EVALUATION OF FORCE DENSITY LEVELS OF LIGHT RAIL VEHICLES

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ABSTRACT

The vibration forces generated by train wheels rolling on steel rails are characterized as force density level (FDL). The FDLs are a key component in predicting vibration levels from future train projects and generally are assumed to be independent of the measurement position and the soil properties. The FDLs are dependent on a number of factors that include track type, vehicle suspension systems, train speeds, and the condition of wheels and rail surfaces. This paper presents the results of train vibration measurements at three sites along Sound Transit's (ST) Central Link and compares the results to previous FDL results from Central Link's startup phase. The effects of speed, train length and track type on FDL were measured. A test train was employed for the measurements at three sites. The tests at the three sites also included supplemental measurements with revenue service trains. The study showed that the vibration of the current ST fleet is lower than the previous measurements apparently because the wheels are in better condition than for the earlier tests. Rail roughness was also measured at all the test sites and their effects on FDL were explored.

INTRODUCTION

Detailed groundborne vibration predictions from new rail transit systems in North America are based on procedures that are given in the Federal Transit Administration (FTA) Guidance Manual (1). This test method was originally developed by Nelson and Saurenman in the 1980s (2). It employs an empirical procedure that assumes that the groundborne vibration forces generated by steel wheels rolling on steel rails are independent of the local geologic conditions. These vibration forces are referred to as the force density level (FDL). In this paper the term FDL refers to the 1/3 octave band force density level. FDL is considered to be a function of the track type, vehicle suspension system, wheel condition, track condition, and other factors described below.

Several computer predictions models based on the assumed sources of groundborne vibration are widely used in Europe (3-*7*). These computer models consider that the following sources of dynamic loads that can be attributed to the vibration force spectra:

- The tie (sleeper) passage frequency that excites vibration at the frequency ($v/\Delta x$) where v is the train speed and Δx is the distance between ties.
- Wheel roughness that contributes to vibration forces between 50 and 125 Hz.
- Imperfect track alignment that acts as a dynamic source at low frequencies.
- Rail unevenness and roughness that contributes at high frequencies.

A study by Auersch compared slab and ballasted tracks and reported that the low frequency amplitudes of groundborne vibration would be potentially reduced for the slab track due to better track quality (4) and the ballast track amplitudes would be lower at higher frequencies due to better damping of the vehicle-track resonance. Another theoretical study showed that short-wavelength roughness can extend the vibration caused by dynamic loads at low frequencies to higher frequencies (*5*). The conclusion is that although a number of apparent factors such as wheel roughness, rail roughness, vehicle dynamics, train speed, and track modulus influence the measured FDL, the importance of each of these factors is difficult to determine without measurements (*8*).

Train vibration levels tend to increase with speed. However, the speed dependency of vibration is very complex to predict. The FTA Guidance Manual suggests that when no other information is available, it is reasonable to assume that groundborne vibration varies as 20×log(speed). The standard approach is to assume a 15 to 20×log(speed) relationship that is frequency independent. Two recent FDL tests showed contrasting results: Testing at the METRO light rail line in Phoenix showed a strong dependence on speed and testing at the Hiawatha Line in Minneapolis showed a weak relationship to speed (*8, 9*). Investigations on the effects of speed on train vibration for the TriMet light rail fleet in Portland showed that between 12.5 and 25 Hz there was pronounced speed dependence on embedded tracks with rail boot and the peak frequency seemed to increase with speed (*10*). A 10 Hz peak that was correlated to the primary suspension resonance frequency was also observed. The same investigation reported that for ballast and tie (B&T) tracks there was strong train speed dependence below 40 Hz but the peak frequency varied and there was no distinct mechanism could be attributed to the peak frequency.

The history of vibration characterization of the Sound Transit (ST) fleet in Seattle includes a study performed during the startup phase of the Central Link in 2007 (*11*). The 2007 study included an FDL measurement using two single-vehicle trains on B&T tracks in the SODO area. One of the test vehicles had a wheel flat that strongly affected the vibration levels above 20 Hz. The conclusion of the 2007 analysis was that a composite FDL, which was basically an average of the FDLs with good wheels and with wheel flats, was a reasonable estimate of FDL for vibration predictions. This was a conservative approach and was justified because of the limited vehicles in the fleet and lack of operational history for the system. The ST fleet has grown since the startup phase and now has well-defined maintenance procedures for periodic upkeep of the wheels and rails. The fundamental question at the beginning of our project was whether the composite FDL from 2007 is representative of the current ST fleet. As a result, vibration measurements were performed at three sites in 2013 to characterize the FDL of the current ST fleet (*12*). In addition, the vibration test program was designed to evaluate the effects of speed, track structure, and rail roughness on FDL.

BACKGROUND

The detailed prediction procedure for groundborne vibration described in the FTA Guidance Manual is based on an empirical method that is defined by the following relationship (*1*):

$$Lv = FDL + LSTM$$

where:

Lv = Vibration velocity level.

LSTM = Line source transfer mobility.

FDL = Force density level.

(All values are in decibels assuming a consistent set of units and decibel references. All levels are based on 1/3 octave band levels.)

FDL is derived from LSTM and Lv measured along an existing system using the relationship described above. A basic premise of the FTA prediction procedure is that FDL is independent of the measurement position.

LSTM is obtained by combining multiple Point Source Transfer Mobilities (PSTM). The PSTM is the relationship between a point vibration force (typically an impulse from an impact) and the resulting vibration velocity response at the measurement position. PSTM characterizes how vibration is transmitted through the soil. To simulate a line source, a series of impacts (point sources) are performed along the centerline of the tracks or adjacent to the tracks and the resulting PSTMs are combined to determine LSTM. The response is measured at multiple distances from the impact line. To derive the FDL, the train vibration velocity levels (Lv) are also measured at the same measurement positions. Theoretically, the FDL derived from the multiple measurement positions should converge to single curve.

TEST PROCEDURE

Vibration testing at Sound Transit was performed in March and April of 2013 at three locations along the Central Link in Tukwila:

- Site 1, Direct Fixation (DF) track in cut.
- Site 2, DF track on aerial structure.
- Site 3, At-grade ballast and tie track (B&T).

The sites represent two different track types (DF and B&T) and three different structures (at-grade, aerial, and in cut). The measurements included LSTM tests performed along the near track centerline at all three sites. A minimum of 40 impacts were performed at each impact position. At Site 3, the impacts were made on the ballast between the ties. Test trains were operated on the near track to characterize train vibration at several target speeds. Vibration from revenue service trains on near and far tracks were measured at the normal operating speeds. The near and far tracks were designated based on their relative proximity to the accelerometer positions. For both Lv and LSTM measurements, PCB model 393A03 seismic accelerometers were located at the following distances from the near track centerline:

- Site 1: 35, 50, 80, 95 and 110 ft.
- Site 2: 15, 25, 50, 100, 110, 120 and 130 ft.
- Site 3: 30, 40, 50, 75, 100, 125 and 150 ft.

LSTM: PSTM was measured at 10 to 13 positions in a line at the track centerline using a drop hammer that drops a 45 or 70 lb weight onto a load cell. The impact was cushioned with shock absorbers to prevent bounces. The impulse was between 2 to 3 msec (0.002 and 0.003 seconds) and had a peak force between 6,000 and 9,000 lbs. The PSTM measurements were spaced linearly or non-linearly depending on the site. The spacing was accounted for when combining the PSTM measurements to derive the LSTM. For the aerial structure, the LSTM was measured by delivering impact forces to the aerial structure between the rails and the reported LSTM includes the structural responses of the aerial structure.

Coherence is an important parameter associated with LSTM measurements. Coherence is a measure of the “quality” of the LSTM data. A coherence close to one indicates a very strong relationship between the exciting force and the resulting ground vibration, and a coherence close to zero indicates a weak relationship between the two. A coherence greater than 0.5 indicates a reasonably good correlation between the vibration source and the receiver. LSTMs that had a coherence less than 0.2 to 0.3 were considered to have poor data quality because the measured responses were affected by background vibration.

Lv: The test train was operated at several speeds to provide the relationship between speed and train vibration. The same 3-car test train was used at all three sites. The test train wheels were visually inspected and the maintenance logs were reviewed before the tests. All wheels were in relatively good condition. The number of measurements at each speed typically ranged from four to six. Measurements of vibration from revenue service trains were performed at the same measurement positions as the test trains. All of the revenue service trains were 2-car consists. The vibration measurements were performed at the following train speeds:

- Site 1: 20, 25, 30, 35, 40, 45, 50 and 55 mph.
- Site 2: 25, 35, 45 and 55 mph.
- Site 3: 20, 25, 30 and 35 mph.

The train vibration recordings were analyzed to obtain 1/3 octave band spectra at 125 msec (1/8 second) intervals. This data was used to obtain Lmax and the rms average vibration over the period each train was in front of the measurement position. The rms average over the time the train was in front of the measurement position is referred to in this paper as Leq. Lmax was the maximum 1-second rms average vibration level. Because the FTA impact thresholds are in terms of Lmax, all the FDLs presented in this paper are for Lmax. Measurements of vibration from revenue service trains were performed after the test train measurements had been completed. A total of 105 train passbys were measured; 26 test train passbys and 33 revenue service trains at Site 1, 31 test train passbys and no revenue service trains at Site 2, and 24 test trains and 11 revenue service trains at Site 3.

Ambient Vibration: All three of the measurement sites were close enough to roadways that some of the data were affected by the ambient vibration generated by traffic and other sources. Poor coherence due to background interference can lead to overestimating LSTM by 10 to 20 dB (*13*). On the other hand, when train vibration is not distinguishable from the ambient vibration, the measured levels can overestimate the true train vibration levels. Although it is evident that the overestimates of LSTM and overestimates of train vibration will tend to counteract each other, it is not possible to determine the FDL with any level of certainty when ambient vibration affects both LSTM and Lv. Train vibration results were carefully evaluated to identify when and at what frequencies the results were affected by ambient vibration. Similarly the data with poor coherence were excluded from the FDL.

Rail Roughness: A specialized instrument called the Corrugation Analysis Trolley (CAT) from Rail Measurement Ltd. was used to measure the longitudinal variation in the rail head elevation. Basically the instrument moves an accelerometer along the wear band on the rail head and integrates the acceleration signal 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.

RESULTS

Measured FDL:

The measured train vibration and LSTM were combined to derive FDLs. The detailed results of Lv and LSTM are not the focus of this paper and are documented elsewhere (*12*). The FDL results from Site 1 through Site 3 are shown in Figure 1 through Figure 3. The FDL curves for Sites 1 and 3 are based on both test and revenue service trains. The FDL curves for Site 2 are based on the test train only.

The results for DF track in cut (Figure 1) show a low frequency peak at 10 Hz and another strong peak at 50 Hz for all train speeds. The 10 Hz peak is distinctly visible for trains at 20 mph and decreases notably at 25 mph before returning as a broad peak at higher speeds. Although there were only single trains measured at speeds of 20, 30 and 40 mph, their FDLs generally follow the trend seen at other speeds. The FDL data between 31.5 and 80 Hz show strong speed dependence. The FDL data above 160 Hz in Figure 1 has high uncertainty due to poor coherence (below 0.3) from the LSTM measurements in that frequency range and therefore is shown in gray.

The results for DF track in cut (Figure 2) show a low frequency peak at 10 Hz and another peak between 50 and 63 Hz at all measurement positions. Similar to DF track in cut (Figure 1), the 10 Hz peak is low at 25 mph before returning as a broad peak at higher speeds. The FDL spectra on the aerial structure show good agreement with the measured FDL for DF track in cut. Similar to the in-cut measurement, the aerial structure FDL between 31.5 and 80 Hz also show strong speed dependence. Due to poor coherence below 10 Hz during the LSTM measurements, the FDL below 10 Hz in Figure 2 is shown in gray.

The FDLs for DF track in cut and aerial structure are comparable, and wherever the data is valid, the difference in levels between the two sites were mostly within 3 decibels. Because both sites have DF tracks, the convergence of the FDL at the two sites validates the assumption that FDL is largely independent of the ground condition. The aerial structure did show some fundamental resonance effects between 10 and 12 Hz but higher order structural resonances were not clearly evident.

Figure 3 shows the measured FDL for B&T track. The FDL at 20 mph shows a sharp 10 Hz peak. There is a hint of a peak at approximately the same frequency at 25 mph. At all speeds, the FDL shows a broad peak between 63 and 80 Hz. With a couple of exceptions, between 16 and 80 Hz, FDL tends to increase at a rate of approximately $20 \times \log_{10}$(train speed). In theory, the DF tracks are expected to have FDLs comparable to B&T tracks up to 31.5 Hz and about 5 dB higher FDL at frequencies greater than 40 Hz. The current results follow that general trend except at the peaks (*14*, *15*). At 50 Hz and 160 Hz, the DF track FDLs are consistently about 10 dB higher than the B&T FDLs at all measured speeds.

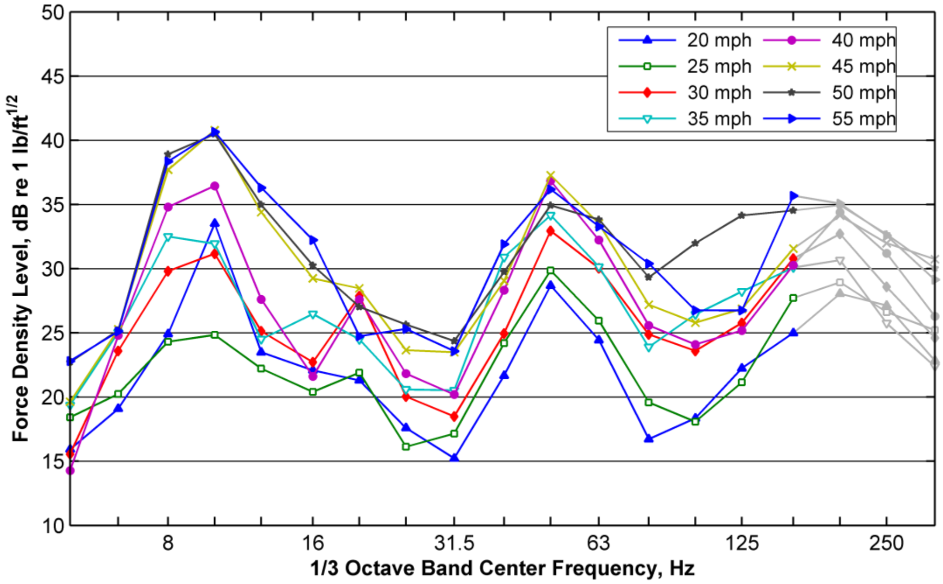

Figure 1: FDL for Direct Fixation Track in Cut, Site 1

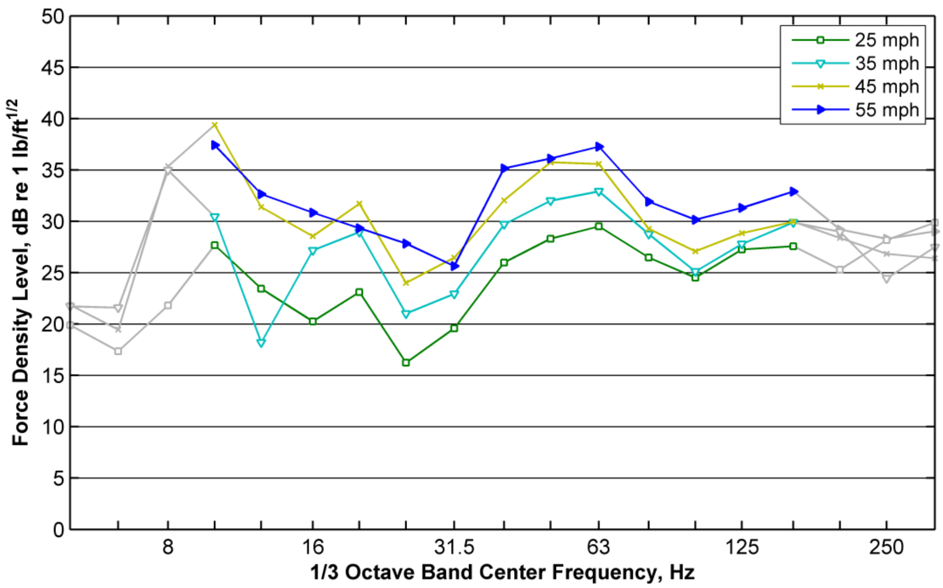

Figure 2: FDL for Direct Fixation Track on an Aerial Structure, Site 2

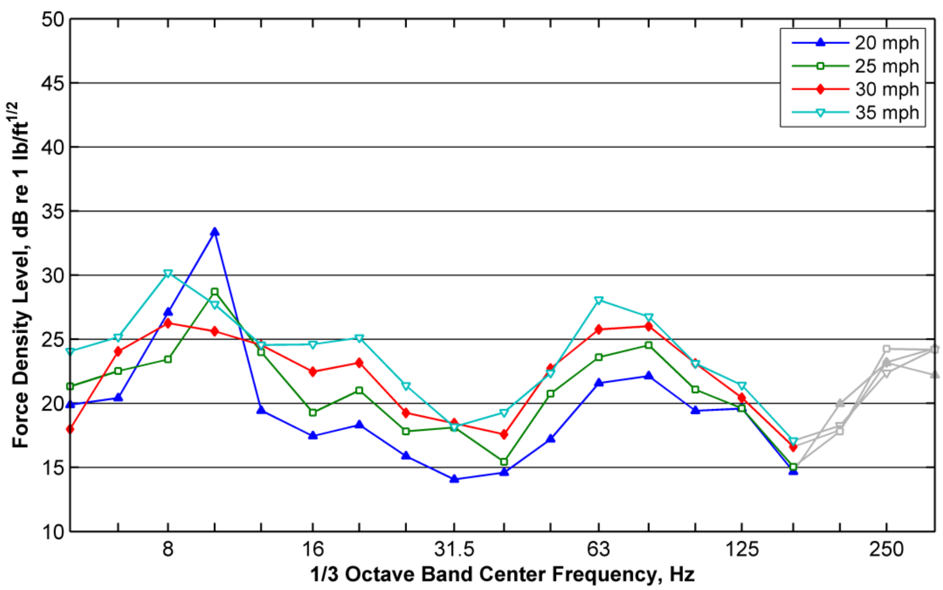

Figure 3: FDL for Ballast and Tie Track At-Grade, Site 3

Comparison of Sound Transit FDL

The FDLs from the 2013 study were compared with the results from the startup phase in 2007. Figure 4 through Figure 6 show FDLs at speeds of 20, 25 and 35 mph. The figures include the following FDL curves:

- B&T (SODO) Wheel Flat: FDL with the test vehicle that had a wheel flat from the 2007 study.
- B&T (SODO) No Wheel Flat: FDL with the test vehicle with good condition wheels from the 2007 study.

- B&T (MLK): FDL from the 2013 study at Site 3.
- DF in Cut (144th St.): FDL from the 2013 study at Site 1.

The SODO-2007 results are based on measurements performed with 1-car test trains. The MLK-2013 and 144th Street-2013 results are based on a composite of the 3-car test train and 2-car revenue service trains. The key points from Figure 4 through Figure 6 are:

- The SODO-2007 wheel flat FDL is substantially higher than the other two FDLs for ballast and tie tracks at frequencies greater than 40 Hz. This appears to indicate that ST maintenance is keeping wheels in good condition and vehicles with wheel flats are uncommon. The conclusion is that the wheel flat FDL is not representative of the current ST LRV fleet.
- For the FDLs from this study there is a peak at 10 Hz when train speed was 20 mph. This peak is not evident in the 2007 results and the reason for this difference is not clear.
- The MLK-2013 FDL tends to be 2 to 5 decibels lower than the SODO-2007 FDL with no wheel flat at frequencies greater than 31.5 Hz and the two are generally comparable at lower frequencies. The one exception is the peak at 10 Hz in the MLK-2013 FDL for a speed of 20 mph.

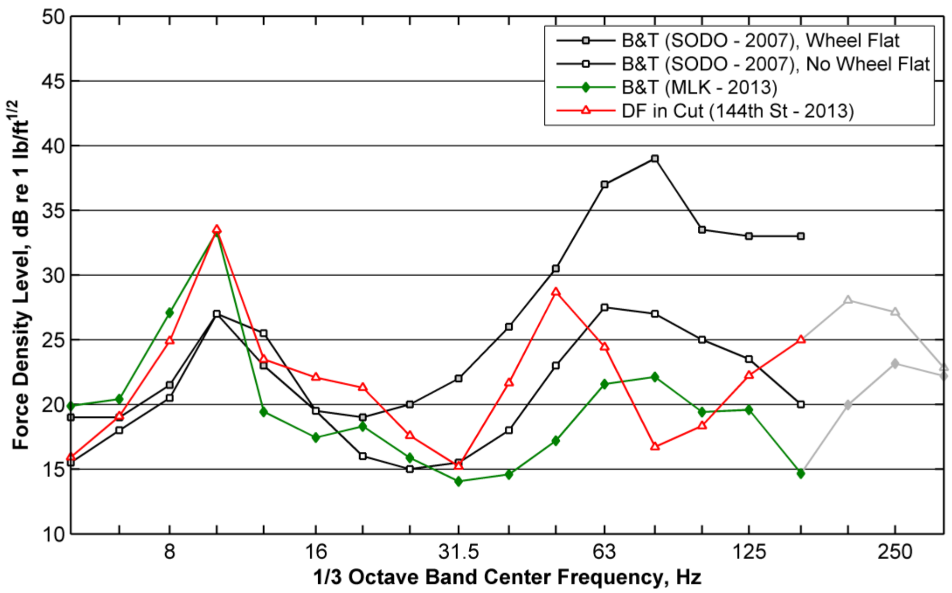

Figure 4: Comparison of FDL for ST LRVs at 20 mph

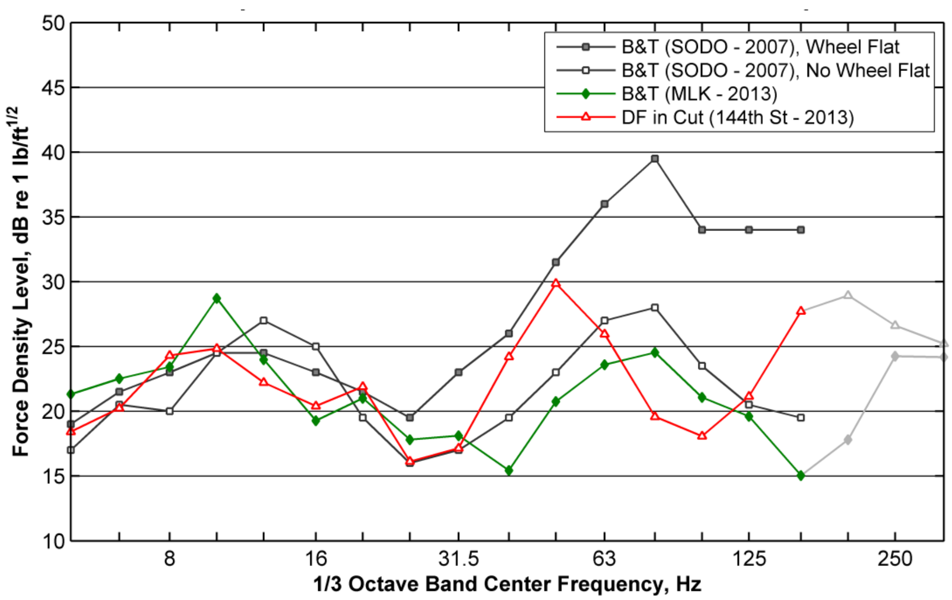

Figure 5: Comparison of Measured FDL for ST LRVs at 25 mph

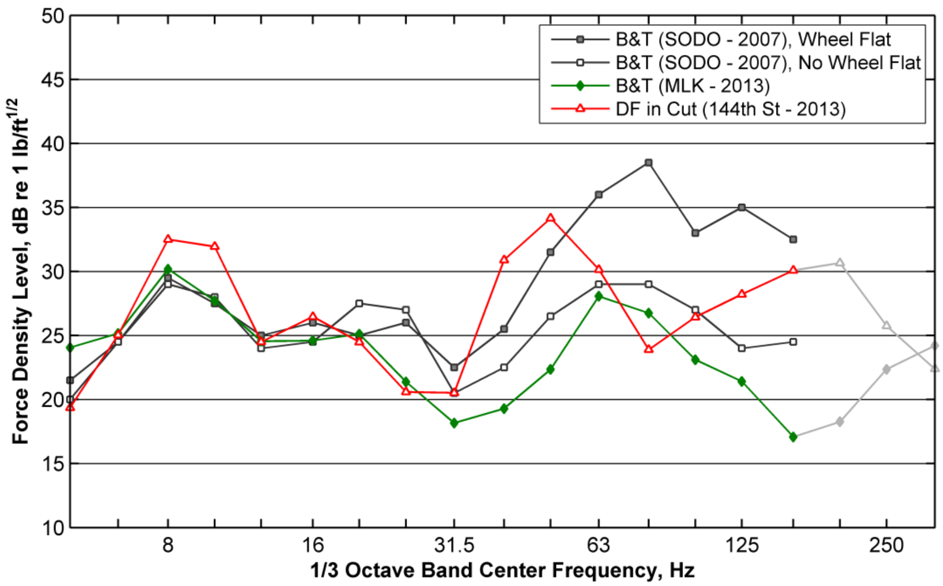

Figure 6: Comparison of FDL for ST LRVs at 35 mph

Effect of Train Length on Wayside Vibration Velocity Levels

The test train results for the 3-car train and for the 2-car revenue service trains were compared to determine whether there is an identifiable difference in vibration levels that could be attributed to the train length. Theoretically, vibration from a 3-car consist is 0.5 to 2 decibels higher than vibration from a 2-car consist. The average difference is expected to be in the range of 0 to 2 decibels with the difference close to zero at distances less than about 50 ft from the track and the difference increasing to a maximum of about 2 decibels at a distance of approximately 300 ft from the tracks.

The differences between 3-car and 2-car trains at different speeds were averaged for each measurement position. The average differences for DF tracks (Site 1) are shown in Figure 7. In Figure 7 the sections of difference spectra that are questionable because of interference from background vibration are shown in gray. Similarly the differences for the B&T tracks (Site 3) are shown in Figure 8. The comparison for Site 3 is somewhat limited because there were only two runs with the test train that could be directly compared to two revenue service measurements. However, each measurement was at seven distances from the track.

The DF track results suggest that the average difference is frequency dependent and is close to zero in the mid-frequency range (around 40 Hz), and greater than zero at higher and lower frequencies (Figure 7). In contrast, the results at the B&T tracks suggest that the difference randomly fluctuates around zero (Figure 8). Our conclusion is that although there were some differences between the 2-car and 3-car consists, the differences were not consistent. In the absence of a detailed dataset for the difference between 2-car and 3-car consists for a given transit system, applying the theoretical effect of length is a reasonable approach.

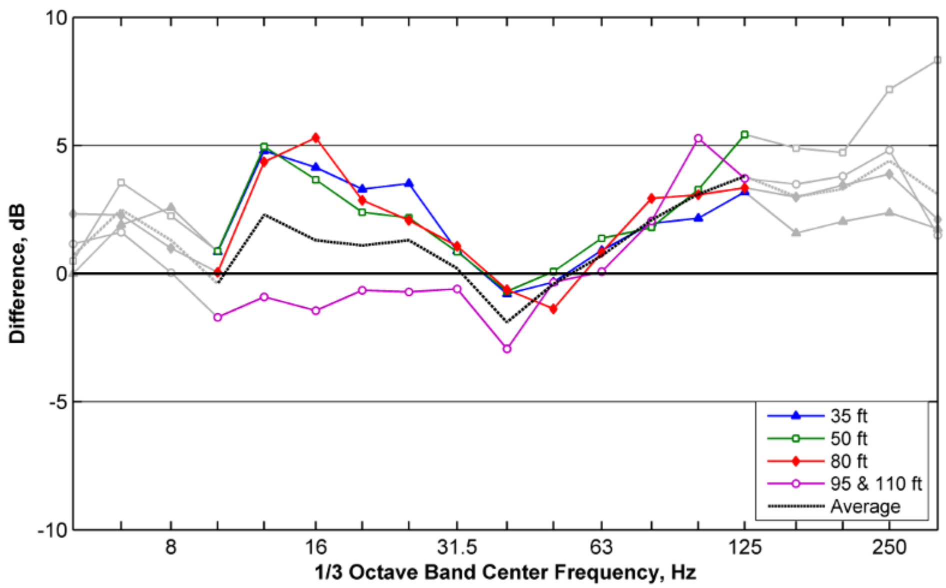

Figure 7: Comparison of Train Length, 3-Car Train Minus 2-Car Train on DF Tracks

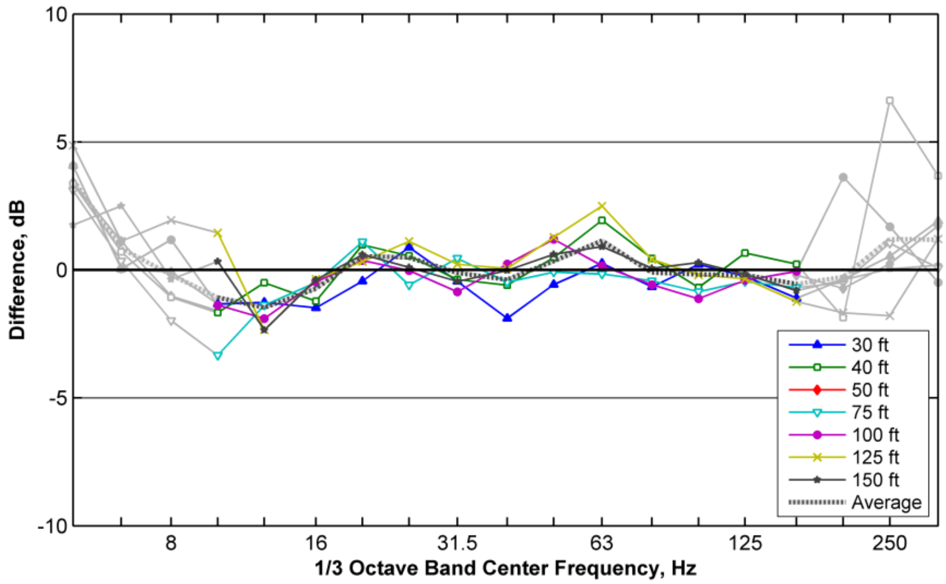

Figure 8: Comparison of Train Length, 3-Car Train Minus 2-Car Train on B&T Tracks

Speed Dependency of FDL

The speed dependencies at different frequency ranges from Site 1 and 3 are shown in Figure 9 and Figure 10. In general, the groundborne vibration varies little with speed at higher frequencies. Below 25 Hz, the DF tracks showed $20\times\log_{10}$(speed) dependence. Similarly, the speed dependence at the B&T test site had a greater speed dependence below 100 Hz. However, as shown in the FDL curves, there was no apparent shift in the peak frequency with speed illustrating the complexity in teasing out the attributes that control FDL peaks. A general conclusion from the speed study shows that the $20\times\log_{10}$(speed) relationship is reasonable to estimate the overall vibration levels for both DF and B&T tracks. However, for a detailed vibration impact assessment the FDL spectra at various speeds for a given track and vehicle type should be used for the predictions.

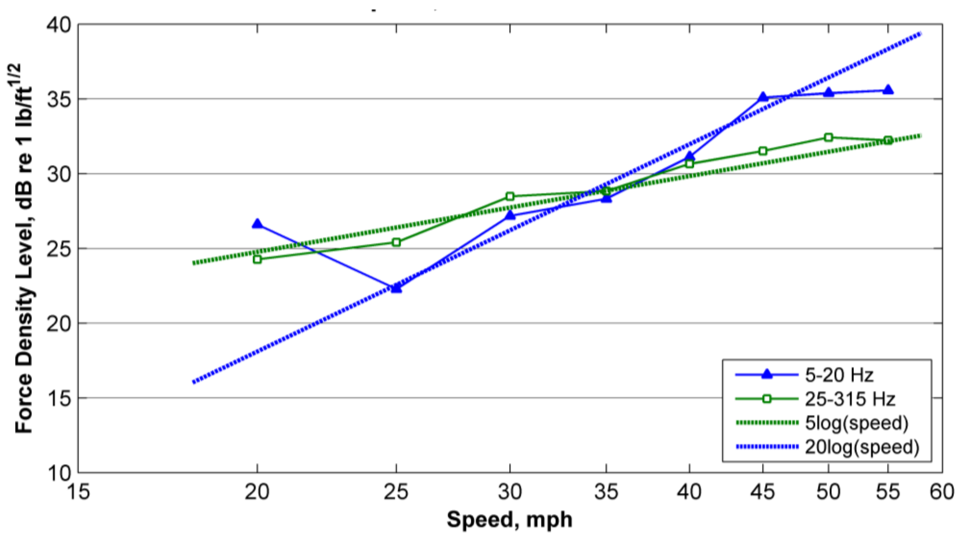

Figure 9: FDL Versus Speed on Direct Fixation Track

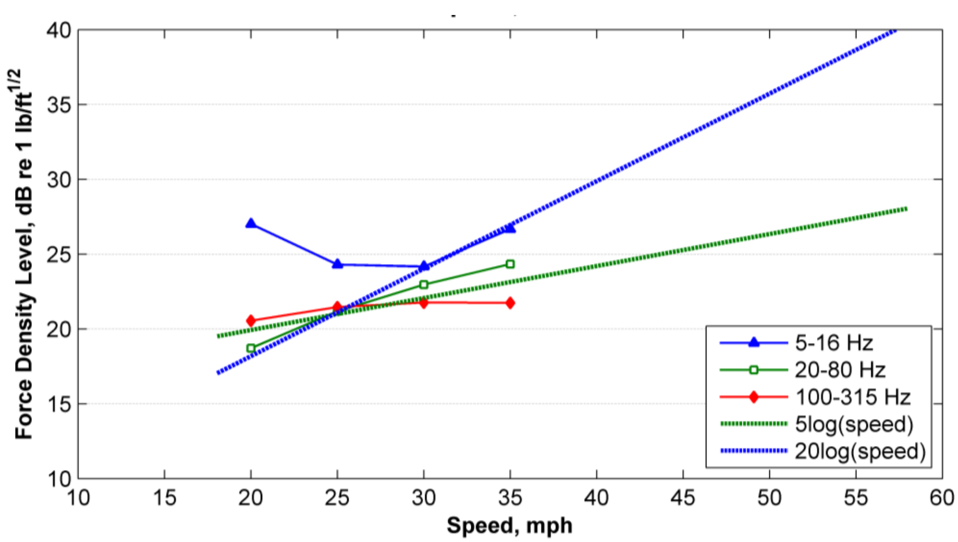

Figure 10: FDL Versus Speed on Ballast and Tie Track

Rail Roughness and FDL

The average roughness results for each measurement position at the three sites on the ST Central Link corridor are shown in Figure 11. At wavelengths shorter than about 400 mm (16 inches), the measured roughness is below the ISO 3095 limit or only a few decibels greater than the limit. However, at wavelengths longer than 400 mm the curves tend to be approximately 10 decibels above the ISO 3095 limit. At a speed of 55 mph, roughness wavelengths longer than 400 mm correspond to vibration frequencies below 60 Hz.

In addition, the detailed spectral plots of roughness show that there is often a peak around 800 mm and a broad peak around 1600 mm. An example of the detailed spectral plots of roughness is shown for the right and left northbound rails at the DF tracks in cut (Site 1) in

Figure 12. At 55 mph these wavelengths correspond to frequencies around 30 Hz and 15 Hz respectively. At 20 mph, the 800 mm wavelength would correspond to approximately 10 Hz.

Figure 11 also compares the average roughness with roughness measurements on an European rail system (*17*). For wavelengths shorter than 200 mm the before grinding roughness is generally similar to the ST rail roughness. The roughness data only extends to wavelengths of 500 mm. However, at wavelengths longer than 200 mm, the before-grinding roughness tends to be less. The after grinding roughness is substantially lower over the full range of 50 to 500 mm.

For each rail roughness test there was a minimum of two measurements with four measurements performed for most rails. Review of the raw displacement data from the measurements showed that in some cases there was substantial variation between the runs. It is not evident what caused this variation. However, a recent presentation indicated that the instrument used for the roughness measurements is capable of providing accurate measurements at wavelengths up to at least 1000 mm (*18*). We are planning to perform further studies to confirm the validity of the longer wavelength roughness data.

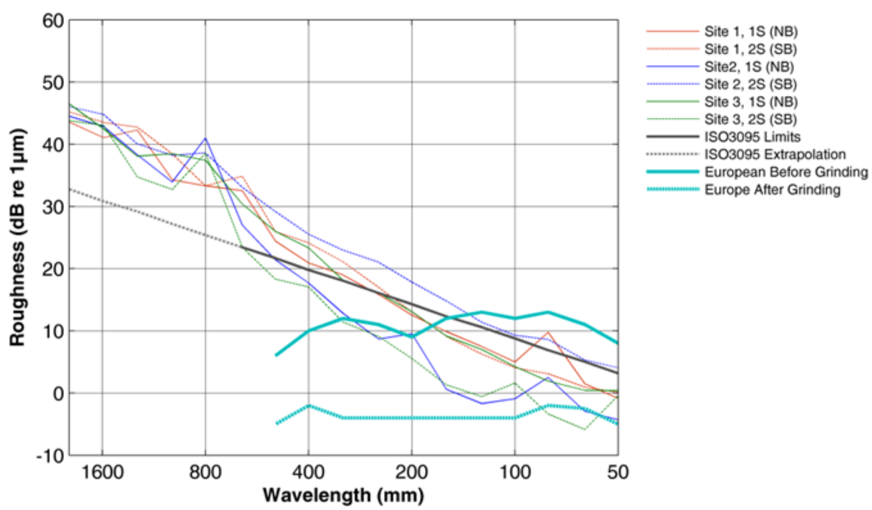

Figure 11: ST Average Rail Roughness Measurements

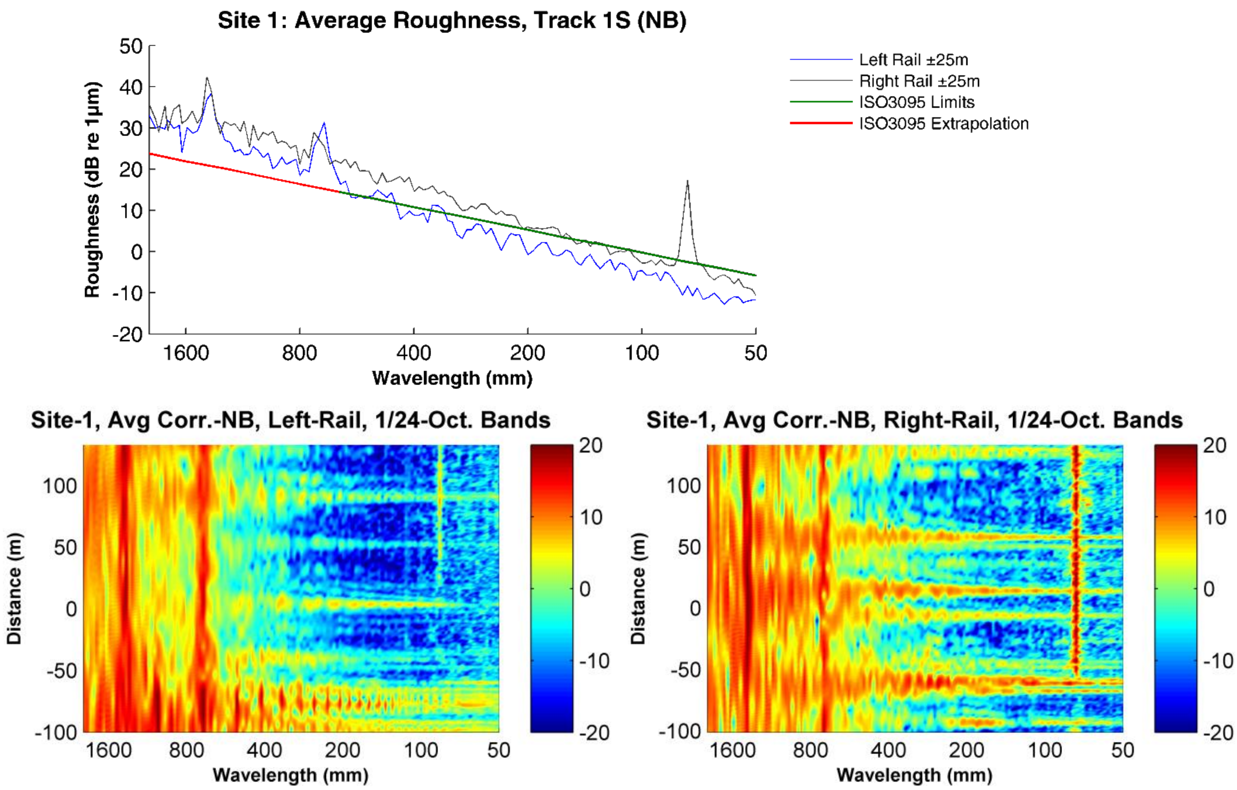

Figure 12: DF Track in Cut (Site 1), Average 1/24 Octave Band Rail Roughness, Track 1S
(The roughness 3-D plots in the above figure are normalized to the ISO 3095 standards. Dark red indicates very high roughness and blue indicates lower roughness than the ISO limits.)

CONCLUSIONS

The following are the conclusions of this study:

- The FDLs for Sound Transit light rail vehicles from the 2013 study agree reasonably well with the FDL results for the No Flat Wheel condition from the 2007 studies. This indicates that ST's maintenance program is keeping the wheel in good condition and avoiding wheel flats that could substantially increase groundborne vibration below 125 Hz. Applying the FDLs based on the current fleet for predicting vibration from future ST project would result in more accurate vibration impact assessment.
- As anticipated, the speed relationship of FDL is complicated and could use more study to enhance the understanding.
- The differences between 2-car and 3-car consist were small and were not always distinguishable.
- The FDL for the two direct fixation track sites are comparable and tend to validate the assumption that FDL is largely independent of the ground conditions.
- Rail roughness test results indicate that there is potential for reducing vibration from the trains if the rails roughness is reduced at wavelengths longer than 400 mm (16 inches). Although the validity of the roughness results needs to be verified, European studies support the conclusion that control of rail roughness could be an effective vibration mitigation tool.

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