1 Ground-Borne Noise and Vibration from Rail Tunnels

1.1.1 This information note describes ground-borne noise and vibration from the operation of trains running in tunnels.

1.1.2 Best practice mitigation measures taken from recent projects in the UK are presented, demonstrating the ability to manage and control the effects ground-borne noise and vibration, hence limiting the impacts on the people and assets located in the vicinity of the infrastructure.

1.1.3 The information provided in this note has largely be adapted from the Impact of Tunnels in the UK report¹, written on behalf of High Speed 2 in 2013. Arup were one of the main authors of the noise and vibration sections of the report.

Noise and vibration

1.1.4 Ground-borne vibration created by train services can propagate through the ground to surrounding buildings where it may result in the vibration of floors, walls and ceilings; which could also be heard as a low frequency ‘rumbling’ sound (called ground-borne sound).

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1.1.6 The ground borne sound level is reported as $L_{pAS_{max}}$ in decibels, where:

- $L_p$ denotes the Sound Pressure Level
- $A$ denotes A-weighting, that represents the sensitivity of the human ear
- $S$ denotes Slow time response over 1 second
- $max$ denotes the maximum value during a single train pass-by.

¹ [http://assets.hs2.org.uk/sites/default/files/inserts/Impacts%20of%20tunnels%20in%20the%20UK.pdf](http://assets.hs2.org.uk/sites/default/files/inserts/Impacts%20of%20tunnels%20in%20the%20UK.pdf)
1.1.7 Airborne noise is usually assessed by considering the predicted levels during operation with the current noise levels. However for ground-borne sound, there are no relevant national or international standards setting criteria for the acceptable levels. The requirements are generally specified for each project and may identify specific buildings of types of buildings that have different requirements. The impact criteria in general use are set out in Table 1. These have been drawn from similar projects in the UK and Ireland (e.g. Crossrail, the Jubilee Line, DART Underground, Dublin Metro North and HS1). These projects assess ground-borne sound in terms of the absolute level of sound generated by a train passing by.

### Table 1 Ground-borne sound impact criteria for residential receptors with illustrative descriptions

<table>
<thead>
<tr>
<th>Impact classification</th>
<th>Ground-borne sound level $L_{PASmax}$</th>
<th>Description</th>
<th>Existing example (where there are similar levels of ground borne noise)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>&lt; 35</td>
<td>The passage of trains may be audible to particularly sensitive people during quiet periods of the day. Very unlikely to cause complaint</td>
<td>Recent rail tunnels such as Jubilee Line Extension and HS1</td>
</tr>
<tr>
<td>Low</td>
<td>35-39</td>
<td>The passage of trains may be audible particularly during quieter periods of the day such as evening or early morning. Level of annoyance is likely to be low with few complaints</td>
<td>Ground floor room 20-70 metres from London Underground Limited tunnel. Levels dependent on tunnel depth, ground-type and train speed</td>
</tr>
<tr>
<td>Medium</td>
<td>40-44</td>
<td>The passage of trains is likely to be audible regardless of the time of day. Levels likely to give rise to some annoyance during quieter periods of the day. There may be some complaints</td>
<td>Ground floor room 10-40 metres from London Underground Limited tunnel. Levels dependent on tunnel depth and ground-type</td>
</tr>
<tr>
<td>High</td>
<td>45-49</td>
<td>Noise from the passage of trains will tend to be prominent and give rise to annoyance regardless of time of day. It is likely that there will be some complaints</td>
<td>Directly above some atypical existing London Underground Limited lines (e.g. shallow tunnel with poor quality jointed rails)</td>
</tr>
<tr>
<td>Very high</td>
<td>&gt;49</td>
<td>During the passage of trains ground-borne noise will probably dominate above noise from other sources (road traffic etc.). Considerable annoyance likely throughout the day and night. There may be some sleep disturbance. Complaints very likely</td>
<td>Directly above some exceptional sections of existing London Underground lines (e.g. extremely shallow tunnel with very poor quality jointed rails)</td>
</tr>
</tbody>
</table>

1. The descriptions relate to the possible subjective impression of these levels of ground-borne noise as a result of the operation of a new railway.
2. The examples are made on the basis that LUL ground-borne noise is of a similar spectral character to that predicted for the passage of trains on tunnelled sections of HS2.
3. The examples for low and medium categories assume an underground railway of similar construction to the London Underground Central Line.
1.2 Factors affecting noise and vibration

Sources of noise and vibration

1.2.1 Once a railway is in operation, the passage of trains will generate vibration in the ground. The level of noise and vibration in neighboring buildings is dependent on the forces applied by the train to the rails and the attenuation between the rails and the buildings. This attenuation can be calculated and the level of mitigation can be designed to achieve acceptable levels of noise and vibration inside buildings.

1.2.2 See Figure 1.

![Figure 1 Transmission of noise and vibration from source to receptor](image-url)
1.3 Control of ground noise and vibration for major infrastructure projects

1.3.1 Over the last 20 years or so, tunnelled rail schemes have been successfully delivered and now operate with no ground-borne noise or vibration impact or a minimised level of impact.

1.3.2 Early rail tunnels caused significant levels of noise and vibration in properties above them. The main reasons were:

- Poor rail alignment: It was difficult to control the exact position of the top of the rail, resulting in additional variations of force between the wheel and the rail. Modern techniques ensure that the rail is positioned far more precisely during construction.
- Rolling stock suspension: The suspension design and operation of early trains meant that the whole mass of the locomotive / carriage or a significant part of the mass would contribute to the dynamic forces at the wheel / rail interface and hence increase ground-borne noise and vibration. Modern train suspension isolates much of the vehicle’s mass from the dynamic forces that cause ground-borne noise and vibration.
- Rail Joints: Originally the rails were made up from 60 feet long sections, connected together with fishplates. These joints produced the “clickety clack” noise heard from a surface railway and the additional impact as each wheel crossed the joint generated an impact force that was transmitted into the ground. Modern track is formed from continuous welded rail removing these impact forces.
- Poor track and wheel maintenance: Much of the noise and vibration generation occurs because of roughness in the rail head and wheel surface. Even though the rail may appear shiny and smooth, there are variations in level that impart additional forces. Modern monitoring equipment and rail and wheel grinding techniques are used to maintain both surfaces to a high standard to reduce the noise from roughness. A high standard of maintenance is also necessary to ensure passenger ride comfort at high speed. These measures reduce wear and tear as well as reducing ground-borne noise and vibration.
- Rigid track supports: The rails were rigidly fastened to sleepers which were supported on a relatively thin layer of ballast in the tunnel. Modern track includes rubber pads directly under the rails to help isolate the vibrations. The track itself is often separated from the tunnel lining to reduce the transmitted vibration.

Thanks to the improvements in track and rolling stock design, the impact of trains running in the newer tunnels, such as the Jubilee Line, is substantially better than from trains running in the older tunnels.

1.3.3 From a ground-borne noise and vibration perspective the differences are considerable and many of the noise generating sources found in old trains and tunnels either no longer exist in modern tunnels or simply cannot occur because of track geometry and train design.

Historical improvements in noise performance

1.3.4 The improvements in rail tunnel performance with time are shown in Figure 2. Since each tunnel affects a large number of properties, the value given is only approximate. The figure
shows the date of opening for each tunnel and the noise level in a building above it. (Points 1, 2 and 4 represent recent measurements taken for old tunnels.) The introduction of the Environmental Impact Assessment process in 1988 is shown by a blue line. Schemes designed after that date have a design aim of $L_{p\text{ASMax}}$ 40dB(A) or lower.

1.3.5 The information shows that the ground-borne noise from tunnels built more than 100 years ago is sufficiently loud to cause complaints (45-55 dB). More recent rail tunnels have achieved much lower noise levels where the use of mitigation has been justified. For the Docklands Light Railway, Jubilee Line Extension and High Speed 1 tunnels (points 12, 13, 14 and 15) the sound levels are negligible (<35dB).

Modern track

1.3.6 The following case studies show how modern track design has been incorporated into schemes to avoid significant effects on the occupiers of residential properties and other noise sensitive receptors located above tunnels.
CASE STUDY: Channel Tunnel Rail Link (CTRL) – Now HS1

**Scheme:** The Channel Tunnel Rail Link (CTRL) is the high-speed rail link between the Channel Tunnel and London. It is 108 km (68 miles) long and runs between St Pancras Station in London to the Channel Tunnel. CTRL carries international and domestic passenger services between 0530h and 2400h, and a growing number of high speed freight services during the day and night. The line was delivered in two sections. Section 1, with a line speed of 300km/h (188mph), runs mainly on the surface from the Channel Tunnel to the River Thames. Construction started in 1998 and operation commenced in September 2003. Section 2, with a line speed of 230km/h (144mph), runs from the River Thames to St Pancras and is primarily in tunnel. Construction started in 2001 and operation started in late 2007. CTRL was delivered on time and within budget. The project includes five ‘green tunnels’ and three major excavated tunnels.

**London tunnels**
- 18km, twin bore tunnel, excavated around 20m to 40m below ground level through sand, mixed sand & clay, and clay ground types.
- Excavated by tunnel boring machines launched from Stratford and Dagenham.
- Trains run at up to 230km/h on low vibration slab track that was specifically developed for CTRL and which sets a new benchmark for the level of ground-borne noise and vibration reduction for a high speed railway tunnel.
- The tunnels pass under or near 4,000+ homes, as well a number of offices and shops, but do not pass especially sensitive properties, such as hospitals or recording studios.
- No complaint about ground-borne noise or vibration has been recorded since the CTRL entered service.
CASE STUDY: Control of ground-borne noise and vibration on Jubilee Line Extension using resilient rail support

Scheme: The Jubilee Line, an extension to Charing Cross of the former Stanmore branch of the Bakerloo Line, opened in 1979 using traditional rail support resulting in significant levels of vibration and ground-borne noise. The line was extended to Stratford from a new turnout south of Green Park in central London. It passes under Westminster, Southwark and east London in tunnel as far as Canning Town, and opened in 1999. The Jubilee Line extension was the first London Underground scheme to be subject to Environmental Impact Assessment, and the first deep tube system to be designed to targets for ground-borne noise and vibration which would result in no significant effects on occupiers of building above the tunnels.

Tunnel and track details: The tunnel is generally 4.35m diameter lined with concrete segments, with some cast iron sections, at a range of depths from 20m-30m. The trains are London Underground tube trains operating at up to 80 km/h. The standard track support consists of resilient rail baseplates designed to meet a target for ground-borne noise of not more than 40 dB LpASmax, found to be the threshold of complaints following the opening of the Jubilee and Victoria lines. There are some sections with floating slab track where the tunnels pass below buildings with highly sensitive uses or buildings with deep foundations close to the tunnels.

Monitoring: Following the opening of the system measurements of vibration and ground-borne noise showed that the design aims had been met.
CASE STUDY: Control of ground-borne noise and vibration on Crossrail using resilient rail support

Image graphic: Crossrail Ltd

**Scheme:** The Crossrail project includes twin tunnels from Royal Oak near Paddington to portals east of Liverpool Street, in Pudding Mill Lane and Victoria Dock, passing under the residential areas of Bayswater and Mayfair, under the West End and the City of London and under residential areas in east London. Following the precedent of the Jubilee Line Extension, the Environmental Statement included mitigation of vibration and ground-borne noise so as to avoid significant effects both for residential; buildings and many highly sensitive buildings such as the Barbican concert hall.

**Tunnel and track details:** The tunnel is designed for the operation of mainline electric multiple units at up to 100km/h and is generally 6.2m diameter lined with concrete segments, at a range of depths of up to 40m. The standard track support will be designed with resilient rail support endeavouring to meet a target for ground-borne noise in residential buildings of 35 dB LpASmax and with a limit for predicted levels not to exceed 40 dB LpASmax. There will be some sections with floating slab track where the tunnels pass below buildings with highly sensitive uses or buildings with deep foundations close to the tunnels. For the first time there ground-borne noise from the temporary construction railway has also been controlled with very few complaints.

**Monitoring:** Monitoring of ground-borne noise and vibration from the operating railway will take place following the start of test running of trains in 2018.
CASE STUDY: Vibration reduction on Victoria Line, high resilient rail fastening

Image credit: Pandrol Ltd

**Scheme:** The rail fastenings on a 120m long section of the southbound Victoria Line between Oxford Circus and Green Park stations were replaced in 2000. The track had conventional cast-iron baseplates fixed to timber sleepers. It was replaced by highly resilient rail fastenings on concrete sleepers.

**Tunnel details:** The northbound and southbound tracks run in separate tunnels, around 25m apart and at 20m below ground level. All of the trains passed at approximately 50km/h.

**Monitoring:** The vibrations of the tunnel structure and the ground surface were measured before and after the track was replaced, as well as nearly a year later. The response from trains on both lines was measured, allowing a direct comparison between the original and replaced trackforms.