Issues in developing accurate groundborne vibration predictions for high-speed rail projects

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Some of the key issues in developing accurate predictions for groundborne vibrations from high speed rail projects are related to the effect of high speeds on force density, the rail roughness, and the availability of limited data for train vibration at very high speeds. The adjustment factor for speeds based on the FRA manual is a $20 \log(\text{speed})$ relationship that is applied across the frequency spectrum. Experience is that this relation has a tendency to exaggerate the effects of speed, especially when the speeds will vary over a wide range as is the case for the proposed California High Speed Rail Project (CAHSR). Another important factor could be relatively long wavelength “undulations” in the rail. At typical rail transit speeds (e.g. less than 60 mph), these undulation will generate vibration energy at frequencies below the range important for ground vibration (e.g., less than 10 to 15 Hz). However, when speeds exceed 120 mph, the frequency of the vibration generated by these undulations will increase and could move into the range important for ground vibration. For example, rail undulations at wavelengths of 3 to 20 ft will generate vibration at 2.6 to 17 Hz at 35 mph, which is usually low enough to not to be a problem. However, a true high-speed rail system will exceed 200 mph. At 200 mph, the frequency range changes to 15 to 100 Hz, which encompasses the frequency range that typical soils are most efficient at transmitting vibration. The lack of existing vibration data from high speeds trains is an important issue for proposed high-speed rail projects. This paper addresses these issues based on the vibration testing and analysis performed for two sections of the CAHSR and our experiences on other recent rail studies.

1 INTRODUCTION

Prediction of ground-borne vibration for high speed rail projects in the US is based on the Federal Railroad Administration (FRA) Final Report on high speed rails\textsuperscript{1}. The vibration impact assessment procedures for high speed trains were presented by Hanson and Saurenman\textsuperscript{2}. The prediction procedure and the vibration impact assessment is similar to the detailed prediction procedures that are given in the Federal Transit Administration (FTA) Guidance Manual\textsuperscript{3} that were originally defined by Nelson and Saurenman\textsuperscript{4}. The procedure is entirely analytical and is based on the assumption that the vibration forces generated by a steel-wheel train traveling on

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steel rails are largely independent of the local geologic conditions. The fundamental relationship for the prediction procedure is:

\[ L_v = LSTM + FDL \] (1)

where \( L_v \) is the vibration velocity level at the ground surface, \( LSTM \) is the line source transfer mobility between the tracks and the receiver position, and \( FDL \) is the force density level.

Tests have shown that the procedure is reasonably accurate assuming that the FDL being used is representative of the future rail traffic and that the LSTM is representative of the receiver position. The FDL to be used for predicting vibration levels from high speed train projects in the US is provided in the FRA Report\(^1\) based on the measurements performed by Saurenman\(^5\). The FDL data was based on measurements performed at various high speed train systems in Europe and the difference in the overall force levels were greater than 5 VdB. It is noteworthy that information on the sub-surface dynamic properties and the condition of the wheel-rail interface during the measurements is not available.

Accurate vibration predictions for the California high speed rail (CAHSR) project using the FRA procedure requires choosing the appropriate FDL and adjusting for variations in operation parameters such as speed and the track conditions such as rail roughness. This paper focuses on the adjustment factors used for speed and the influence of rail roughness on dynamic forces at high speeds.

### 2 BACKGROUND

A number of studies are available on the topic of ground vibration from high speed trains for existing systems in Europe and Japan\(^6-11\). The analytical models and measurements of high speed trains suggest that determining the source of vibration excitation from high speed train traffic is a complex phenomenon. This section discusses a few of the papers on vibration predictions to show some of the key factors that influence the FDL and the ground vibration.

Madshus and Kaynia\(^6\) studied the track-embankment-soil response and vibration generation from high speed train passbys on soft ground. Their studies showed that the force density of high speed trains is similar to normal trains except at speeds approaching the critical speeds. The train speed at which the dynamic response is expected to reach the maximum is called the critical speed. The critical speeds are dependent on the train type, track conditions and the soil characteristics. Train vibration measurements at a track section in Ledsgard, Sweden, showed that for soft soils the critical speed was 145 mph\(^6\). The vibration levels started increasing steeply above 124 mph and peaked at 145 mph. At speeds higher than 145 mph the vibration amplitudes decreased. They concluded that the dynamic properties dominate at high speeds in the far-field and for soft soils there is an amplification of the vibration amplitude from the dynamic component at high speeds.

Lombaert and Degrande studied the ground-borne vibration from the static and dynamic axle loads of high speed trains\(^11\). Their studies showed that the quasi-static tie passage contribution dominates the track response and the dynamic contribution dominates the far-field response. In the same study predicted and measured vibrations in the far-field showed only a moderate increase with increasing train speeds. Because the soil was stiff at the measurement locations the trains did not approach the critical speed even at 220 mph.
Auersch\textsuperscript{10} studied the excitation force from high speed trains, including the measurements performed for the FRA Report\textsuperscript{1,5} and concluded that the vibration from the high speed trains on high speed tracks showed amplification around 12 and 50 Hz similar to regular transit trains on normal soils. Based on the recent studies\textsuperscript{6-11} the key sources of dynamic loads that contribute to the vibration force spectra are the imperfect track alignment at low frequencies and the rail roughness at high frequencies. In addition the track is also excited at the tie passage frequency.

In summary the excitation occurs due to static and dynamic loads between the wheels and the rail. The static loads influence three different frequency range: 1) the regular static part at very low frequencies and are not relevant in the far-field 2) the irregular static part at the mid frequencies caused by the scattering of the axle impulses by a randomly varying soil and 3) the regular dynamic part at high frequencies caused by the variations in track modulus between the ties that periodically varies as a train passes. The dynamic loads are caused by the wheel roughness, rail roughness, track modulus, vehicle dynamics and the train speeds. For high speed trains, in addition to the above mentioned dynamic loads, there is also amplification of amplitude associated with the critical speed controlled by the soil stiffness.

This paper looks into the following factors for high speed train:

- Train speed: It is generally assumed that FDL is increases with train speed at a rate of 15 to 20 log(speed). The true speed dependencies of FDL and the frequencies of various excitation sources are very complicated and can vary considerably between systems.
- Soil conditions: A fundamental assumption is that the FDL is independent of soil. This appears to be a reasonable assumption at least to the first order. Random variation of soil properties under the tracks has been identified as a potential source of dynamic forces that transmits energy to the far field. The stiffness of the soil is a key parameter to determine the critical speeds for the trains and should be factored in the vibration predictions at high speeds.
- Rail roughness: Rail roughness with wavelengths greater than 2 inches can result in dynamic excitation at frequencies in the ground vibration range. For example, a roughness or corrugation with a 3 to 20 ft wavelength which is not a problem at normal train speeds will generate vibration in the 32 to 107 Hz range at 200 mph. Also, any irregularities in the rail, such as a bad weld, will tend to generate vibration over a broad frequency range.

### 3 Force Density for High Speed Trains

The force density level for high speed train projects in the US is based on the vibration measurements shown in Fig. 1 through Fig. 3. Fig. 1 shows the measured vibration velocity for three high speed trains in Europe: TGV in France, X2000 in Switzerland and Pendolino in Italy. The LSTM from the vibration measurement sites are shown in Fig. 2. Although the LSTM is so different between the three sites the normalized FDL shown in Fig. 4 is almost similar. It is noteworthy that the FDL is normalized for speed using an adjustment 20*log(speed). The Pendolino FDL is the recommended FDL for the CAHSR vibration predictions because the vehicle would be similar to the Pendolino system.
3.1 Speed Dependence of High Speed FDL

The FRA manual recommended 20$log(speed)$ speed adjustment for force from trains. However recent experiences in the US and Europe\textsuperscript{11,12} show that the true speed dependencies vary between 10 to 15 \textit{log(speed)} for most train speeds. The measured vibration for the Thayls high speed train system over a speed range of 135 to 200 mph is shown in Fig. 5. The train was operating at sub-critical speeds and based on this data the train vibration changed at the rate of 12$log(speed)$. Therefore it is pertinent to revisit the reference FDL for high speed trains provided in the FRA Report. A key question is if the normalized FDL at 150 mph should be used. Based on the discussion above it seems appropriate to use the FDL at the measured speed and apply the speed adjustment of 12 to 15$log(speed)$ rather than using the FDL normalized to 150 mph in the FRA Report as the starting point. The potential effects of using 20$log(speed)$ as a speed adjustment factor for vibration prediction is illustrated in Fig. 6. An overall vibration of 70 VdB at 120 mph was used as the starting point. Assuming that 12$log(speed)$ is the actual variation with speed, applying the FRA adjustment factor would over-predict vibration impact by 2 dB at 220 mph and under-predict by 2.5 dB at 60 mph. The results of the incorrect predictions are discussed in the next section for a section of the proposed CAHSR.

3.2 Effect of Speed for the CAHSR Project

The speed profile of the proposed CAHSR are projected to vary between 60 and 220 mph. In the Southern California the projected speed profile varies between 60 mph and 125 mph and in the Central Valley the speeds are projected to approach 125 mph. To illustrate the effect of speed a section of the CAHSR corridor was analyzed for vibration impacts using a fictitious speed of 60 mph and the results are presented in Table 1. The table shows that the total number of vibration impacts could be under-predicted by 40% with the used of 20$log(speed)$. Similarly for sections in the Central Valley it would be critical to not over-predict the vibration impacts.

3.3 Soil Characteristics for the CAHSR Project

Another key parameter that needs to be evaluated for the high speed rail projects is the soil behavior. The ground sub-surface in the Southern California region is typically stiff and the proposed maximum speeds are 125 mph. Therefore it is unlikely for the train speeds to match the shear wave speeds of the soil for this section.

The soil sub-surface in the Central Valley is less stiff and at speeds of 220 mph there is a potential for the trains to approach the critical speed. This could result in higher vibration at greater distances from the track. A study of the shear wave speeds of the sub-surface will provide a better understanding of the vibration propagation at high speeds. Therefore it seems that for the accurate prediction of vibration impacts from the high speed trains evaluation of the soil shear wave speeds is critical.

4 RAIL ROUGHNESS AND HIGH SPEED TRAIN VIBRATION

Rail roughness is another important parameter that needs to carefully analyzed for any new train project. Some of the issues related to rail roughness are more important for high speed train projects than normal speed train projects.
Measured Amtrak FDL at 75 mph along a potential shared track alternative for CAHSR is presented in Fig. 7. The measurements were performed at three track sections located within 3 miles. The results show that the FDL varies by up to 5 VdB at 40 Hz and 10 VdB at 125 Hz. The variation in the FDL data seems to be caused by rail roughness variations along the track. At higher speeds these variations would be amplified and the frequencies potentially shifted. This data highlights the need for understanding the rail roughness issues and factoring it in the predictions.

5 CONCLUSIONS

This paper discussed the key issues related to predicting vibration for the CAHSR project. The recommendations from this study are:

- The CAHSR vibration predictions should use the Pendolino FDL data at 120 mph as the starting reference FDL and avoid using the FDL normalized to 150 mph in the FRA Report.
- For speed adjustments a $15\log_{10}(\text{speed})$ relationship would be most appropriate. Use of $20\log_{10}(\text{speed})$ should be avoided as it tends to over-predict impacts at high speeds and under-predict impacts at lower speeds.
- The shear wave speeds of the sub-surface is essential for the CAHSR project to ensure accurate prediction of vibration effects at the critical speed.
- Where there are shared track alternatives, it would be pertinent to study the effects of rail roughness and factor it into the vibration predictions.

6 REFERENCES


Table 1- Number of Impacts versus Speed Adjustment Factors for a CAHSR Section

<table>
<thead>
<tr>
<th>Speed Adjustment Factor</th>
<th>Number of Vibration Impacts</th>
<th>Single-Family Residences</th>
<th>Multi-Family Residences</th>
<th>Total</th>
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<tr>
<td>20\log\text{speed}</td>
<td>38</td>
<td>78</td>
<td>116</td>
<td></td>
</tr>
<tr>
<td>10\log\text{speed}</td>
<td>88</td>
<td>101</td>
<td>189</td>
<td></td>
</tr>
</tbody>
</table>

(Note: The data present in this table are just an illustration and not actual data)

Fig. 1 – Measured Vibration Velocity for Three High Speed Trains in Europe

1.5
Fig. 2 – Measured LSTM at the High Speed Vibration Measurement Sites\textsuperscript{1,5}

Fig. 3 – High Speed Train FDL from the FRA Report\textsuperscript{1,5}
Fig. 4 – High Speed Train FDL Normalized to 150 mph

Fig. 5 – Measured Peak RMS Vibration Velocity for Thalys High Speed Rail
Fig. 6 – Speed Adjustments for Vibration Predictions

Fig. 7 – Measured FDL for Amtrak at Three Different Sites Along the Proposed CAHSR Corridor