PREDICTION OF NOISE & VIBRATION IMPACTS DUE TO THE OPERATION OF TEMPORARY CONSTRUCTION RAILWAYS DURING TUNNELLING WORKS
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Abstract

SRL was recently required to predict the impact of a proposed Temporary Construction Railway (TCR) for the Crossrail project to meet stringent noise and vibration criteria whilst minimising costly acoustic mitigation.

Initially we adopted traditional methodologies to predict the vibration level within buildings above. Unfortunately we have no source (tunnel wall) vibration data for this specific combination of train, track type and tunnel. We used data from “similar” situations but there was significant uncertainty surrounding this data.

We therefore used the Pipe-in-Pipe prediction software (developed by Dr Mohammed Hussein and Dr Hugh Hunt) where you input the physical data for the train, track and tunnel and it predicts the vibration “from scratch”. Unfortunately, this method assumes continuous weld rail and not jointed track and the criteria was in terms of $L_{max}$.

Though each prediction method had a significant shortcoming; comparing the two sets of results gave us more confidence in our findings.

Both methodologies pointed to vibration being significantly below the threshold of feeling in all locations, but ground borne noise was predicted to be a potential issue in certain buildings.

We “calibrated” the prediction models using measurements we took of the operational TCR simultaneously on the tunnel wall and on the surface. Perhaps unsurprisingly, our measurements strongly indicated that the traditional method (using the actual tunnel wall levels) was more accurate than the Pipe in Pipe model for this particular circumstance (ie with jointed track).

To date, our client Dragados Sisk JV has bored nearly 20 km of the Eastern tunnels (Contract C305) below thousands of homes, schools and other noise sensitive locations with only one meaningful complaint from a resident located directly above the tunnel. This is a very good indication that our prediction of the temporary construction railway noise and vibration impact is robust.
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1. Introduction

Following lessons learned on the Channel Tunnel Rail Link (or HS1) project, where residents raised issues about noise from the Temporary Construction Railway (TCR), stringent acoustic criteria were placed on the Crossrail project. These undertakings were passed on to the tunnelling contractors. A requirement was written into their contracts not only to “ensure compliance with the requirements”, but also to demonstrate this would be the case before they started tunnelling under any noise sensitive properties.

Dragados Sisk JV, who had secured the contract to bore the longest section of tunnels (the “Eastern Tunnels” - from Farringdon Station to Custom House and Stratford, see figure 1.1 below), appointed SRL to provide this service.

**Figure 1.1 - Eastern Section of the Crossrail Route**

Amongst other aspects of noise and vibration control on the project, we were instructed to provide the two documents required by Crossrail in relation to vibration generated by the TCR, namely:

- Prediction Methodology report and
- “Demonstration Report” containing our predicted noise and vibration levels along the route.

A key factor of the Demonstration Report, was the inclusion of *actual measurement data* in order to calibrate and validate our Prediction Methodology.
The TCR, which carries people and materials (such as the tunnel lining segments) to the Tunnel Boring Machine (TBM), is as the name suggests, a temporary structure. It must be removed at the end of the tunnelling process to make way for the permanent railway (which will be laid onto a high performance isolated track slab).

It would be a time consuming and costly exercise to weld all the sections of track together, especially bearing in mind that some sections will only be used for a few weeks. It would be even less practicable, both in terms of time and cost, to implement the measures usually adopted to control vibration from permanent railways, such as the aforementioned isolated slab or even ballast on ballast mat.

Recommendations were included in the Tunneller’s contract by way of an “Informative”, which were based on the assumptions used for the Environmental Statement for the project, including:

- the use of smooth track (new rail without corrugations or discrete irregularities)
- controlling joints so that the heights of adjacent rails differ by no more than 2mm
- the use of resilient pads in the track where appropriate
- a TCR train speed limit of 15km/h
- soft suspension to the locomotive and rolling stock
- a maintenance programme to stop the track deteriorating over time.

The Eastern Tunnel route passes directly under the Barbican Estate (which in addition to large numbers of residential properties, includes a Concert Hall, Theatre and Cinemas), so onerous noise and vibration conditions were placed on the operation of the TCR, especially during performances within the Concert Hall. Additional requirements included reducing the train speed to 5 km/h and installing enhanced track isolation systems.
2. Prediction Methodology

The objective of our work was to predict vibration (and ground-borne noise) levels within sensitive buildings along the route of the tunnel.

The simplest form of the calculation is:

\[ R = S + T \]

where:
- \( R \) is the level at the Receiver or Receptor
- \( S \) is the source level
- \( T \) is the transfer function between source and receptor

The figure below shows a more detailed sequence showing the steps needed to calculate the vibration level in the building.

**Figure 2.1 - Key Steps from Train to Building**

- Step 1. Wheel/Rail Interaction
- Step 2. Track into tunnel wall
- Step 3. Tunnel wall into Ground
- Step 4. Through Ground to Surface
- Step 5. Losses from Ground to Foundations
- Step 6. Amplification due to Building Structure
- Resultant Vibration Level in Building

This gives the “feelable” vibration from which the ground-borne noise level in the building can be calculated from the vibration level in the structure.

In reality, the large number of variables and unknowns mean that accurate prediction is all but impossible. Our approach was therefore to try and keep things as simple as possible, using existing methods and models to calculate each step in the above chain.
2.1 Transfer Function

The transfer function is the “bit between the source and the receptor”.

Although the “receptor location” is normally fixed, in that it is pre-defined within the criterion, the “source level” can be measured anywhere between the actual device creating the noise and/or vibration right up to the receptor position:

Figure 2.1.1 - How to Define the Source Level

Our pragmatic approach to this problem started by taking what we already knew. Transportation Noise Reference Book (Nelson)\(^1\) contains comprehensive methods and data covering all the aspects needed for Steps 3 to 6 in Figure 2.1. So all we needed now was the vibration level in the tunnel wall.

As we had no data ourselves for anything like the particular train/track/tunnel configuration being proposed, our options were to:

a) measure the same train in a similar tunnel elsewhere
b) calculate the level using Steps 1 & 2
c) find reliable vibration data for this particular train/track/tunnel configuration.

We were unable to locate a suitable TCR which was operating at the time (a), so we searched existing literature (and the internet) for tunnel wall vibration levels (c). The information we found varied significantly, and the actual parameters for each situation were generally not stated. The train speed was always given but most of the other factors (about the train, track, tunnel and the measurement location, etc) were not.

So we had a method for predicting building vibration levels based on tunnel wall vibration levels but no “source” data that we could rely on.
Accon Ltd (the acoustic consultant working for the Western tunnels) introduced us to a prediction model which was being developed by Dr Mohammed Hussein and Dr Hugh Hunt, called Pipe-in-Pipe. This software predicts the surface vibration “from scratch” based on the physical data for the train, track and tunnel (ie steps 1 to 4 in Figure 2.1). It also allows for isolation so we could estimate the effects of isolating the basic trackform (which was steel rail laid on simple steel sleepers straight onto the tunnel invert).

One drawback was that Pipe-in-Pipe is based on continuous weld rail and not jointed track. Obviously, we expected the wheels running over the joints to be the cause of the highest vibration levels. The ground-borne noise criteria for the project was in terms of $L_{max}$, so it would almost certainly be the joints which were the key factor.

We now had two prediction methodologies which between them covered all Steps 1 – 6 in Figure 2.1, yet each one had a significant shortcoming:

- for our original model we had no reliable source data
- the Pipe-in-Pipe software didn’t allow for jointed track.

From this, we developed a pragmatic approach (agreed by Crossrail’s Noise & Vibration Manager), which was a combination of prediction and measurement:

- Use both methodologies to establish a likely range of vibration levels.
- Provide our results for a number of agreed buildings to enable Crossrail to compare them against predictions by Arup Acoustics Ltd (who designed the operational railway).
- Take measurements at the earliest opportunity to compare with our predictions.
- The TCR would be operating before we could take any validation measurements and due to the high degree of uncertainty at this early stage, we agreed it was better to be safe than sorry in relation to all the noise sensitive properties located above.
- Use our measured data to modify our prediction model(s) if required.
- The track was designed such that the solid and isolated sleepers were interchangeable. This meant that if there were any problems with the solid sleepers, they could be upgraded retrospectively, see section 3.
3. Track Design

The solid and isolated sleepers were designed such that the rails were exactly the same height. This was to enable the sleepers to be upgraded if required.

**Figure 3.1 - Solid Steel Sleeper (“Track A”)**

![Solid Steel Sleeper Diagram](image1)

**Figure 3.2 - Isolated Steel Sleeper (“Track B”)**

![Isolated Steel Sleeper Diagram](image2)
4. Validating the Prediction Methodology

The objective was to get sufficient data to give us confidence in our approach, rather than necessarily fully validating every part of the model with large quantities of measurement data. The general approach was to measure at 3 points in the chain, see figure 4.1.

Figure 4.1 - Validation Survey Measurement Locations

Gathering sufficient data posed a significant challenge, dealing with matters such as:

- gaining access to the tunnels
- finding suitable surface locations which are both accessible and have low background vibration levels
- finding suitable buildings to measure in (without inadvertently making the occupants more sensitive to any noise or vibration)
- even the “Sod’s Law” aspects such as trains aren’t running on the planned day of the survey
- the financial budget and timescales constraints.
5. Tunnel to Surface Measurements

The first survey was designed to validate the prediction methodology between the tunnel wall and the surface. We measured a number of temporary construction train pass-by's during the quietest time of the day (i.e. between 23:00h and 03:00h) along a section of tunnel which contained un-isolated track. Measurements were taken simultaneously on the tunnel wall and at the surface location shown on the figure below. The black lines indicate the approximate route of the west bound tunnel where the trains were running.

**Figure 5.1 - Site Location of Providence Wharf Survey**

The train operating on the night of the survey comprised a Personnel Car and 2 flat cars being pulled by a Schoma CHL-200 loco (total length 35.3 m). No tunnel lining segments were being transported during this survey.
5.1. Train Speed Measurements

The speed of each train pass was measured using two light beams set up 50m apart. Two pairs of photo sensors were positioned to beam across the tunnel, attached to the walkway and on the opposite wall. The sensors (senders and receivers) fed back a signal to the measuring instrument when the beam was interrupted by the train.

**Figure 5.1.1 - Light Beam Sensors set up to Measure Train Speed**
5.2. In-tunnel Measurements

The accelerometer was fixed perpendicular to the tunnel wall half way up the tunnel (i.e. at “3 o’clock”) and the graph below shows a typical trace. The “spikes” correspond to wheels going over joints in the track.

**Graph 5.2.1 - In-tunnel Vibration Level vs Time of a Typical Train Pass-by**

The graph below shows the frequency content of the tunnel wall vibration (root mean square acceleration) of the 10 train pass-bys measured during the survey.

**Graph 5.2.2 - In-tunnel RMS Vibration Level (dB) vs Frequency of 10 Train Pass-bys**

The solid lines are trains travelling one way and the dotted lines are the return journey which, as can be seen from the graph, are all slightly but noticeably lower than the outward journeys (by 2-3dB above 100Hz). Speed was not the factor, and the trains were similarly loaded in both directions, so the most logical conclusion was that the difference was due to engine of the outward train having to work harder uphill, whereas it coasts downhill on its return.
5.3. Surface Vibration Measurements

The surface measurement was at a similar chainage to the in tunnel measurement. Despite the levels being very low, we got three 'clean' readings. Graph 5.3.1 below shows other sources were present and could easily be mistaken for TCR pass-by’s. The TCR is the first event (up to around 50 seconds) whereas the next event (between 60 s and 70s) was actually a DLR train. We could confidently determine this by playing the recorded WAV file of the vibration through a sub-woofer. You could hear the “clunk, clunk, clunk” of the TCR whereas the DLR train was a much higher frequency whining noise.

Graph 5.3.1 - Surface Vibration Level vs Time of a Typical TCR Pass-by

Graph 5.3.2 below shows the frequency content of the 3 ‘clean’ surface measurements. Also included is the background level, measured during periods when no TCR trains were running. This shows that we were able to measure significant vibration between 31.5 - 200 Hz.

Graph 5.3.2 - Surface Vibration Level (dB) vs Frequency of 3 Train Pass-by’s

The peak at around 16Hz (or 960rpm), was also present in the “background” vibration. This strongly indicated that this was not therefore due to the trains. The survey location was around 60m from one of the Blackwell tunnel vent shafts and so it is very likely that the ventilation fans are the cause of this peak. We therefore ignored the data below 31.5Hz in our assessment. In any case, they would have no effect on humans as vibration at these frequencies and levels cannot be heard (as ground-borne noise) and are well below the threshold of feeling.
5.4. Testing the Prediction Methodologies

Pipe In Pipe Method

The graph below shows the Pipe in Pipe prediction (based on “poor track condition”) versus an actual measurement. This indicated that, though the prediction is reasonably accurate in the mid frequency range, this method seemed to be overestimating the level at 160Hz and above. And it is this frequency range which has a significant effect on ground-borne noise level.

**Graph 5.4.1 - Pipe in Pipe Prediction vs Surface Measurement**

So we concluded that, although Pipe in Pipe had been a safe method for use in the early stages of the project, it was not necessarily ideal for the value engineering stage of our assessment.
Ungar and Bender Method

Next I looked at the methodology which takes the tunnel wall rms vibration levels and predicts the surface rms level by deducting the losses due to geometric spreading and dissipation through the soil (ie material damping). This shows a much better correlation at frequencies above 125Hz.

Graph 5.4.2 - Ungar & Bender Prediction Methodology vs Measurement

As stated earlier, the vibration levels are well below the threshold of feeling so the most important issue is ground-borne noise. The difference in ground-borne noise between the measured actual and predicted levels was no more than 2dBA for the 3 trains we were able to record.
6. Isolation Pad Performance

The object of this survey was to establish how effective the “Track B” design (see section 3) performed in terms of isolating train vibration. All trains were travelling at between 14 and 15 km/h during this survey.

Measurements were again taken halfway up the tunnel wall (i.e. at “3 o’clock”), perpendicular to the wall. One accelerometer was located at the mid point of a 70m section of Track B whilst the other was located around 50m from one end of this section of Track B.

The graphs below show the typical rms acceleration of a train pass-by. The blue line is the vibration level measured whilst the train was travelling on Track A and the red line is the level with the same train on Track B around 30 seconds later.

**Graph 6.1 - Typical RMS Acceleration (dB) of a Train Carrying Tunnel Lining Segments**

![Graph 6.1](image)

**Graph 6.2 - Typical RMS Acceleration (dB) of an Unloaded Train**

![Graph 6.2](image)
6.1. Testing the Pipe in Pipe Prediction Methodology

The graph below shows the measured isolation for 5 train pass-by’s (both as individual events and also the average) against the prediction by Pipe in Pipe.

**Graph 6.1.1 - Measured Insertion Gain of 5 Train Events vs the Prediction**

![Graph showing measured and predicted insertion gains](image)

There are definite similarities, in that you can see peaks at 31.5Hz and 250Hz in both the actual and prediction. But there is also a significant difference: the actual performance exhibit a low frequency resonance (around 6.3Hz) which is not predicted by the Pipe in Pipe model. This is almost certainly due to the weight of the train (something not factored into the Pipe in Pipe model).

The “actual” data exhibits the classic shape of a 2-degree of freedom system. This type of system has two masses supported on top of each other like this:

![Diagram of a 2-degree of freedom system](image)

In this situation, the upper mass \( m_2 \) is the body of the train, with the spring \( k_2 \) and damper \( c_2 \) representing the train’s suspension.

The lower mass \( m_1 \) is the bogie and rail, with the spring \( k_1 \) and damper \( c_1 \) representing the isolation pads.

The result in this situation was that the Track B isolation is performing significantly better (typically up to 10dB better) than was predicted in the critical frequency range of 40 - 250Hz. So once again, for the purposes of our initial assessment, Pipe in Pipe appeared to have been a safe method to use, but perhaps not for the value engineering stage of our assessment.
7. Ground-borne Noise (and Vibration) within Buildings

To date, we have had very limited opportunities to measure inside buildings along the route.

One of the main issues is finding suitable properties. To do this, we need to find someone willing to allow us into their building for a few hours, but what reason do we give to turn up with lots of “complex measuring equipment”? The last thing we want to do is potentially alert them to any low level noise which they then become more attuned to (and possibly annoyed by).

From our client’s (and Crossrail’s) perspective, the project is going well if no-one complains. And Dragados Sisk certainly have no reason to instruct us to take measurements as long as this is the case. We did manage to get into one property (around 35m from the tunnel) but the levels of noise and vibration were so low that the trains were undetectable by either our surveyor or our equipment due to the relatively high daytime background levels. Although this was disappointing for us, it was seen as very positive by our client.

Since tunnelling began on the Eastern Tunnels in November 2012, our client has bored nearly 20 km of tunnels below thousands of homes, schools and other noise sensitive locations and there has been only one meaningful complaint.

This was from a resident located directly above the tunnel at one of its shallowest points (around 20m below the surface). We predicted ground-borne noise to be around $37\text{dBA} L_{A_{\text{max},s}}$ in this house and this was therefore within the $40\text{dBA}$ criterion. We acknowledged, however, that the train would almost certainly be audible as a low frequency rumble at this location. Unfortunately (for us), our client visited the property, found that it was audible and instructed their track laying team to replace the basic sleepers (“Track A”) with the isolated ones (“B”) in the immediate area. All this happened within 72 hours, before we had the chance to visit the property and take any measurements.

The occupants (and Crossrail) were very happy with our client’s swift resolution of the matter. It demonstrated both our client’s commitment to minimise disturbance and that the well-thought-out design (to have interchangeable sleepers) worked perfectly. We were disappointed, however, as a golden opportunity to further validate our method had been missed.

A few weeks later another person in the same area called the Crossrail Helpdesk to say that they “thought they could hear something occasionally but weren’t sure”. We predicted train noise to be very quiet (below $30\text{dBA}$) at this house but we took the opportunity to visit and take measurements anyway. As expected, the levels were very low and barely measurable. The best we got out of it was that our surveyor was certain they heard one train pass-by and measured the noise during this event. The good news was that analysis of this measurement strongly supported our prediction.

And although we don’t wish for any more complaints, we do hope that there will be further opportunities to gather more data before tunnelling finishes in the summer.
References


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