Notes on technical issues for the vibration assessment for the Chiltern Line Upgrade through Wolvercote

1. Introduction

I have tried to write the notes below in an accessible style without using unexplained jargon. I hope the result is clear rather than too wordy or patronising. What I can reasonably relate is inevitably limited; I do not intend here to write a text book. These notes are not intended to become the basis for further to and fro. They are, rather, an attempt to provide material that addresses the questions that have already been asked. These have raised concerns in the Wolvercote area only and so this document focusses mainly on the issues in that part of the line.

These notes are provided for the local planning officers to use. Answers to technical questions given by the planning officers may refer to these notes. The terms of reference under which I have been engaged do not include correspondence with residents. My terms of reference are limited to advice to the LPAs, post enquiry, regarding the assessment of vibration in the discharging of the conditions under which planning permission has been granted.

You will find, in here, some implied criticisms of the understanding applied at various stages of the process. I have weighed my concerns over these in my conclusions about the adequacy of assessment of vibration. I am not here to defend or demolish the work that has been done, nor to judge its academic standard. The Independent Expert’s role is only to advise the LPA on whether the assessment is sufficient, reasonably to say that the impact of vibration will be within the VDV target set. This is not an absolute judgement. Precedents for projects such as the current line upgrade have to be acknowledged in judging what it is possible to ask of the current project in terms of extent of study and level of certainty.

The inclusion of material in these notes means that questions have been asked in that technical area. It does not necessarily mean that it has a material bearing on the judgement of the adequacy of the vibration assessment.

2. The generation of vibration by trains

Vibration is generated at the track in two ways. (Other mechanisms are imaginable but the two have been found sufficient to account for observed vibration).

1. The first is the moving deformation pattern in the track under the axles of the train. At a fixed point on the ground under the track, this causes a time history of (mainly) vertical movement, *i.e.* vibration. However, this does not propagate away from the track unless the speed of the train is greater than the wave speeds of vibration in the soil. (On Oxford clay, it would have to be somewhat greater than 400 km/hr even for the clay at the surface, untreated.)
2. The second mechanism arises from the dynamic forces as the masses of the axles of a train are accelerated up and down as the train travels over the unevenness (‘roughness’) of the track. Long wavelengths of roughness produce the lowest frequencies of vibration, short wavelengths produce the higher frequencies, according to the equation (frequency = velocity/wavelength). Vibration generated this way does propagate[1].

Vibration generated at the surface of the ground under the track propagates along the surface of the ground (a bit like water waves) moving out in circular wave fronts. They do not propagate much down into the ground. These waves are loosely called ‘Rayleigh waves’ after the scientist who first solved the mathematical problem behind their existence at the surface of a homogeneous material[2]. If the ground is shaped, *e.g.* the

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[1] Strictly, there is also a Doppler shift as well but this acts to blur the response to a single wavelength over a range of frequency; axles moving towards reduce the frequency of the vibration at a point in the ground slightly, and axles moving away increase it.

[2] There is more than one such wave possible, and they are more precisely referred to as different orders of PS-V

railway track lies in a cutting, the waves follow the shape of the ground, always propagating on the surface. The amplitude of the waves is greater in soft soil than in stiff soil and accordingly it is soft soil conditions that are associated with vibration strong enough for people to feel in their homes.

The speed of the slowest Rayleigh wave, (that carries most of the energy) is about 0.91 times the shear wave velocity in the soil. Since the properties of the soil change with depth, this has an effect on the amplitude of the vibration at different frequencies as well as its propagation speed. In Oxford clay, the wavelengths of vibration are from about 30 m at 4 Hz (about the lowest significant frequency component from freight trains) to about 1.5 m at 80 Hz, the highest frequency relevant to human perception. At 4 Hz the scale of the wave is large and is affected by the soil stiffness (shear wave velocity) at depth of the order of 10 m or more. As frequency increases, the wave shape becomes smaller with shorter wavelength and soil properties nearer the surface play the greater part.

2.1.Track quality

Since the roughness of the track is the source of propagating vibration, good track maintenance is a way of keeping the vibration to a minimum. The smoothness of track with a poor foundation deteriorates more rapidly than track with good foundation. In particular, vibration impulses can be associated with ‘wet spots’ (where the foundation has become weak or penetrated) or bad rail joints where ballast has already been damaged by impact forces. An overhaul of the foundation before relaying the track is reduces vibration problems in the long term, especially as repair techniques are available to the modern civil engineer that were not when the foundation was first made.

Two properties along the line (not in the Oxford area of the route), at railway crossings, are extremely close to the track such that the vibration may be due to mechanism 1 (above). Even though the VDV criterion is not predicted to be breached (nor is it in the VDV monitoring in the EIS), Network Rail have offered *ex gratia* (and ‘for expedience’) to renew the foundation completely and replace it with a modern foundation in short lengths. This will produce a much stiffer and stable foundation that is expected to ‘*reduce the risk of’ (sic)* higher levels vibration substantially, but at considerable expense.

NR may legitimately prefer not to refer to this as vibration ‘mitigation’ as it is not necessitated by any prediction of the VDV threshold being exceeded. However, it is still engineering that has been done for vibration reasons with a cost.

Note that the VDVs measured at Oddington Crossing are due to the particular circumstances of the track at the crossing and the monitoring location (in the building, only 3.5 m from the track, immediately adjacent to a rail joint)[3]. (They may even be due to heavy road vehicles going over the very bumpy road crossing. The unattended VDV monitoring equipment cannot tell. Lorries going over speed bumps cause high levels of vibration.)

3. VDVs and the spectrum of vibration.

In the vibration monitoring exercise at various representative properties, VDVs were measured over several days. In this measurement, weighting filters are used that account for human perception of vibration. (This is analogous to the A-weighting of sound that accounts for the frequency sensitivity of the human ear to derive sound levels in dBA.) However, unlike a sound level, the VDV is a ‘dose’ value. (A bit like a dose value of radiation exposure.) That is, with time as the train passes it builds up a total value that correlates with an average person’s perception of vibration comfort in their environment. Thus, the limit criterion for the project is a dose for the whole 16-hour day-time period of vibration is a VDV of 0.4 $ms^{-1.75}$ and half of this for the night-time period. (For noise, the LAeq is used which is not quite the same as a dose value, but represents the equivalent sound level over the whole period. In noise, this is what correlates with a person’s perception of their noise environment.[4]). The VDV associated with a single train passing event can be added

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wave.

[3] Google streetview shows sufficiently well.

[4] Both VDV and LAeq have been justified (derived) by extensive tests of human response and are established in British and International Standards. They are the accepted means of putting a value to the vibration/noise experience of transport or industrial noise and vibration.

to show us the effect of a number of trains. It is not a simple addition, however. The effect goes up according to the fourth root of the number of train passing events. This tells us that we would have to have 16 times as many trains to double the VDV.

The VDV is therefore a useful measure of ‘the amount’ of vibration a person perceives. However, it tells us little about the frequencies involved nor even very much about the amplitude of vibration at a particular time during a train passing by.

Vibration has been measured by Atkins using transducers that register acceleration. The Atkins reports show some spectra of acceleration. However, people perceive vibration amplitude (roughly) in proportion to its velocity amplitude rather than its acceleration amplitude. (In the calculation of VDVs, the weighting filters are largely doing a conversion from acceleration into velocity.) The weightings for human perception of vibration look much flatter if expressed in velocity terms. It is therefore more useful to plot a spectrum of vibration in terms of the velocity amplitude rather than acceleration. I have therefore re-plotted some examples of the measurements from the Atkins reports; see Figure 1.

The scale of amplitude is expressed, as it is for noise, in terms of decibels (dB).

In Figure 1, the vibration at 8.5 m is plotted for a passenger train (dashed lines) and a freight train (solid line) (not the stone train). It can be seen that the vibration from either is about the same level except that the freight train causes components of vibration below about 10 Hz where the passenger train does not excite any significant vibration. As we move to distances further from the track, the higher frequencies fall in amplitude more than the lower frequencies (the lower frequencies will not fall significantly at all compared to the 8.5 m of this plot for the distances of the studied line-side properties). It is the vibration below 10 Hz that makes the difference that we feel between a freight train going past and a passenger train going past. It is the lower frequencies that really matter.

These spectra are very typical for train ground vibration although there is quite a lot of variation from place to place.

The black dashed line indicates the nominal threshold of perception. Of course, some people are more sensitive to vibration than others, but it is known that as soon as vibration amplitude can be felt it starts to give rise to public complaints. I would expect this example to be feelable in line-side properties by many people.

The perception threshold of 100 dB (re 1 nm/s) corresponds to a rms level of 0.1 mm**/s** vibration velocity amplitude in any one-third octave frequency band (*i.e.* the standard band-width resolution of the spectra that we use; an octave is a doubling of frequency so a 1/3 octave is a band-width from a frequency *f* to a higher frequency $2^{(1/3)}f$). It is in line with the 0.15 mm/s to 0.3 mm/s over all the frequency range that is quoted in the project’s public information document.

Note that, these example spectra do not necessarily represent the mean or highest vibration values measured by Atkins, they are just examples that they chose to show for the purposes of seeing the frequency content and the relationship between the different directional components. Atkins do not present these particular examples for any other reason. Moreover, a spectrum is, by its nature, an average during a train pass-by and not a maximum.

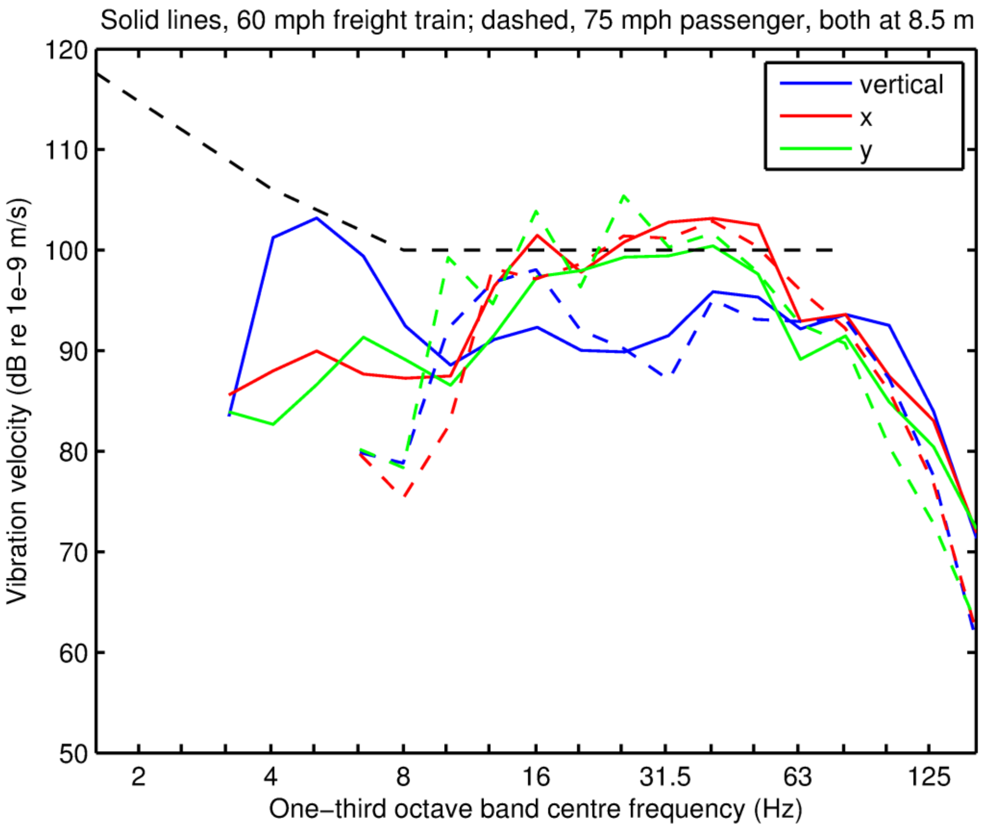

Figure 1. Measured vibration examples, replotted from the Atkins reports in terms of vibration velocity.

4. What is it about a vehicle that can make vibration worse from one than another?

The spectrum of Figure 1 serves to show us that vibration in the frequency range from 10 Hz to 80 Hz from the freight trains is not very different from that of the passenger trains. The freight train vibration, however, has strong components between 4 Hz and 8 Hz that are not present in the passenger train spectrum. Since lower frequencies of vibration do not decay with distance as fast as higher frequencies, it is this low frequency content that gives freight train vibration more impact at properties further from the track.

The difference between freight and passenger trains is that passenger trains have two layers of suspension.Freight trains (and locomotives) generally have only a single stage of suspension and it is stiffer than the passenger train suspension (although the spring stiffness of the suspension of many wagon types is designed to become softer when they are empty.) It is the fact that there is a single, stiffer suspension that makes the difference in spectrum between passenger and freight vehicles below 10 Hz.

The main parameter of the train that affects the vibration is the mass of the axle that is below the lower stage of suspension spring and the stiffness of that spring. The static axle load (the total tonnage borne) does not affect the propagating vibration (roughness mechanism of generation, 2) although it does affect the moving deformation pattern vibration generation mechanism at the track, 1).

4.1.Speed

Since the speed of movement of trains is slow compared to the speed of Rayleigh waves in the ground, there is no other significant effect of increased speed on the level of vibration than the fact that a particular frequency now then excited by a longer wavelength of the roughness. Roughness amplitudes increase with wavelength and so, therefore, does the vibration. The spectrum of roughness (vertical profile plotted against wave-length) is measured regularly on the whole NR network and although the amplitude of roughness varies the slope of the spectrum, the rate of increase of vibration with wavelength is more constant. The rate of increase of vibration with speed is thence about 4 to 6 dB per doubling of speed (6 dB is a doubling of amplitude).

I am satisfied that the speed increment has been properly taken into consideration in the predictions. One of the main reasons for the measurements on the main line was to limit the speed change over which this estimation had to be made. A three times speed increase would (using the upper limit of the rule of thumb given above) be expected to lead to a three times increase in the amplitude of the vibration. This means a 2.3 times increase in the value of the VDV because of the shorter train passing time at the higher speed. This is the biggest factor in the increase of the predicted VDVs over those measured in the environmental impact assessment.

5. Checking the comparative responses of different sites

5.1.Boreholes

Borehole data is useful to discover what materials may be involved in the propagation of vibration. Boreholes are made by simple observation of the material that emerges at different depths as the hole is dug. The description of the material follows conventions and is based on the apparent material (silt, sand, clay, gravel, limestone), the coarseness and the colour.

For the dynamics of vibration propagation, only the layer depths are directly useful and the mechanical parameters must either be measured separately or estimated from experience of the apparent materials.

The most important parameter is the shear wave speed of the material (different in each soil layer). The speeds of 'Rayleigh waves' are slightly lower than the shear wave speed. Rayleigh waves propagate along the surface of the ground (rather differently from the vibration that emanates from tunnels) and carries the bulk of the energy transmitted from the track to the line-side property. Very simply, soft materials have lower shear wave speeds and lead to higher levels of propagated vibration. The layer depths where there is a strong shear wave velocity change have an influence on the frequency dependence of the transmission of vibration.

The mass density is of only secondary importance as it varies little for soils. The compression wave speed completes a mechanical description of the material but this is not so important for vibration propagation. The water content of the soil has an effect only on the compression wave speed and has little effect on surface wave propagation.

Unfortunately the shear wave speed of soils is seldom measured. It is related to a shear modulus but this is not the same shear modulus that is measured by civil engineers for the purpose of large strain, static load-bearing calculations; it is of a different order of magnitude. Seismic surveys carried out for construction engineering purposes measure the compression wave speeds to detect different layer depths. Shear wave seismic surveys are really limited to a few exercises that have been carried out where great geotechnical detail was justified. Usually where done it is for ground vibration studies but is only done for a small minority of these.

5.2.Clay, gravel and alluvium

The material covering much of the south east of England is clay. Its shear wave speed varies little though its colour can be grey, brown or 'green' depending on what it was stained with as it was laid down. In traditional naming it can be called London, Oxford or Kimmeridge Clay depending on its location and following the boundaries of deposits on the map. Around Wolvercote and in the Oxford area generally there are very deep layers of clay (or the order of 60 m quite commonly). (You may come across the term 'mudstone'. In modern geological terminology almost everything sedimentary in the UK is some kind of 'mudstone'. Sadly, in the process of global standardisation the local descriptive names in the UK are lost. 'Mudstone' includes clay, limestone, lias and even millstone grit.)

Clay very near the ground surface has a high water content and is relatively soft. This is the mechanism by which clay becomes ‘weathered clay’. This is because it softens with the absorption of water where the pressure it is otherwise under from the material above, is relieved. This process takes very roughly from 20 to 70 years and so material in Victorian cuttings is usually weathered despite coming from a greater depth when originally exposed.

Close to rivers, surface deposits of alluvium occur. This is loose material that may contain, sand, silt and gravel as well as clay. It is generally soft material, with low shear wave velocity, and can lead typically to higher railway vibration in alluvial areas near rivers.

The clay in areas such as Oxford typically also has ‘inclusions’ of sand or gravel. This varies from gravel grains within the clay which affect the shear wavespeed of the clay very little, or loose (and fairly pure) sand which has a low shear wave speed similar to surface clay, to compacted gravel which, at depths of only a few metres, has a shear wave speed a little higher than surface clay. Alluvial or river terrace deposits do not have shear wave speeds comparable to limestone or similar stiff materials.

5.3. *Relevant borehole data*

Around Wolvercote there are fortunately a relatively large number of boreholes which are published on the British Geological Survey website. BGS scanned records go back about 100 years. Modern records follow conventions of description and can be very clear. Older records may be much more difficult to interpret. The policy is to put all information that can be published on the website uncritically whether a good record of a deep borehole or notes of very little of relevance (to us at least) for instance, about a shallow pit.

For our purposes we need a borehole to be at least about 10 m deep. The modern information taken for the A34 or A40 is good. Unfortunately, though relevantly located for us, the Lakeside pit record (SP41SE157) is a little vague on distinctions that would help us decide probable wave propagation parameters. It does, however, indicate layers below the topsoil (down to only 4.5 m) as all being clay which it describes as stiff or firm.

A more useful borehole (modern, clear data to greater depth) is given by borehole SP40NE57. This appears still to be in the area characterised by clay in the first few metres rather than sandy/gravelly deposits closer to the main line and river.

For the parameters close to the mainline and river representing L1/L2 at the junction, good bore-holes are found to the north of the junction in SP41SE506 and to the south in SP50NW512. These two are very consistent.

5.4. *Where to measure vibration*

The proper way to assess propensity of a ground location or area to ground vibration is from measurements of vibration. The approach echoed by the words of the enquiry are ‘at a representative similar site’. In practice measurement sites are often not particularly close to any specific building of interest. A great deal of judgement and compromise has to be made in choosing an available sufficiently representative site. Land ownership and the politics of an enquiry or other considerations often limit the choice; engineers are not free to ignore these constraints, even in the pursuit of good science. In this case emphasis was put on obtaining data from trains at relevant speed. I approve of this because the biggest factor in the change from the current to the future VDVs is the change of train speed.

The question has therefore been raised in submissions to Oxford City Council of the suitability of the sites ‘L1’ and ‘L2’ at Wolvercote junction in predicting vibration at Wolvercote.

5.5. *A rough check of comparative vibration response at various locations*

In February 2013 Atkins had carried out their first set of measurements for their prediction scheme. These were made on the mainline at a location where the relevant rolling stock travelled at roughly the speeds of upgraded line between Bicester and Wolvercote.

I inspected borehole data and carried out some simple calculations of vibration response using my judgement of the likely parameters of the soil. This exercise was only intended, and can only be used, as a check of the reasonable suitability of the site. It is not direct measurement evidence, and factors that also affect vibration such as the track structure, and vehicle dynamics do not feature. Please do not take these calculations to be any more than they are intended to be, ‘a sanity check’ or a demonstration of likely, rather than known, effects.

When first commenting on the ‘schemes of assessment of vibration’ in February 2013 (as they stood then, not how they are now), I looked at borehole information and was concerned that the location where initial measurements had been made had a (albeit thin) layer of limestone only a few metres below the surface. I used some simple calculations of vibration response which I used to demonstrate to the LPAs that Atkins first measurement location was not suitable. That data was not used. Atkins then chose the site L1/L2 at Wolvercote junction for measurements which had to represent the whole area from Wolvercote to Bicester.

The simple calculation predicts vertical and lateral response (radially) from a unit vertical dynamic force applied over a small circular area of the ground surface. The calculation method[5] has been used by many people internationally as part of the way of determining shear wave speeds and other dynamic properties of the ground.

Fortunately for guidance on material parameters in Oxford clay, measurements of the dynamic properties of the relevant materials, have been carried out at Steventon[6], close to the Great Western Main Line, another Oxford clay site south of Reading and in London on simlar clay. These measurements are consistent in that showing layers close to the surface having shear wave speeds of the soft, near-surface material of 120 m/s and 400 m/s eventually at some depth. The layer depths are not the same at these sites as at Wolvercote; the boreholes provide light on that. For the parameters of gravel (200 m/s), compacted gravel (245 m/s), and alluvial deposits (80 m/s) I have used other shear wave measurements at sites within my experience in the UK.

Figure 2 presents the velocity response (‘mobility’ is response velocity divided by the exciting force) at 10 m for various idealisations of the ground layers at different locations.

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[5] Kausel, E and Roesset, J.M., Stiffness matrices for layered soils, Bulletin of the Seismological Soc. Am. 71(6), 1743 – 1761.

[6] N. Triepaischajonsak, D.J. Thompson, C.J.C. Jones, J. Ryue, and J.A. Priest. Ground vibration from trains: experimental parameter characterization and validation of a numerical model. Proc. IMechE Part F: Journal of Rail and Rapid Transit 224F, pages 140–153, 2011.

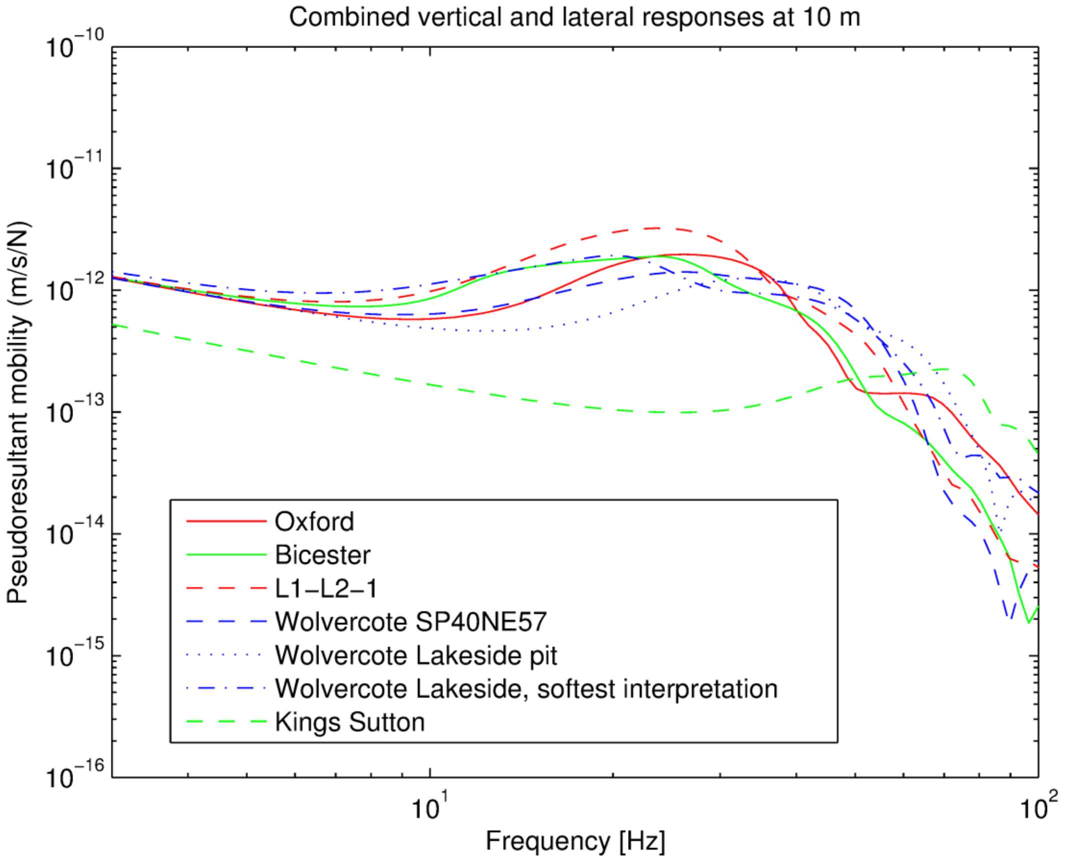

Figure 2. Simple calculation of relative vibration responses to a constant amplitude (unit) load at 10 m.

The Oxford, Bicester and Kings Sutton responses are those presented in my notes made for the LPAs in February 2013. The significantly lower response at King Sutton means that a prediction scheme based on these measurements would likely predict levels of vibration below what could be expected alongside the Bicester - Oxford line. In comparison to this the curves representing locations closer to the Oxford - Bicester line are much closer together. They all come together at very low frequency because, at low frequency, the vibration transmission depends on the deeper situated material and I have seen that throughout the whole area the ground becomes the same stiff Oxford clay at some depth. No other, much deeper, rocky material is expected to have influence in the frequency range we are interested in.

For Wolvercote, within that line, specifically I have made three calculations. One based on my best interpretation of the SP40NE57 bore hole and two, more uncertain in interpretation, based on the lakeside pit information (SP41SE157); a 'best' interpretation and one that errs on the side of assuming soft materials.

For the L1/L2 site the borehole information is clear but I have erred on the side of caution by assuming a compacted gravel shear wave speed for the gravel layers that are labelled as river terrace deposits. A higher response is indicated at the L1/L2 site over most of the frequency range. Only the more pessimistic interpretation of the Lakeside data exceeds this slightly.

6. 'Feelable' ground vibration and ground-borne noise and the US FTA guides

The USA government guidelines on environmental impact assessment of vibration from trains is a prominent document that is easily found on the internet. Some correspondence on the Chiltern line upgrade has therefore referred to this. It is important to understand that this document is primarily concerned with *ground-borne noise* rather than feelable vibration. Ground-borne noise is the rumbling **sound** transmitted to buildings above underground railways as vibration through the soil. This is a topic that has important differences from the study of whole-body vibration we are currently concerned with.

- Vibration from surface trains leads to '*whole-body'*[7] vibration that is felt. It is subject to the frequency weighting that mimics the human body's sensitivity to feeling vibration and is limited, because of that to 0.5 Hz to 80 Hz.
- The assessment of vibration that is perceived as noise is subject to the frequency weighting for human hearing (A-weighting) that puts heavy emphasis on much higher frequencies. Typically, this means frequencies between 50 Hz and 250 Hz.
- Vibration from trains on the surface is transmitted by 'Rayleigh waves' that travel along the surface only. These transmit low frequencies well.
- Vibration that is perceived as noise is associated with train in tunnels because vibration is transmitted from underground is transmitted by different types of wave, 'body waves' (*i.e.* travelling through the interior of the soil). This leads to spectrum content of higher frequency.
- The environmental impact assessment for tram systems, even on the surface, have to address ground-borne noise because they produce vibration of significant levels only in the 63 Hz to 100 Hz bands and pass properties sometimes extremely closely or even within building structures (*e.g.* shopping centres). Trams seldom cause whole-body feelable vibration.

An aside ..

The difference in concerns in the USA compared to the UK is reflected in two recent studies the two governments commissioned. A 'TRCP' study in the US studied 'Ground-borne noise and vibration in buildings caused by rail transit', 2009, (Project D12, web document 48, downloadable from www.trb.org/PublicTransportation.) This is entirely about ground-borne noise, the reference to vibration is only as the source and mechanism of propagation of noise. It refers heavily to, and seeks to update, the 1970s and 80s studies that are reflected in the TRCP Guide. In trying to interpret this report it is important to understand that when it says loosely that 'noise level' = 'vibration level', this is only a statement that noise is proportional to vibration velocity. The 'equals' only works if you use the curious mixture of imperial and metric (SI) units such that dB of vibration velocity in 10^{-6} *inches/s* turns out to make the proportionality constant close to unity in comparison to sound pressure dBs based on 2×10^{-5} *Newtons/metre*^{2}.

Our own DEFRA commissioned the study 'Human response to vibration in residential environments, Project NANR209, reports 1 to 6, 2011 that can be downloaded at DEFRA's website. (Each of the reports 1 to 6 are very long; if you want to look I suggest gleaning what is of interest from the 300+ page report 6, or looking at my own very brief summary in 'Measurement and assessment of ground-borne noise and vibration', 2nd Ed, The Association of Noise Consultants, 2012.

These studies are purely about the perception of vibration as their titles suggest. There is nothing about vibration mechanisms.

Ground-borne noise was rightly dismissed at the Inquiry as a concern in the current line upgrade since the only short bit of tunnel is under a busy road roundabout and not sufficiently close to any residential property.

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[7] The term 'whole body' distinguishes the vibration from other important vibration phenomena that affect humans such as 'hand-arm' vibration (leading to white finger industrial injury from power tools *etc.*). Here 'whole body' just means 'the vibration you feel when you environment shakes' (vehicle, building, earth).

Road noise and vibration would drown out anything from the railway there anyway.

Even in deep cuttings, surface trains transmit vibration as waves that follow the surface of the ground. They have to be cut off from doing so by a complete tunnel ring to cause vibration to be transmitted from within the body of the ground.

6.1.Mitigation of vibration

In the American TRCP guide, various mitigation options are discussed as possible track engineering. These consist of either vibration isolation mechanisms in the design of the track or (more unusually) trenches. These address higher frequency vibration for ground-borne noise concerns. Various manufacturers' track designs that lower the resonance frequency of the rail support are relatively commonplace in underground railways to treat ground-borne noise. The resonance here is of the mass of the axle and part of the track (*e.g.* the rails and sleepers) on the spring stiffness of the support (a layer of ballast stone) or a rubber component in baseplates or slab track design. Vibration at frequencies above the resonance frequency of the track is 'isolated' (reduced) from the ground much as a car suspension isolates vibration from the road. However, at the resonance frequency, vibration is amplified. The resonance frequency is typically around 30 to 40 Hz so this isolates the vibration associated with ground-borne noise but would make a typical surface railway spectrum assessed for whole-body vibration *worse*[8].

Trenches also treat higher frequency vibration. A well-established rule of thumb is that the depth of trench to achieve any significant reduction has to be about 0.6 times the wave-length of Rayleigh waves. For the short wavelengths at higher ground vibration frequencies, this can sometimes allow a barrier to be formed against propagation of ground-borne (*e.g.* a retained trench down the side of a subterranean wall to protect an underground floor of a large building near a tramway). At the important 4 to 8 Hz range for freight trains, the depth of a trench in clay would have to be around 10 metres (for 8 Hz) to 20 metres (for 4 Hz) deep. A trench without retaining walls can have sides no more steep that about 30 degrees. It would be like digging a very deep canal. There is no room within railway land for this. Steel pile retaining walls cannot get a trench more that about 5 or 6 m deep at most (the soil pressure that has to be retained becomes enormous; any struts across the gap just transmit the vibration anyway). Putting in steel sheet piling causes far higher levels of vibration that even the worst freight train. Such pile driving could not be carried out close to residential buildings.

The mitigation that Atkins have suggested (but not applied) is to put a soft rubber mat under the ballast. This is a vibration isolation solution of the very sort that leads to an amplification of low frequency vibration. Atkins have only a measured benefit of this to go on, *i.e.* difference in vibration before and after installation. Such measurements are strongly contaminated by an improvement in the smoothness of a re-laid track and other associated differences. They do not therefore generally accurately show the amplification at the lowered resonance frequency. Track designers use calculation models. (Such calculations are my bread and butter work). I would not recommend the installation of such a track for whole body vibration without such an analysis.

So what can be done for low frequency, surface propagating vibration? The simplest and most obvious answer is to reduce the roughness. This is done regularly by the tamping operations on track. This sets the sleepers level in the ballast layer. With time, the sleepers settle at different rates within the ballast and tamping has to be done again. Tamping maintenance loses effectiveness for old damaged track foundation (where 'wet spots' and underlying unevenness keep 'coming through') and for old worn-out ballast (full of fines and with rounded edges to the grains so that they no longer hold their position with respect to each other[9]). The foundations left by the Victorians were poor compared to the repairs or rebuilding that modern

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[8] The statement in Section 6.5.6 of the EIS 'There are well established engineering methods for reducing vibration from trains, which introduce a resilient element into the track form which reduces the vibration transfer to the receptor' has to be regarded as unknowledgeable in the context of whole-body vibration. However, it implies no specific promise. It is unfortunate that there and in the submissions of Atkins, this misunderstanding of the availability of some standard mitigation option of resilient track seems to have prevailed.

[9] Please accept this as a very simple statement of a very deeply studied subject. Ballast replacement and track-line and level maintenance are the railways' biggest costs and much research and improved technology has gone into this.

geotechnics achieve. Better track foundations lead to smoother tracks and slower decay into roughness. The experience of vibration over time is thus improved and the risk of impulsive vibration problems significantly reduced.

Thus track replacement, especially where foundation is repaired, does lead to lower vibration. If a track engineer receives complaints of recently increased vibration at locations on his patch he can choose to do tamping maintenance. However, this is usually automatically triggered by the regular measurements of roughness that are made on the whole network. The primary reason for these measurements is, of course, the smoothness of ride for the passenger. Higher speed passenger lines are given higher categories of specification of smoothness for the track engineer to maintain.

It has been established in past cases that reduction of the speed of trains is not to be regarded as a ‘reasonable means’, *i.e.* the railway cannot be forced to do this as a means of mitigation. (If no ‘reasonable means’ of mitigation are applicable, no mitigation has to be done.) However, if reduction in the speed of trains were to be entertained as an option, it would require that trains through Wolvercote would have to travel at the current speed of 25 mph rather than the planned speed of 60 mph in order to bring the projected VDVs down by a factor of two.

Another aside ..

Good quality campaigns of vibration measurements are very rare as they are costly. Carefully controlled measurements made on designed ‘laboratory apparatus’ are almost non-existent. (If interested find the EU research project ‘RIVAS’ on the internet). Measurements are usually only gathered at ‘unusual’ places on real railways for comparatively small scale studies; observations rarely include vehicle parameters, track roughness and careful seismic surveys of the ground. Measurement surveys have repeatedly proved not to be interpretable without advanced computer models of vibration. (Many researchers have not applied any knowledge of the mechanisms and influences of many paramaters, they just report what they observed in the result of it all. Their reports should be read accordingly.)

In about the last 20 years some researchers in the UK, Belgium, France, and Japan have developed the necessary computer modelling techniques. Only more recently have they then been applied in any systematic studies.

However, the models are not applied or even available to most. In summary then, be careful therefore if looking at research papers based only on measurements. This applies to papers that are too old to benefit from the computer models as well as by those without the models. There are many conference papers in this subject area, where people have presented measurements *because they have found something unusual*. (Researchers are keen to show they may have discovered something different, which does not follow the usual pattern. That does not mean the exception will occur again in Oxford.)

The literature is also full of statements such as ‘clay soils lead to higher levels of vibration than sandy soils’ or ‘the cutting I measured at showed higher levels of vibration than the at-grade section of line I measured at’; without relating this to the material properties of the particular soils at particular sites or to the ground layers, the track construction and its roughness spectrum, the vehicle parameters *etc.*, such generally stated empirical conclusions within theoretical analysis to explain them are a little meaningless.

6.2.Cuttings and embankments

The effect of cuttings has already been discussed. There is little effect on the propagation of vibration of a normal cutting as the surface waves follow the surface of the ground even though it is not flat. Time has allowed the materials at the bottom of a cutting to weather to similar conditions as other areas of ground surface, particularly where the ground is a deep drift of clay without any bedrock layers close to the surface.

There is an effect in cuttings where sometimes poor drainage conditions have led to a more damaged foundation than at better drained locations. Thus, the track may deteriorate faster between maintenance cycles and respond less well to maintenance.

Embankments on the Victorian-built network were made merely by heaping surface material (usually from the nearest cutting) in order to continue the elevation of the track. No geotechnical engineering was used (soil reinforcement, treatment, or compaction, geotextile/geoweb layers, or even good drainage). Some cinder (from steam days) and old ballast often forms a thin top layer. Thus, an embankment of 2 or 3 metres height has small effect in altering the propagation conditions compared to what would have been beneath the track if it were ‘at grade’.

Modern embankments are very different. They have all the benefits of geotechnical design to make a stable foundation which leads to lower maintenance requirements. They are very stiff in comparison to old embankments (high shear wave speed) and so tend to lead to lower non-propagating near-track vibration as well as lower roughness for the generation of propagating vibration. This is why I approve of NR installing new embankment at the two vibration-sensitive crossing sites on the line.

7. Transmission into buildings

Some correspondence has been concerned about the fact that vibration has been predicted on the ground surface outside a property rather than inside. It has been suggested that amplification can occur inside the property and this should have been taken into account. The main effect in the current issue would be the ‘reception’ of vibration into the foundations of the buildings, *i.e.* to do with how a wall is excited by vibration in the soil under it. A wall will respond differently to the ground around it because it is of different material and because it averages the effect of the ground vibration over a strip or area.

The propagation of vibration within a building is not of great concern in the present case because of the low frequency range and the size of residential buildings along the route. The propagation of vibration is more the concern of the ground-borne noise topic and for large multi-storey office buildings, large theatres or conference centres.

It is normally the practice to set up a model of vibration propagation at the ground surface and then apply empirical factors for the effect of transmission into a building. Large computer models are sometimes used to study the response of important buildings above new railway but the diversity and number of small buildings along a route (and the lack of influence the railway engineers have over other people’s existing buildings) usually means that environmental impacts are predicted using empirical terms from a few studies that have been undertaken (and published for all to use).

The most widely used empirical information of this kind is reported in American research reports from the 1980s. Figure 3 copies some curves for the loss of vibration amplitude in its transmission into building foundations. This is re-published in several places in the literature. It is based on measurement campaigns in Japan, US and Canada. Some extra data exists in a recent study for residential properties in the UK. The result is very similar to the curve in Figure 3 for single family residences.

The data show that the amplitude of vibration of the walls of a building are significantly lower than the vibration outside, say, of the order of half (6 dB lower over the frequency range for whole-body vibration). There then arises the question of amplification by resonances in the floor. For residences this is unlikely to take place below about 16 Hz as the floors are small in area and lightly constructed. They are, in comparison to floors which do amplify significantly, well damped. (Amplification is much more of an issue in a very large buildings with large floors between steel frames or mezzanine floors, or ‘floor slabs supported on columns’.) It has been found that the 1st floor in UK houses, the worst affected floor, typically has about the same level of vibration as the outside ground.

This is not a hard and fast rule but previous practice has not extended to examination of residences individually anyway. The collective approach here is the way it has been done and for a line upgrade a departure from this practice cannot be expected.

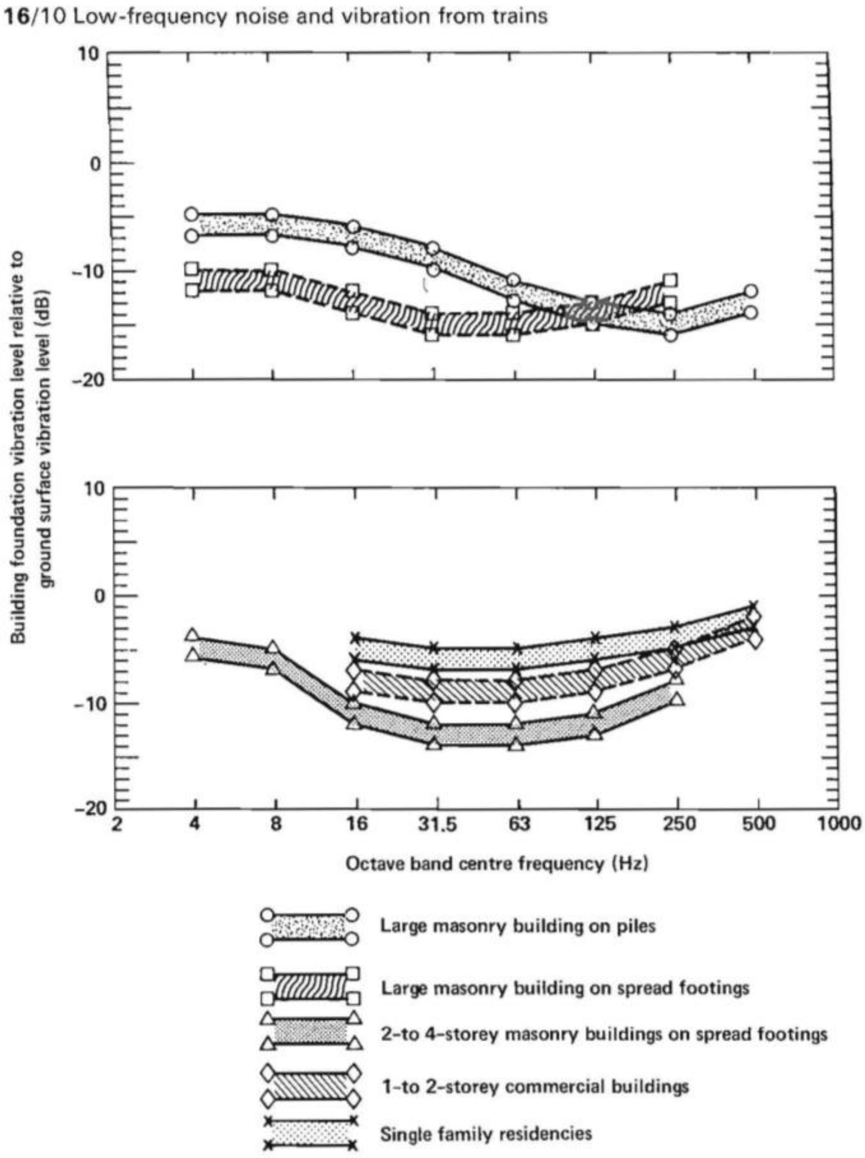

Figure 3. Empirical terms for the transmission of vibration into buildings related in the US FTA studies (here from the Transportation Noise Reference Book, P. M. Nelson, Butterworths, 1987).

8. Building damage criteria

Assessment of vibration in buildings for the likelihood that they may cause building damage is covered by BS 7385, which itself is now aligned with an international standard (ISO 4866). BS 7385 provides PPV threshold below which there is said to be no evidence even of cosmetic damage to buildings. In this context, ‘cosmetic damage’ is described as hair-line cracks in plaster and the like.

Cracks in buildings however, do exist. In clay areas only brand new buildings do not display the evidence of clay shrinkage that occurred particularly due to the relative drought in southern England in the last couple of decades of the 20th century. Therefore cracks are not deemed to be evidence of vibration damage. Only measured levels of vibration that are known to cause cracks can be (or is) regarded as evidence. An appendix in BS 7385 makes this very clear.

The BS 7385/ISO 4866 threshold is reproduced in Figure 4.

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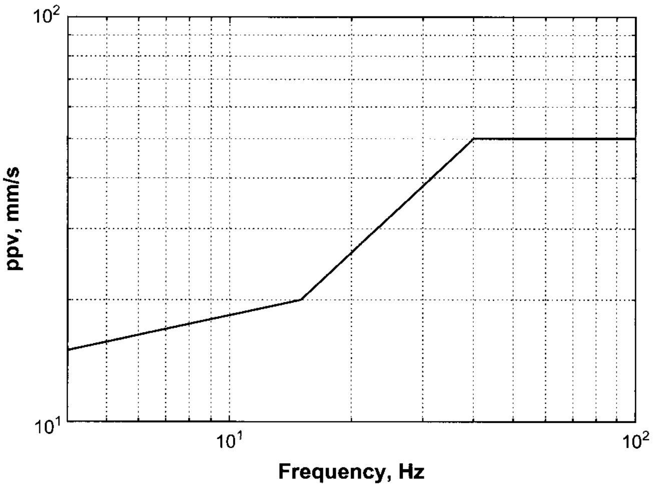

FIGURE 12-5 Criterion for potential cosmetic damage to light-framed buildings from BS 7385 o

Figure 4. Cosmetic damage threshold.

The standards state the threshold as a function of the dominant frequency in the vibration to which a building is subject. Vibration at 1 Hz has to exceed 5 mm/s peak particle velocity; at 4 Hz it is 15 mm/s and above 40 Hz it is deemed that a PPV exceeding 50 mm/s is required to trigger the risk (not certainty, the standard emphasises) of cosmetic damage. In the EIS it is implied that 15 mm/s PPV would be the limit criterion for the project.

PPVs cannot be converted to corresponding rms amplitude values. However, bearing in mind that complaints of vibration arise when the level just exceeds the threshold of perception at 0.1 mm/s rms, and that a doubling of vibration amplitude is regarded as a step up in discomfort level, it becomes clear that vibration of sufficient magnitude to cause building damage could not be lived with for comfort. I have come across building damage due to railway vibration only once in more than 25 years' experience. This was due more to the building method, with breeze block walls which were not tied in at the corners of the building, than the actual level of vibration. It was not in or near Oxford.

9. Uncertainty

There is always known to be uncertainty in ground vibration predictions (and also other environmental assessment values such as air pollution as well as noise. The setting of the design target limits has to consider this as well as the prediction of future VDVs and of course the limits are set with a knowledge of prediction practice. Of course a limit is also set in the knowledge that 0.41 $ms^{-1.75}$ is not perceptibly different from 0.39 $ms^{-1.75}$ but a limit has to be set somewhere at a single numerical value.

The criterion here is not set such that the vibration will not be perceptible. Nor has it been said that the VDV will not increase over its current value. It is set on the basis that if the project designs to a limit of a certain value then the experience of vibration will be in line with what is deemed acceptable. This is despite there being a great deal of variation in individual people's response to vibration.

Reasonable erring on the side of caution has been carried out in the predictions here in line with good practice. This is termed the application of the '*worst credible case* reasonably foreseeable'. There has also been a careful look at results where they come within a factor of two of the limit criterion, not just when the prediction exceeds them.

It is not the practice to imagine all possible variances in the prediction, then align them all in the worst direction and come up with a 'worst *in*credible case'. (I quote this saying by a former head of noise and vibration for BR.)

10.Finally

The reasons for measurement of vibration at L1 and L2 were only partly to provide information for the predictions. It was necessary to add to the VDV measurements made for the environmental impact assessment because they provided no idea of decay with distance or of frequency content. However, distances are not changing significantly at the Wolvercote properties (it is more important at the Bicester end of the line).

A simple and approximate check of the reasonableness of the VDVs expected at Wolvercote can be performed.

At the Quadrangle the EIA-measured VDV over several complete days on the 2nd storey, inside the building. $VDV_{day\text{-}time}$ was up to a maximum of about 0.04 $ms^{-1.75}$ and $VDV_{night\text{-}time}$ also 0.04 $ms^{-1.75}$.

The train speed through Wolvercote is to be raised from 25 mph to 60 mph. This implies a factor of increase, based on 6 dB per doubling of speed, of 1.9.

The worst increase in numbers of trains is that of 1 freight train during the night-time period to 8 during the night time period. Factors of increase of passenger trains and freight trains during the day are smaller. The factor of 8 intensification, if applied to all trains, would imply a factor of increase of 1.7 (or assuming that the night-time dose depended entirely on freight train vibration). For the daytime, the bigger possible factor of 1.7 would depend on assuming that the VDV were due entirely to the passenger trains.

Thus day-time or night-time VDVs can be estimated at no more than around 0.13 $ms^{-1.75}$. A reasonable margin still exists even in the night-time case before the VDV criterion is exceeded. This extremely simple ‘checking’ estimation is very close to the values estimated in the Chiltern Railways Noise and Vibration Policy document for the line improvement, document CD/1.29/2.1, 2011. This check does not rest at all on the measurements at L1 or L2, the Atkins prediction scheme, nor on any of the work done by Atkins.

Overall, given the considerations I have outlined, it is hard to find a reason to expect the VDVs to exceed the levels predicted, cogent enough to reject the discharge of the planning permission condition.