. These seem to have been caused by artifacts from the last grinding that did not roll out.

- Although the short and long wavelength roughness on the 1S rails tends to be higher, the corrugation peaks on the 2S track are more distinct.

The general conclusion from looking at just the average results shown in Figure 3 are that the rails are in reasonably good condition and some noise level reductions could be achieved by rail grinding that removes the corrugation peaks on the 2S track and the broadband roughness on the 1S track.

However, a detailed review of the results indicates that the above conclusions may be too simplistic. Figure 4 shows the measured displacement along the rail head over a distance of 50m (164 ft). The plots are over ±25m with the zero point at the microphone positions for the noise measurements. The plots on the left in Figure 4 are with the raw data filtered to remove all wavelengths longer than 2 m (6.5 ft). The plots on the right are the same raw data filtered to remove all wavelengths longer than 200 mm (7.8 in.).

All of the runs on Track 1S showed long-wavelength and short-wavelength roughness with a pattern (see Figure 4) that has a period of 1 to 2m similar to the wavelength of the long-wavelength roughness. Both of these patterns seem to be residual features from the rail grinding two years prior to the noise measurements.
Figure 3: 1/12 Octave Band Roughness, Site 2

Site 2: Avg Roughness Track 1S (NB), 1/12 Oct. Bands

Site 2: Avg Roughness Track 2S (SB), 1/12 Oct. Bands

Comparison of Noise and Rail Roughness at Site 2

This section analyzes how well the roughness measurements would predict the wayside noise levels at Site 2. Based on roughness data shown in Figure 3, we would expect the following:

- On Track 1S, sound levels would be relatively high (i) above 400 Hz for 35 mph trains and (ii) above 600 Hz for 55 mph trains.
On Track 2S, sound levels would be lower than on Track 1S but with distinct peaks corresponding to roughness peaks. For example, at 35 mph, these peaks correspond to frequencies of 196 Hz, 391 Hz, 782 Hz, 1,203 Hz, and 1,565 Hz, respectively.

Figure 5 compares the trackside noise measurements at Site 2 for revenue service trains at 35 mph. A few key points from Figure 5 are:

- The 1/3 octave band spectra do not show much evidence of strong peaks caused by the roughness peaks.
- At frequencies greater than 1,000 Hz, noise levels on Track 2S are 1 to 2 decibels higher than on Track 1S. As discussed above, based solely on the roughness data, we would expect noise levels in this frequency range on Track 2S to be lower than on Track 1S.
- At frequencies less than 1,000 Hz, noise levels tend to be 1 to 2 decibels lower on Track 2S except in the 315 and 630 Hz bands.

The above observations are not consistent with the roughness data shown in Figure 3. The effects of the prominent wavelengths on noise from test trains measured on the trackside microphone are shown in Figure 6. The graphs in Figure 6 show the average 1/12 octave band spectra for at the trackside microphone for speeds of 25, 35, 45 and 55 mph and cover the frequency range of 250 to 2500 Hz. The vertical lines in Figure 6 indicate the frequencies that the roughness peaks correspond to. Some key observations from these figures are:

- At some speeds there are spectral peaks that line up almost perfectly with the expected corrugation frequency. For example, at 25 mph the largest peak lines up with 13 mm and at 35 mph the largest peak lines up with the 20mm wavelength.
- In other cases even the largest peaks in the sound spectra do not line up with any corrugation wavelengths.
- It appears that the sound level increases at speeds where a corrugation wavelength corresponds to a frequency of 800 Hz, indicating that that the track system strongly responds to a force input that is close to 800 Hz.

Thus the noise and roughness data from Site 2 indicate that there may be factors other than the roughness of the wear band that affect noise levels. Several factors that may be contributing to the observed noise levels are:

- A residual effect of the rail grinding is that the rail head is relatively smooth in the wear band and relatively rough outside the wear band.
- Although Site 2 was tangent track, there is some track curvature near the measurement position that could have affected the wheel/rail contact location.
- Assuming wheels are rolling smoothly on the rail head, peaks in the sound level spectra are influenced by both the wavelengths of the roughness and the mechanical input impedance of the rail system. The strongest sound level peaks may be occurring where a resonance of the rail system corresponds to the roughness wavelength.
- The most important conclusion at Site 2 is that the measured noise levels are approximately 2 decibels greater than the FTA reference sound levels and it is feasible to reduce noise levels through appropriate grinding.
Figure 5: Comparison of Average SEL Spectra, Site 2, Trackside Mic, Revenue Trains, 35 mph

The SEL and Lmax spectra for Track 1S have been normalized to a distance of 3.3 ft from the near rail using the relationship $10 \times \log(7.5/3.3) = 3.6$ decibels

Figure 6: Site 2, Average Test Train SEL, Track 2S, Trackside Microphone, 1/12 Octave Band Spectra
SITE 3 TEST RESULTS (AT-GRADE B&T TRACK)

Site 3 was located where the Central Link is B&T track in the middle of MLK Boulevard. The following are the details of this measurement site:

- The wayside microphone was located on the east sidewalk of MLK 30 ft from the Track 1S centerline.
- A trackside microphone was located 3.3 ft (1m) from the left rail of Track 2S and 7.5 ft (2.3m) from the left rail of Track 1S.
- The 3-car test train was operated in both directions on Track 1S, which is the normal northbound track.
- Test Trains: There were 19 valid measurements of the test train passbys, four at 20 mph, four at 25 mph, eight at 30 mph and three at 35 mph.
- Revenue Service Trains: The noise from revenue service trains was measured from three trains on Track 1S and 11 trains on Track 2S.

Site 3 Noise Results

The average SEL and Lmax for train speeds of 35 mph on Track 1S and Track 2S are shown in Table 1. The average sound levels are normalized to 2 cars and distances of 7.5 ft for the trackside microphone and 30 ft for the wayside microphone.

The average levels in Table 1 show that Track 1S was 4 decibels quieter than Track 2S at the trackside microphone and about 2 decibels louder than Track 2S at the wayside microphone. This is an unexpected result that may be due to differences in the effective roughness of the left and right rails. If this were true, then the left rail of Track 2S should be rougher than the left rail of Track 1S because for both tracks the left rail is closer than the right rail to the trackside microphone. Also the wayside result would mean that the right rail of Track 1S is rougher than the left rail of Track 2S. However, the roughness results discussed later do not validate this indicating that the noise generating mechanisms involved factors other than just the rail roughness in the center of the wear band.

Table 1: Site 3 Comparison of Normalized Noise levels, 35 mph

<table>
<thead>
<tr>
<th>Track</th>
<th>Train type</th>
<th>SEL (dBA)</th>
<th>Lmax (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Trackside (7.5 ft)</td>
<td>Wayside (30 ft)</td>
</tr>
<tr>
<td>Track 1S</td>
<td>Test train</td>
<td>87.4(1)</td>
<td>83.9(1)</td>
</tr>
<tr>
<td></td>
<td>Revenue</td>
<td>87.6</td>
<td>84.5</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>87.5</td>
<td>84.2</td>
</tr>
<tr>
<td>Track 2S</td>
<td>Revenue</td>
<td>91.5(2)</td>
<td>82.7(3)</td>
</tr>
<tr>
<td>Difference (Track 1S minus Track 2S)</td>
<td>--</td>
<td>-4.0</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Notes:

The following are the normalizations used in this table:

1. 3 car to 2 car train adjustment for SEL: -1.8 dB. Lmax needs no adjustment.
2. 3.3 ft to 7.5 ft: -3.6 dB.
3. 45 ft to 30 ft: +1.8 dB.
Figure 7 shows the measured SEL and Lmax noise levels for a 2-car train at the wayside microphone plotted as a function of speed. There are several observations from this figure:

- Both the SEL and the Lmax for most train passbys on Track 1S are above the FTA reference level curve.
- In contrast, SEL and Lmax for all of the revenue service trains measured on Track 2S are below the FTA reference level curve.
- The speed dependence for SEL is in the range of \((10 \text{ to } 15) \times \log(\text{speed})\), which is lower than the FTA assumed speed dependence. In contrast, the speed dependence of \(30 \times \log(\text{speed})\) for Lmax (Track 1S only) is close to FTA assumed speed dependence. The discrepancy for SEL may be due to traffic noise affecting the SEL measurements.
- Perhaps the most important observation from Figure 7 is that the measured train noise levels on Track 2S are all below the FTA reference levels while those on Track 1S are above the FTA reference level. This seems to indicate that it is feasible to reduce wayside noise levels at Sound Transit through track maintenance procedures that maintain a smooth surface on the rail head.

Figure 7: Site 3, Measured Noise Levels Normalized to 2-car Trains, 50 feet

**Site 3 Roughness Results**

Figure 8 shows the average rail roughness measurements for each rail in terms of 1/12 octave band spectra. The figure shows the following:

- The roughness at wavelengths less than 20 mm on Track 1S (NB) is 8 to 10 decibels above the ISO 3095 limits. At 35 mph this corresponds to acoustic noise at frequencies greater than about 1000 Hz.
- The roughness on the Track 1S left rail is consistently greater than the roughness of the right rail. For wavelength longer than 50 mm, the difference is greater than 10 dB. For wavelengths shorter than 50 mm, the difference is 5 to 8 dB.
- There is a sharp peak in the roughness spectra for both rails at around 45 mm that corresponds to 340 Hz at 35 mph.
For Track 2S (SB) rails, roughness at wavelengths shorter than 50mm tends to be equal to or slightly higher than the ISO 3095 curve. The primary exceptions are the sharp peaks in the right rail roughness at wavelengths of 47.1 mm, 23.5 mm, 15.9 mm and 11.8 mm. There are peaks in the left rail roughness at similar wavelengths, although the magnitudes are lower and the peaks tend to be at slightly higher frequencies.

The general conclusions from the results are that the rails are in reasonably good condition. Also, Track 1S would be expected to generate higher noise levels than Track 2S except for the roughness peaks on the 2S left rail.

Figure 9 shows the plots of raw roughness data for the four rails over a distance of 50 m (164 ft). The measurements for the 2S right rail were similar to the measurements for the 2S left rail and the 1S right rail. The peaks in roughness amplitude for Track 1S left rail are typically ±5 to +10 µm and the peaks in roughness amplitudes for Track 2S right rail are typically ±3 to ±5 µm, about half that of Track 1S left rail. A difference in the roughness amplitudes by a factor of 2 would be expected to cause noise levels to be 6 dB different if all other factors are equal. The difference of approximately 6 dB in roughness for these two rail is confirmed by referring to the 1/12 octave band spectra in Figure 8. The roughness at wavelengths shorter than 50 mm for the Track 1S left rail are around 2 dB and for the Track 2S right rail are around -4 to -5 dB (ignoring the peaks in the roughness spectra). As discussed in the next section, this difference is reflected in some of the noise data.

Figure 8: 1/12 Octave Band Roughness, Site 3
Figure 9: Site 3 Displacement vs. Distance, ±25 m for Run 2, (a) Left Rail, Track 1S, (b) Right Rail, Track 1S, (c) Left Rail, Track 2S, (d) Right Rail, Track 2S
Comparison of Noise and Rail Roughness at Site 3

One question is how well the roughness measurements would predict the wayside noise levels at Site 3. The wayside noise measurements show that Track 1S was louder than Track 2S. A contradictory observation is that at the trackside microphone Track 2S was louder than Track 1S. The difference in the noise levels at the two microphone positions are shown in Figure 10, which shows the trackside microphone spectra with the frequencies that correspond to three of the roughness peaks marked with vertical blue lines. The roughness peaks do not line up exactly with the sound level peaks, but they are close enough to suggest that the sound level peaks are related to the roughness peaks. Another observation is that without the peaks, the Track 2S spectrum would be approximately equal to the Track 1S spectra for revenue and test trains at wavelengths longer than 11.8 mm, which corresponds to frequencies below 1,325 Hz.

Now referring to wayside microphone in Figure 10 it can be seen that the positions are reversed. The Track 2S spectrum is lower than the Track 1S spectra for test and revenue trains at all frequencies. Possible reasons for this reversal are:

1. The manner in which roughness peaks affect wayside sound levels diminishes with increased distance from the tracks.
2. At the trackside microphone the noise generated at the closest rail dominates and the noise from the far rail contributes little to the noise levels. At the wayside microphone, both rails contribute to the noise level, although the far rail would still be expected to contribute less than the near rail.

Perhaps the most important observation from the noise measurements at Site 3 is that at the wayside microphone, trains operating on Track 1S were about 2 decibels louder than the FTA reference level and trains operating on Track 2S were 1 to 2 decibels lower than the FTA reference level. Some key observations on factors resulting in higher wayside noise levels are:

1. The general roughness in the rail head wear bands that exceeds the ISO 3095 limits at wavelengths that have the strongest influence on train noise loudness. However roughness is not a perfect predictor of noise.
2. The increase in rail roughness at the fringes of the wear band and outside the wear band could play a role in noise increases.
3. The corrugation-like roughness that shows up as strong peaks in the roughness spectrum appear to cause significant noise level increases when the roughness wavelength corresponds to some type of resonance in the rail system.
4. Propagation over the ballast may be reducing noise levels by 1 to 3 dB.
CONCLUSIONS

The detailed evaluation on noise from Central Link light rail operations revealed a number of interesting results. The key conclusions are:

- The correlation between noise and rail roughness are not as direct as indicated in some theoretical evaluations. In particular, peaks in the roughness spectra do not always correlate with peaks in the noise spectra.

- In spite of the imperfect correlation observed between roughness and noise, it is clear that smoother track and wheels is the first step in achieving low noise levels.

- The noise levels from Central Link rails are 2 decibels higher than the FTA reference levels. The data indicate that careful initial grinding of future new alignments could potentially result in at least 4 decibel lower noise levels similar to Track 2S at Site 3.

- No rail corrugation was noted but there are some strong roughness peaks that probably are residual effects of rail grinding. This shows that improper rail grinding is not easily resolved through “rolling out” of imperfections.

- A general observation is that although no corrugation was noticed on both test sites, we are aware of several light rail systems where corrugation started to form approximately 10 years after the systems opened.

- Without periodic rail grinding the wayside train noise can be expected to increase as rail roughness increase.

- It appears that proactive preventive maintenance might help to achieve noise levels that are equivalent to that measured from Track 2S of Site 3.

Further investigation over a reasonable length of period will be required to verify these preliminary observations.
REFERENCES