Cole Jarman

Barbican Estate: LUL Noise and Vibration

Measurements and Mitigation

Report 18/0197/R3

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Measurements and Mitigation

Report 18/0197/R3

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Introduction

1 Report Content

1.1 Underground train noise and vibration is perceptible in a number of residences on the Barbican Estate. These have led to complaints which started to emerge in the 1970's but there is written evidence of complaints and subsequent noise studies dating back to 1990.

1.2 The Corporation of London (CoL) are currently engaged in discussions with London Underground Limited (LUL) to determine the level and extent of the disturbing noise, the primary causes of it and what measures can be implemented in order to mitigate it. Cole Jarman (CJ) have been instructed by CoL to review the work undertaken to date, carry out independent measurements and provide independent input into those on-going discussions.

1.3 The first part of this report sets out the results of measurements undertaken at selected locations on the Barbican Estate above the Circle, Metropolitan and Hammersmith and City lines. The measurements were carried out between 17th and 19th July 2018. The results are largely in line with those obtained by London Underground Limited (LUL) in their own investigations of the same properties, and they confirm that levels are high enough to exceed criteria for acceptability that are commonly applied in these circumstances.

1.4 Discussions have been held between LUL and the Corporation of London (CoL) regarding the level and extent of the disturbing noise, the primary causes of it and what measures can be implemented in order to mitigate it. Some information on the configuration of the underground railway lines has been provided by LUL and some information has been obtained through research by CoL.

1.5 The second part of this report aims to summarise what is known about the LUL lines, their interface with the Barbican structure and the levels and causes of the noise and vibration generated. It also identifies where further information would be helpful to clarify understanding and considers what measures might be available to LUL and CoL in order to mitigate the effects of the railway on the Barbican residents.

1.6 The attached Glossary of Acoustic Terms defines and explains the noise and vibration indices used in this report. It also contains a 'Noise Thermometer' which presents the levels at which everyday sounds can occur, giving some context the levels of train pass-by noise that are set out in this report.

Part 1: Measurements

2 Methodology

2.1 Locations

2.1.1 Measurements were carried out at:

- Brandon Mews, living room and kitchen (ground floor);
- Defoe House, bathroom and bedroom;
- Gilbert House, living room and kitchen;
Lambert Jones Mews, living room and kitchen (ground floor).

2.1.2 These locations are shown relative to the LUL railway lines below.

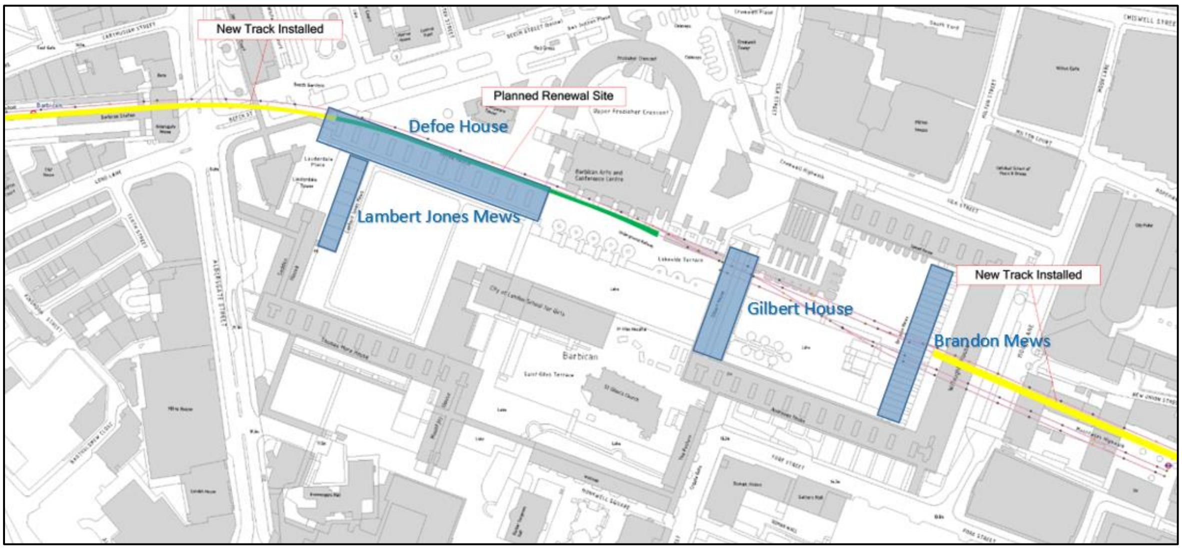


Figure 1: LUL track alignment and configuration below the Barbican Estate

2.2 Timing

2.2.1 Attended measurements were carried out on Tuesday 17th July within each of the above properties as follows:

- Brandon Mews: 11h30 to 12h00;
- Defoe House:12h30 to 13h30;
- Gilbert House: 14h30 to 15h15;
- Lambert Jones Mews: 15h30 to 16h00.

2.2.2 In addition, continuous noise and vibration logging was carried out within:

- Brandon Mews, living room: 17th July - 16h30 to 18th July - 10h00;
- Defoe House: 18th July -11h30 to 19th July -11h00;

2.3 Instrumentation

2.3.1 Attended measurements and unattended logging of noise and vibration levels were carried out using calibrated instrumentation as follows:

Item	Manufacturer	Type
Tough book PC running Samurai real time analyser software	*Panasonic*, and *Noise & Vibration Works*	Soundbook 4 channel interface + siNoise version 1.1.25
Microphone	*GRAS*	41AL
Acoustic Calibrator	*Norsonic*	1251
Accelerometer x3	*Dytran*	3191A1 (10V/G)

T1 Equipment used during LUL train pass-by noise and vibration measurements

2.3.2 Three accelerometers were used to obtain tri-axial vibration data as follows:

- Channel 1: vertical z-axis;
- Channel 2: horizontal x-axis – orientated approximately parallel with the LUL tracks;
- Channel 3: horizontal y-axis – orientated approximately perpendicular with the LUL tracks.

2.3.3 The three accelerometers are fixed within a metal block that holds them in mutually perpendicular orientations, and the metal block sits on three spiked feet. The spikes allow the block to make firm contact with the underlying structure even when it is set up on carpet, which was necessary at some measurement locations.

2.3.4 The equipment was set to monitor the maximum noise and vibration level during each consecutive 1-second period. This enabled us to capture and report the following information for each train pass-by:

- Noise: $L_{Amax,f}$ and one-third octave band $L_{max,f}$ (20 Hz to 2,500 Hz), dB re 2 x 10^{-5} Pa;
- Vibration: $L_{max,f}$ and one-third octave band $L_{max,f}$ (6.3 Hz to 200 Hz), dB re 10^{-6} ms^{-2}.

2.3.5 The actual frequency range over which noise and vibration data were recorded is greater, but we have limited reporting to the indicated range for simplicity of presentation and to focus on the important spectral components of the overall noise and vibration levels.

2.3.6 Supplementary attended measurements were made using additional calibrated instrumentation as follows:

Item	Manufacturer	Type
Sound Level Analyser	*Norsonic*	140 *(serial no. 1405822)*
Vibration Analyser	*Norsonic*	140 *(serial no. 1403015)*
Accelerometer x1	*DJB*	A/120/V

T2 Supplementary noise and vibration measurement equipment

2.3.7 Norsonic 140 (serial no. 1405822) was set to measure noise levels, while Norsonic 140 (serial no. 1403015) was connected to the DJB accelerometer, which was in turn affixed to an appropriate hard surface using beeswax, and set to measure vibration levels in the vertical (z-axis) only.

2.3.8 Each meter recorded data during each consecutive 1-second period.

2.3.9 The purpose of the supplementary measurements was to double check and validate the data recorded on the Soundbook and detailed results are not set out in this report.

3 Results

3.1 Vibration Levels

3.1.1 It should be noted that at this stage of our analysis we are presenting data for vibration levels in the vertical (z-axis) only. This has been found to be the dominant vibration component and therefore gives a fair indication of the overall tri-axial vibration levels at any given location.

3.1.2 In addition, we believe that the data presented in the various LUL reports pertains to vertical vibration level only, and a comparison between the CJ data and the LUL data has more substance if vibration is assessed on a like for like basis.

3.1.3 The tri-axial vibration data remains available for further analysis should be deemed helpful at any stage of the on-going investigation.

3.2 Time Histories

3.2.1 Time histories of the noise and/or vibration levels are available over the full period for which measurements were carried out. In the case of Brandon Mews and Defoe House, the extended monitoring periods means that a significant amount of data has been acquired. We are not attempting to present it all in this report.

3.2.2 Instead, we have assessed the data and selected a number of shorter time periods during which train pass by noise or vibration levels are materially above the ambient conditions and therefore provide data which lends itself to analysis. The time varying noise and vibration levels are set out for these shorter time periods in the following figures:

Brandon Mews

18/0197/THNV01: 17th July, 11h52 to 11h56: attended measurements, 4 pass-bys;
18/0197/THNV02: 18th July, 05h20 to 05h40: unattended measurements, 4 pass-bys;
18/0197/THNV03: 18th July, 08h00 to 08h10: unattended measurements, 8 pass-bys.

Defoe House

18/0197/THNV04: 17th July, 12h33 to 12h43: attended measurements, 5 pass-bys;
18/0197/THNV05: 19th July, 05h20 to 05h40: unattended measurements, 4 pass-bys;
18/0197/THNV06: 19th July, 08h00 to 08h20: unattended measurements, 8 pass-bys.

Lambert Jones Mews

18/0197/THNV07: 17th July, 15h50 to 16h00: attended measurements, 4 pass-bys.

Gilbert House

18/0197/THNV09: 17th July, 14h36 to 14h47: attended measurements, 5 pass-bys.

3.3 Train Direction

3.3.1 We are unable, at present to distinguish between east and west bound operations as we do not have access to the LU intranet application 'Trackernet replayer'. The information can be obtained if the time history information is sent to LUL (Noise and Vibration Section) who will be able to advise whether the direction of train travel (east or west) for each individual occurrence.

3.3.2 For the purposes of this stage of the data processing, the information is not deemed crucial, although it will be sought if or when a more detailed analysis of noise and vibration effects is undertaken.

3.4 Overall Levels

3.4.1 The noise and vibration levels attributable to LUL train pass-bys in each of the assessed properties is set out in table T3 below:

Property	Noise Level $L_{Amax,f}$ (dB re 2 x 10^{-5} Pa)			Vibration Level $L_{max,f}$ (dB re 10^{-6}g)		
	No. Events	Range	Average	No. Events	Range	Average
Brandon Mews	16	39.7 – 49.4	45.1	16	90.9 – 101.6	95.9
Defoe House	16	36.6 – 47.8	42.3	16	87.0 – 92.2	89.4
Lambert Jones Mews	4	45.6 – 50.9	48.4	4	94.7 – 98.3	96.4
Gilbert House	-	-	-	5	79.2 – 89.5	84.7

T3 LUL train pass-by noise and vibration levels at the Barbican Estate

3.5 Noise and Vibration Spectra

3.5.1 The frequency content of the noise and vibration signals captured for each individual pass-by shown in the time histories has been analysed to determine an aggregate spectrum in each receptor property. The results are set out in the following figures:

Brandon Mews: 18/0197/TOB01;
Defoe House: 18/0197/TOB02;
Lambert Jones Mews: 18/0197/TOB03;
Gilbert House: 18/0197/TOB04.

4 Observations

4.1 Time Histories

4.1.1 LUL train pass-bys are identified on the time histories with a red outline.

4.1.2 At Brandon Mews and Defoe House a clear correlation can be seen between the vibration levels and the noise levels. The primary indicator is an increase in vibration levels (shown as ▪▪▪▪) over a period of between 7 and 12 seconds. A confirming indictor is a commensurate rise in noise levels (shown as ▬▬) over the same time period.

4.1.3 Noise levels changes, although identifiable, are less obvious than vibration level changes due to the fact that LUL pass-by noise levels are not significantly higher than the ambient or background noise during parts of the day when people are active are there are multiple airborne noise sources contributing. This is less of an issue for vibration since very few naturally occurring sources can excite a building structure to the same extent as an underground train pass-by.

4.1.4 Comparing the data acquired at different times of the day at Brandon Mews and Defoe House, it is clear that both noise and vibration generated by LUL train pass-bys exceed the background levels by a greater amount during the very early morning when most people are sleeping than they do later in the day when people are active. The absolute noise levels are not on aggregate higher in one period vs, another, although clearly there is variation from one pass-by to another. However, train pass-bys will almost certainly be more perceptible during the otherwise quiet hours (very early morning or very late evening), which is to say they will seem louder and may be more disturbing since they protrude above the background noise level to a greater degree.

4.1.5 At Lambert Jones Mews, the time history confirms the subjective impression that train pass-bys generate noise levels that were difficult to distinguish above the ambient noise that prevailed at the time of the recording. The vibration trace clearly shows when pass-bys occurred and the noise trace indicates corresponding changes that would almost certainly be audible and more noticeable at times when the background noise levels are lower.

4.1.6 At Gilbert House the vibration trace clearly indicates the passage of LUL trains whereas the noise trace does not. This corresponds with the observation on site that vibration is feelable but structure borne sound is not audible. This correlates exactly with the experience of the residents of this property.

4.1.7 One effect of train induced vibration that should not be overlooked is its propensity to lead to secondary noise effects such as rattling of loose building components, fittings, ornaments or crockery. This effect has certainly been commented on by at least one of the residents, although the noise levels so induced do not form part of the result we report.

4.2 Overall Levels

4.2.1 The overall noise and vibration levels presented in section 3.3 above can be compared to those reported in the most recent LUL reports for the individual receptor properties.

Property	Noise Level (dB re 2 x 10^{-5} Pa)			Vibration Level (dB re 10^{-6}g)		
	CJ	LUL West	LUL East	CJ	LUL West	LUL East
Brandon Mews	45.1	45	48	95.9	88	94
Defoe House	42.3	42	32	89.4	94	75
Lambert Jones Mews	48.4	37	37	96.4	76	76
Gilbert House	-	-	-	84.7	85	81

T4 Comparison of LUL and CJ measured train pass-by average noise and vibration levels

4.2.2 It should first be noted that the CJ data currently does not distinguish between west bound and east bound trains, and the average values stated is for all recorded movements. Since the average stated is an acoustic energy, or logarithmic, average of the individual measured levels, the result will be more influenced by the higher recorded values. It is therefore likely that the CJ average value reflects more closely the higher west or east bound values quoted by LUL.

4.2.3 It should also be noted that some differences in the values recorded by each party does not necessarily:

- Indicate that one set of data must be incorrect or invalid; or
- Provide evidence that there has been a demonstrable change in the noise or vibration conditions over the time period between the two sets of measurements.

4.2.4 While both of these factors remain a possibility, the data must be viewed in the light that each set is for a sample of train pass-bys only and there are numerous reasons why the noise and vibration generated by one train differs from that generated by another of the same type. This natural variability must be accepted as being a strong contributing factor to differences in reported values, although it could be minimised by undertaking more comprehensive sets of measurements to gain a better statistical view.

Noise Levels

4.2.5 Taking this natural variability into account, the pass-by noise levels recorded by each party at Brandon Mews and Defoe House are consistent.

4.2.6 At Lambert Jones Mews, the CJ data indicate markedly higher noise levels than those recorded by LUL at this property in February 2015. The report in question, RP-R1712 dated 3rd March 2015, identifies the measurements were made in the downstairs bedroom: the CJ measurements were carried out in the downstairs living room. It should be noted that during the CJ measurements the property was occupied and there was a fair amount of activity noise being generated by the occupants. While we have tried to exclude this from the indicated pass-by noise levels so far as possible, we cannot be 100% certain that this activity does not have some residual effect on the stated levels.

4.2.7 It is, of course, possible that LUL track or operating conditions have changed in the 3+ years since the LUL data were recorded, and we are aware that the rolling stock replacement program could well be a contributing factor. If we need to substantiate this proposition it would be prudent to carry out further measurements at a time when the property is unoccupied and ambient noise levels are otherwise low (e.g. early on a weekday morning).

Vibration Levels

4.2.8 At Brandon Mews, the CJ data suggest levels are similar to, but marginally higher than, those recorded by LUL in June 2017 (N&V-R2093 dated 20th June 2017). The differences are not great and do not point to an obvious systematic change in conditions.

4.2.9 At Defoe House, the CJ average levels are within the range of west and east bound values indicated in the LUL report N&V-R2351 for measurements carried out on 17th May 2018. It should be noted that the LUL report does not explicitly tabulate the measured vibration levels, and the values set out in Table T4 above are estimated from the time history shown in Figure 2 in that report. In any event, it is unlikely that there has been a systematic change in conditions in the 2-month period between the measurements.

4.2.10 At Lambert Jones Mews, the finding for vibration is very similar to that for noise in that the CJ recorded vibration levels are demonstrably higher than those reported by LUL in 2015. In the case of vibration levels, however, the ambient conditions produced by occupants of the property are not significant, and the CJ reported values are considered to accurately reflect vibration generated by LUL train pass-bys. The differences could be due to a change in track or operating conditions or they could be due to differences in measurement location or methodology. In any event the differences should be confirmed and explored further.

4.2.11 At Gilbert House, train pass-by noise is inaudible but vibration is perceptible. Both sets of measurements confirm this and both sets result in comparable recorded vibration levels.

4.3 Noise and Vibration Spectra

4.3.1 Structure borne noise due to LUL train pass-bys exhibits a characteristic frequency peak at 50 – 63Hz in all properties where that noise is audible. Subjectively, it is characterised as a low frequency thudding or rumbling noise.

4.3.2 At those properties, the vibration signal contains components at other frequencies, both above and below the 50 – 63 Hz range, but in all cases the correlation between the energy content in the vibration signal and the noise signal is clear to see.

4.3.3 At Gilbert House, the frequency content of the vibration signal is different, with a peak energy at the much lower frequency of 12.5 Hz. This is indicative of the source vibration being modified by the response of the building structure which, effectively, filters out the higher frequency audible components (at 50 - 63 Hz) but which amplifies the lower frequency energy due a resonant response of the structure.

4.3.4 The resonant mode at play is not known. It could be a response of the floor slab on which the measurements are made or it could be a whole building response given that it is supported on relatively slender concrete columns above Barbican Water. Either way, subjectively the vibration perception in Gilbert House is quite different to that experienced in the other buildings which have been assessed in that is characterised by a more ‘bouncy’ feel with a strong resonant component.

4.3.5 The structural response at Gilbert House is a factor that may need to be considered in more detail when determining possible means of mitigating the LUL train pass-by effects.

5 Context

5.1 Noise Criteria

Ground Borne Train Noise

5.1.1 There are no British Standards for assessing ground-borne noise from trains. Guidance is therefore drawn from Local Authority (LA) guidelines developed for HS1 as well as assessment criteria for the Crossrail project. These are summarised in table T5.

Building	Source	Limit
Residential dwelling	LA guidance for HS1	35 dB L_{AFmax}
Residential building, Offices, Hotels, Schools, Colleges, Hospitals, Laboratories, Libraries	Crossrail	40 dB L_{ASmax}

T5 Underground train ground-borne noise criteria

Who Guidelines

5.1.2 On 10th October 2018, the WHO 2018 Environmental Noise Guidelines were published. The main purpose of the guidelines is to provide recommendations for protecting human health from exposure to environmental noise arising from various sources including railways. For the first time, WHO have provided threshold values that are specific to the individual sources, and for railways these values are: 54dB L_{den} for average exposure and 44 dB L_{night} for night-time exposure. WHO strongly recommends reducing noise levels produced by railways below these values, as above them noise from railways is associated with adverse health effects.

5.1.3 The WHO noise thresholds are presented in noise metrics that aggregate the effects of train pass-bys over a 24-hour period in the case of average exposure and an 8-hour (23h00 to 07h00) period in the case of night-time exposure. In addition, they are external values intended to apply at the most exposed façade of any affected building within which people are living, working or carrying out recreational activities.

5.1.4 Applying these guidelines to the assessment of LUL train pass-bys affecting people living in the Barbican Estate is therefore not appropriate, as they provide no assistance in determining the effects of individual pass-bys experienced within a dwelling as structure borne noise.

5.1.5 More relevant in this instance are the WHO: Night Noise Guidelines for Europe 2009. These include a summary of effects and threshold levels for observed effects, and in relation to events best characterised by the L_{Amax} value, threshold levels that are supported by sufficient evidence are:

- 32 – 42 dB $L_{Amax,\ inside}$ thresholds for biological and sleep quality effects

Sufficient evidence: A causal relation has been established between exposure to night noise and a health effect. In studies where coincidence, bias and distortion could reasonably be excluded, the relation could be observed. The biological plausibility of the noise leading to the health effect is also well established.

A number of instantaneous effects are connected to threshold levels expressed in L_{Amax}. The health relevance of these effects cannot be easily established. It can be safely assumed, however, that an increase in the number of such events over the baseline may constitute a subclinical adverse health effect by itself leading to significant clinical health outcomes.

5.1.6 The WHO 2009 guidelines are therefore consistent with the thresholds values adopted for the assessment of new railway projects giving rise to ground borne noise.

5.2 Feelable Vibration

5.2.1 Relevant feelable vibration criteria are set out in British Standard BS6472:2008, which looks at the vibration dose value (VDV). For information, the vibration dose value ranges and their equivalent probabilities of adverse comment are listed below.

Vibration dose value ranges ($ms^{-1.75}$) which might result in various probabilities of adverse comment within residential buildings

Place	Low probability of adverse comment (1)	Adverse comment possible	Adverse comment probable (2)
Residential, 16h day	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
Residential, 8h night	0.1 to 0.2	0.2 to 0.4	0.4 to 0.8

(1) Below these ranges adverse comment is not expected
(2) Above these ranges adverse comment is very likely

T6 Table 1 of BS6472:2008

5.2.2 VDV values have not been recorded in each property and it is therefore more instructive to consider the effect of vibration generated by individual pass-bys.

5.2.3 In addition, the older 1992 edition of the standard can also be used, as this provides useful information regarding the perceptibility of vibration at different frequencies. While the targets in BS6472:1992 are less representative of human perception, they can be useful when considering engineering means to control vibration.

5.2.4 BS6472:1992 defines a reference Curve 1 which can approximate the threshold of human vibration perception. The curve has different values for vertical and horizontal motion and is determined between 1 and 80Hz.

5.2.5 For residential buildings at night the standard suggests a multiplying factor of 1.4 to this Curve 1 would typically be acceptable. This curve has been added (as ——) in figures 18/0197/TOB01 to TOB04 in order to determine the degree of perceptibility of the recorded vibration levels.

5.3 Measured Levels

5.3.1 The LUL train pass-by noise levels measured by CJ in all properties, with the exception of Gilbert House, exceed all of the relevant thresholds set out in Section 5.1. The aggregate pass-by noise level measured by CJ exceeds the thresholds value by the following amounts, depending on which threshold value is selected (32 dB $L_{Amax,f}$ being the lowest and 42 dB $L_{Amax,f}$ being the highest):

- Brandon Mews: 3 - 13 dB;
- Defoe House: 0 – 10 dB;
- Lambert Jones Mews: 5 – 15 dB;
- Gilbert House: N/A.

5.3.2 These excesses are corroborated by LUL's own measurements.

5.3.3 The measured LUL pass-by vibration levels are assessed in third octave bands on each of figures 18/0197/TOB01 to TOB04. It can be seen that, with the exception of Defoe House, all properties are subject to pass-by vibration levels that exceed the relevant threshold in the frequency region for which energy is the highest.

Part 2: Mitigation

6 Noise and Vibration Features

6.1 Character

6.1.1 Structure borne noise due to LUL train pass-bys exhibits a characteristic frequency peak at 50 – 63Hz in all properties where that noise is audible. Subjectively, it is characterised as a low frequency thudding or rumbling noise.

6.1.2 At those properties where train pass-bys are clearly audible, the vibration signal contains components at other frequencies, both above and below the 50 – 63 Hz range, but in all cases there is a clear correlation between the energy content in the vibration and the noise signals.

6.1.3 At Gilbert House, the frequency content of the vibration signal is different, with a peak energy at the much lower frequency of 12.5 Hz. This is indicative of the source vibration being modified by a resonant component (or components) of the transmission path which, effectively, filters out the higher frequency audible components (at 50 - 63 Hz) but which amplifies the lower frequency energy.

6.1.4 The resonant mode at play is not known. It could be a response of the Gilbert House structure, such as the floor slab on which the measurements are made or a whole building response given that it is supported on relatively slender concrete columns above Barbican Water.

6.1.5 Alternatively, it could be a feature of the track installation, which on this particular section have the ballast supporting deck supported on resilient rubber bearings. Further details of the resiliently supported track sections are set out in Section 3.1 below, but there is a possibility (so far unchecked and therefore uncorroborated) that the system has a resonant response at 12.5 Hz.

6.1.6 Either way, subjectively the vibration perception in Gilbert House is quite different to that experienced in the other buildings which have been assessed in that is characterised by a more ‘bouncy’ feel with a strong resonant component.

6.2 Track Replacement

6.2.1 It should be noted that since the measurements referred to above were undertaken, a section of track at the western end of the Barbican Estate has been replaced. We understand this to be that section coloured green in Figure 1 above, and the works have involved replacing the ballast and then installing flat bottomed rail on concrete sleepers (replacing bull head rail on timber sleepers).

6.2.2 We also understand that jointed rail has been replaced by continuously welded rail.

6.2.3 Anecdotally, this has led to a reduction in the levels of noise and vibration perceived by the occupants of Defoe House. Measurements undertaken and reported by LUL on 5th and 9th October 2018 identify that noise levels are indeed lower in two apartments in Defoe House than were recorded in May 2018.

6.2.4 It is also worth noting that the annotation in Figure 1 suggests that there is a section of track between the eastern end of the Arts Centre running beneath Gilbert House, past the Guildhall School of Music and Drama (GSMD) and beneath Brandon Mews which has not been replaced and which is not scheduled to be replaced. It is important to clarify LUL intentions with regard to this section of track and why it is deemed that no replacement is necessary, if that is indeed their judgement.

7 LUL Tracks

7.1 Known

7.1.1 Appendix A is a copy of a report received from LUL following a track walk by LUL Noise and Vibration Section. The report is extremely helpful in establishing the line configuration and type of track form installed beneath different parts of the Barbican Estate.

7.1.2 Figure 5 of that report is replicated as Figure 2 below as it provides a very helpful overview of the LUL system directly beneath the Barbican Estate.

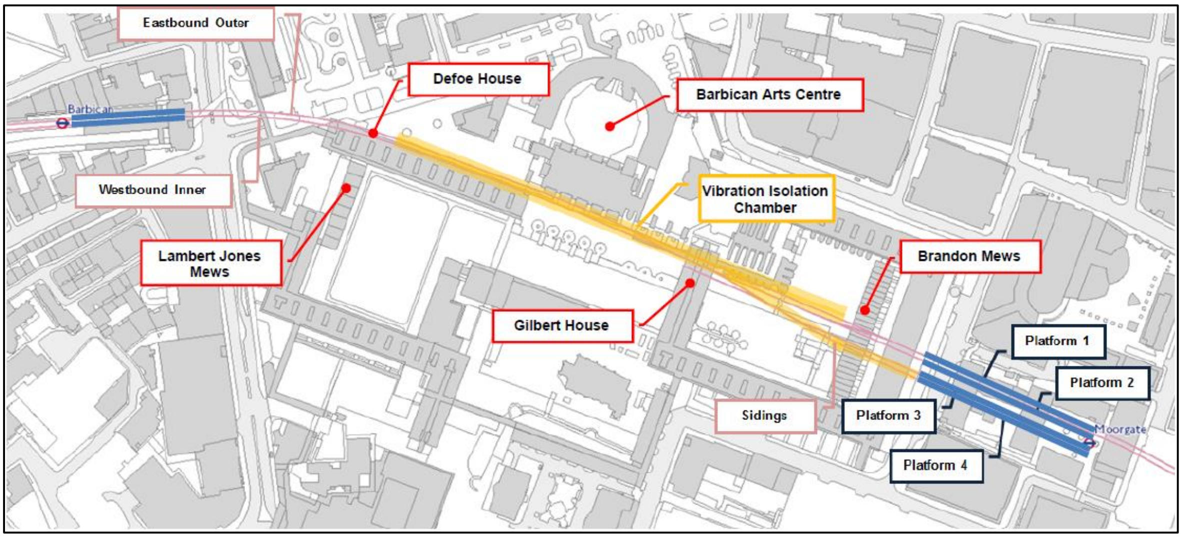


Figure 2: LUL track alignment and configuration below the Barbican Estate

7.1.3 The following important points are worth noting:

Cut and Cover Tunnel

7.1.4 Originally, the railway running across the site comprised surface tracks, but these were realigned and covered over prior to construction of the Barbican Estate. This was started in about 1959 and involved straightening the alignment of the tracks between Moorgate and Aldersgate (now renamed Barbican) stations. It also involved a reversal of the gradients, such that the railway was dropped to a low spot between the two stations, some 15 ft. 6 in. (4.7 m) below the original level.

7.1.5 The foundations of the covered railway were cast on in-situ bored piles, with the enclosing structure designed in reinforced concrete. The roof of the tunnel containing new, realigned railway was also of in situ concrete but where a roof was installed over existing railway pre-cast construction was used.

7.1.6 The form of construction, commonly referred to as 'cut and cover', means that the LUL lines are contained within relatively shallow tunnels, the structure of which would need to be carefully coordinated with the foundations and lower levels of the later built Barbican buildings.

7.1.7 This is in contrast to the deep bored tunnels that have been constructed for Crossrail and which pass under the Barbican Estate substantially lower than any part of its foundations or other structure.

Ballast Track Form

7.1.8 For its entire length beneath the Estate every track on the LUL line takes the form of rails fixed to sleepers supported by ballast. Our understanding is that the sections of track coloured yellow and green in Figure 1 are flat head rail on concrete sleepers, while the uncoloured section is older bull head rail on timber sleepers.

7.1.9 Photos of each of these track types are shown in the LUL report attached as Appendix A.

Vibration Isolated Railway

7.1.10 The section of track coloured yellow in Figure 2 has the ballast carrying concrete deck supported on resilient rubber bearings as a means of reducing noise and vibration transmission from the railway to the buildings above. Photos of the resilient bearings and their support details are shown in the appendix, but effectively the arrangement forms a lower, accessible chamber beneath the railway deck via which the bearings can be accessed for inspection, maintenance replacement etc.

7.1.11 The arrangement is shown in Figure 3 below, which is an image taken from a Higg & Hill cross section drawing N18203 dated august 1966, as supplied by LUL:

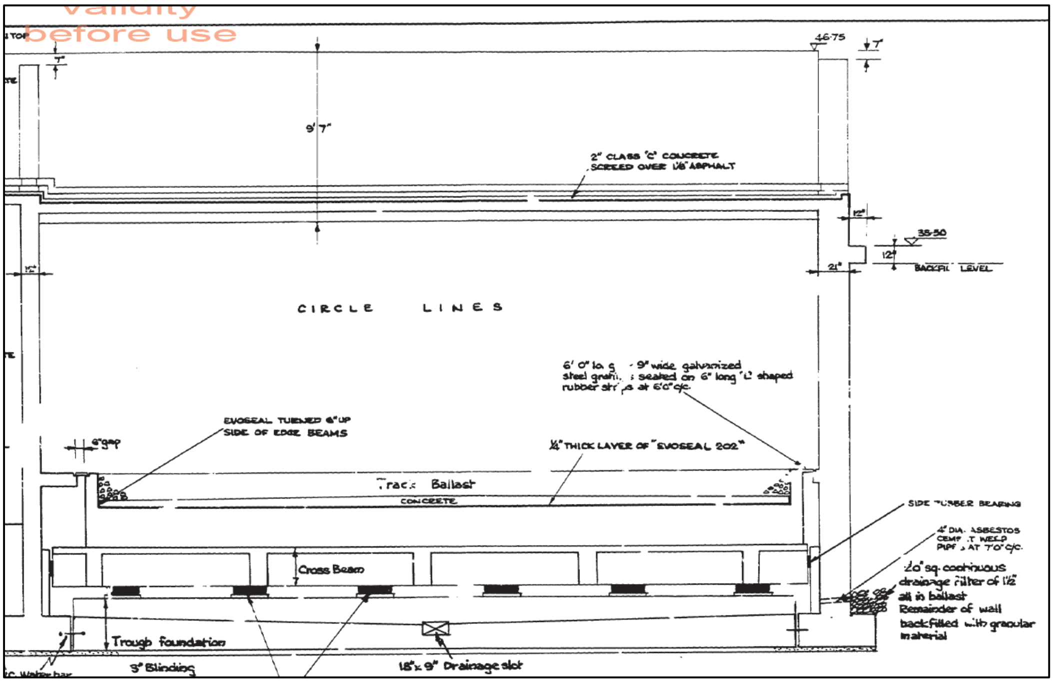


Figure 3: Cross section through part of LUL tunnel containing vibration isolation supported track deck

7.1.12 The isolated section of track runs for just over 300m beneath both the east and west running lines but plainly does not run under the entire length of the Estate. The following is of note:

- The transition between un-isolated and isolated track occurs beneath the western end of Defoe House, approximately between cores 4 and 5. This correlates with the experience of people living within the building that noise and vibration levels do cause disturbance at the western end of the building but this reduces to the point of no complaints arising from residents of the eastern end (closest to the Barbican Centre);

- Noise from LUL train pass-bys is not audible within the Arts Centre nor the GSMD. We have previously carried out measurements of background noise levels within the Barbican Concert Hall, and LUL train pass-bys were not feelable and not audible above the background noise level of NR18;

- Pass-by noise is not audible within Gilbert House, but vibration is feelable. As noted in Section 2.4 above, the frequency content of the vibration indicates that it is affected by a resonance within the transmission path, either within the structure of Gilbert House or possibly a feature of the resiliently supported track bed;

- The isolation system does not extend along the main running tunnels under Brandon Mews nor Willoughby House. Train pass-bys have led to significant complaints from some residents of Brandon Mews living above the running track and measurements carried out in this building indicate levels well above the appropriate thresholds. To our knowledge, no complaints have arisen from occupants of Willoughby House and no measurements have been carried out there;

- The sidings leading into platforms 3 and 4 of Moorgate Station do benefit from being isolated for their full length beneath the Barbican Estate. We understand there are very few positioning movements along these sidings.

Rail Discontinuities

7.1.13 Points, crossings and other discontinuities such as track joints are significant in that they all lead to higher levels of vibration being generated as wheels roll over them compared to smooth track. This in turn leads to higher levels of noise and vibration in receptor dwellings whose occupants can often experience the impact forces generated as a 'thumping' noise each time a set of wheels pass over the discontinuity.

7.1.14 Page 2 of the report attached as Appendix A describes the location and identifiers for points and crossing located beneath the Barbican Estate. Taking the length along track given in the report we understand:

- Points and crossing 35(a) and 35(b) are located beneath Brandon Mews, approximately lining up with Number 14. These are located on an un-isolated section of the track;
- Points and crossing 31(a) and 31(b) are located beneath Gilbert House, adjacent to the GSMD. These are located on an isolated section of the track.

7.2 Unknown

7.2.1 To better understand the full influence of the LUL railway on the transmitted noise and vibration there are some matters requiring clarification.

Vibration Isolated Railway

7.2.2 As noted above, the isolated track does not extend beneath the entire Barbican estate, with the transition between isolated and un-isolated track occurring beneath Defoe House and beneath the gardens immediately to the east of Brandon Mews. It is normal for the transition from rigid to resilient track to occur gradually with stiffness gradually decreasing (or increasing in the opposite direction).

7.2.3 We have no details of how the transition has been engineered in this instance and would like confirmation of whether any specific provisions have been made.

Track Joints

7.2.4 We believe that sections of track that have not recently been replaced (see the uncoloured track segments between GSMD and Willoughby House in Figure 1 above) comprise jointed rail (bull head type on timber sleepers). In contrast, those sections that have been recently replaced are continuously welded rail (flat bottomed on concrete sleepers).

7.2.5 It would be helpful to have full details confirmed.

Rail Discontinuities

7.2.6 Although not identified in the Appendix A report, we understand that a discontinuity has been cut into the rails directly beneath Gilbert House. We have been informed that it was only after this work was undertaken that residents of Gilbert House began to be disturbed by vibration from LUL train pass-bys.

7.2.7 We do not have details of vibration levels within Gilbert House before and after the discontinuity was introduced, so we cannot confirm or comment on whether the correlation is correct.

7.2.8 However, we have accessed the low level areas beneath Gilbert House adjacent to the Circle Line running tracks and it was my subjective impression that when trains ran over a discontinuity in this area, there was a very significant degree of impact noise generated. It is my impression that if this associated with a break in the rails, then there may well be a significant height differential either side of the break.

7.2.9 The question is, if the break is necessary, can adjustments be made to minimise the degree of impact caused when train wheels roll over it (or them, if in both rails)?

8 Barbican Buildings

8.1 Structure

8.1.1 The railway predates the Barbican Estate and the realignment and tunnelling works were carried out prior to any of the estate being built.

8.1.2 The relationship between the structure of the Barbican Estate buildings and the LUL railway is understood to be as follows:

Lambert Jones Mews

8.1.3 We have no details of the structure for Lambert Jones Mews, but given that this is a relatively low-rise town house structure, we would anticipate it is built on a ground bearing slab, founded at a much higher level than the base of the running tunnels. We do not believe there is a direct structural connection to the LUL running tunnels, although the two structures are located physically very close to each other.

8.1.4 Transfer of vibration from passing trains into the properties in Lambert Jones Mews would be via the soil separating the two adjacent but independent structures.

Defoe House

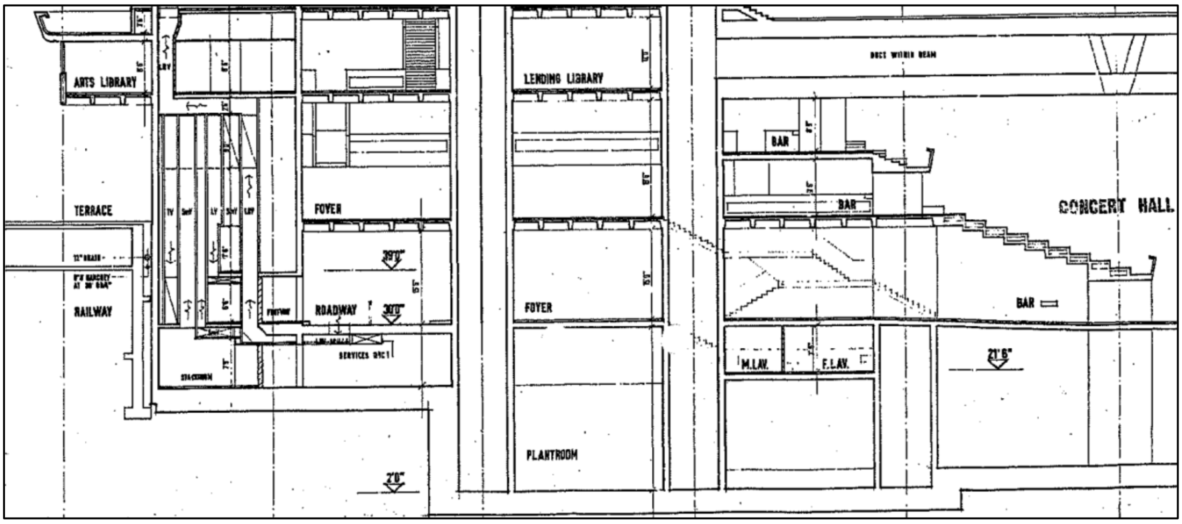
8.1.5 We believe that Defoe House is not structurally connected to the LUL running tunnels. A limited inspection of the interface between the two, undertaken from the lowest accessible parts of Defoe House, reveals an arrangement as shown in the photos below.

Interface of Defoe House structure with LUL running tunnel, showing a clear gap of ~400mm

8.1.6 The gap between the tunnel and Defoe House is in the order of 400mm. The gap is observed to extend from the very bottom of both structure to a point above the roof of the tunnel. The Defoe House structure spans above the tunnel and, so far as we were able to observe, the two remain independent of each other.

Arts Centre

8.1.7 We have not had the opportunity of inspecting the interface between the Arts centre and the LUL Tunnels, but the image below is taken from a cross section drawing GL/P/101C dated 21 April 1969. At this location the running tunnels are located on isolation bearings.



LUL tunnels sit below the Terrace but not connected to the main structure of the Arts Centre

8.1.8 It is certainly and advantage that the highly sensitive Concert Hall is located some distance from the LUL tunnel. There are other, less sensitive spaces such as plant rooms, the roadway and foyer spaces that act as buffers between the two.

Guildhall School of Music and Drama

8.1.9 We believe that the LUL tunnel is similarly separated from the building structure in the case of the GSMD, but we do not have images or drawings that clearly demonstrate this. We do know that at this location that the running tunnels are located on isolation bearings.

Gilbert House

8.1.10 We do not have images or drawings that clearly identify the structural details of Gilbert House nor how they interface with the LUL tunnel. However, given its position between both the Arts Centre and the GSMD, we would expect that it too remains independent as it spans across the tunnels. It is, however, in very close physical proximity.

8.1.11 At this location the running tunnels are located on isolation bearings.

Brandon Mews

8.1.12 We believe that Brandon Mews is structurally connected to the LUL running tunnels to a significant extent. Like Lambert Jones Mews this is a relatively low-rise town house structure, and we would anticipate it is built on a ground bearing slab, founded at a higher level than the base of the running tunnels.

8.1.13 However, Brandon Mews spans directly across the LUL tunnels, and the arrangement within the basement of the building clearly reveals the location of the tunnel and how the Brandon Mews structure appears to be built directly on top of it for the spanning section.

8.1.14 The arrangement is shown in the photos below.

Basement of Brandon Mews spanning across the LUL tunnels, the top of breaks into the space

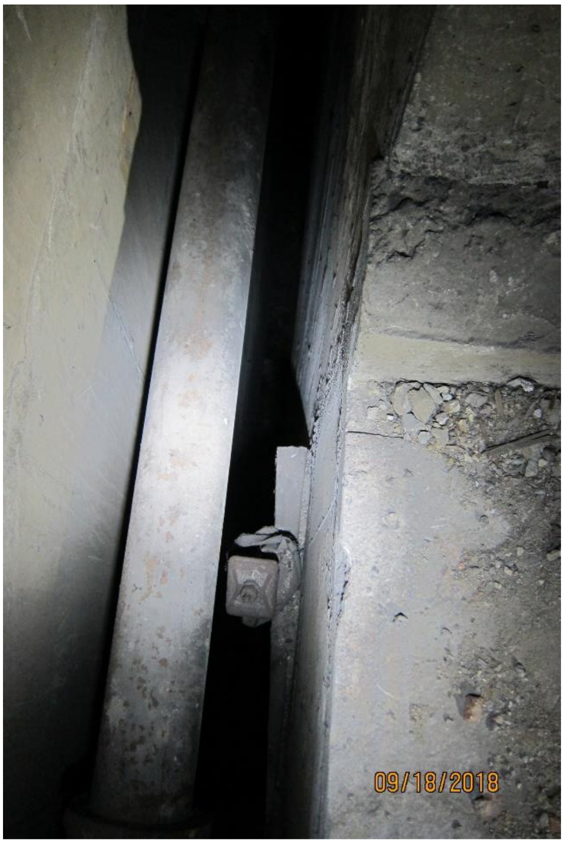
8.1.15 The direct physical connection between Brandon Mews and the railway tunnel, together with the fact that the track has not recently been replaced and contains points and crossings directly beneath the building all contribute to the relatively high levels of noise and vibration experienced at this location.

8.2 Bridging

8.2.1 Even where structures are independent, the separation between them is not large and there are a number of built or installed elements that can or do form a connection.

Services

8.2.2 There are locations where services are routed in the space between the Barbican structure and the tunnel. Examples are shown in the images below.



Soil/water pipe at Defoe House

Electric cable on the tunnel at Gilbert House

8.2.3 There is the risk that where services are clearly connected to both the building and the tunnel structures, they provide a direct transmission path for vibration between the two. This is particularly the case where the service may span between an isolated section of the tunnel and the adjacent structure.

8.2.4 A related concern is that even if services to not actually bridge from tunnel to building, they could form obstructions for the accumulation of debris or discarded materials which could in turn act as bridging elements.

Constricted Locations

8.2.5 There are locations where, even in the absence of services, the design and construction of the tunnels leads to a particularly narrow separation to the adjacent building structure. Examples are shown in the images below.

Isolated tunnel adjacent to Barbican structure

Flexible connection at 'pinch point'

8.2.6 As noted above for services located between the two structures, care must be taken to ensure that at points of constriction there is no direct transmission path for vibration. Similarly, it is important that pinch points do not form obstructions for the accumulation of debris or discarded materials which could in turn act as bridging elements.

9 Mitigation Options

9.1 Housekeeping/Maintenance

9.1.1 There are a number of relatively straightforward and cost effective measures that can be implemented to reduce the levels of noise and vibration transmitted into the Barbican residential areas. Each measure on its own is not expected to have a significant effect, but taken together, and implemented carefully across the estate, they would be expected to lead to worthwhile results.

9.1.2 We term these housekeeping or maintenance measures and they should be considered to control the effects of underground train operations without a significant or costly intervention.

Within Tunnels

9.1.3 Options are only available to LUL and include:

- *Rail discontinuities:* where points and crossings or breaks in the rail for other engineering reasons, these should be inspected and adjusted with the aim of maintaining the vertical and horizontal offsets to the minimum possible either side of the discontinuity. It is essential that this is undertaken with the clear intent of keeping induced vibration levels to a minimum;

- *Rail joints:* although they are similar in nature and effect to other rail discontinuities, we deal with rail joints separately as in newly installed rail they are not inevitably required and particularly bad rail joints may be symptomatic of rail requiring replacement anyway. Irrespective, all rail joints should be inspected and shimmed/ground as required in order to maintain the vertical and horizontal offsets either side of the joint to the minimum possible;

- *Rail grinding:* regular inspection and grinding of rails should be undertaken to minimise surface roughness and ensure that rails remain free from undulations;

9.1.4 *Wheel grinding:* regular inspection and grinding of train wheels should be undertaken to correct wheel flats.

Outside of Tunnels

9.1.5 This activity may fall to either LUL and CoL/Barbican Estate to undertake but essentially requires the interface between the LUL tunnels and the structure of building across the estate to be inspected at as many locations as possible. As appropriate, the relevant steps may be:

- *Removing debris:* remove any surplus material bridging between the tunnel and the adjacent structure;

- *Adjusting services:* check that any services located within the void between tunnel and estate structure are not causing a direct or rigid connection. Modify services or the method of support as required.

9.1.6 These activities are particularly important in those sections of the tunnel that incorporate the resilient supports.

9.2 Engineering Intervention

9.2.1 Based on the levels of noise and vibration measured by us and LUL in Defoe House, Lambert Jones Mews and, in particular, Brandon Mews, the mitigation required to achieve acceptable standards will require a more significant degree of intervention than the measures outlined above. Such intervention is only within the gift of LUL as it will require substantial modifications to the running track beyond the section that is already on isolated supports.

9.2.2 Appendix B contains a graphic presented to CoL by Crossrail which identifies the typical benefits that can be achieved by different forms of track isolation currently available to railway engineers. Focussing on the ballast track form options, it can be seen that the provision of an Under Ballast Mat is capable of reducing vibration levels by between 5 and 12 dB compared to the current ballast track form installed under the Barbican Centre.

9.2.3 In our view, an engineering intervention that ought to be capable of reducing the LUL noise and vibration impact across the Barbican estate in a practicable manner would comprise:

- Replace that section of track under the estate that still comprises jointed bull head rail on timber sleepers with continuously welded, flat bottom rail on concrete sleepers;
- That section of track beneath Brandon Mews and Willoughby House that is not within the isolated tunnel shall incorporate an appropriate Under Ballast Mat [1] [2] [3];
- That section of track between Barbican Station and Defoe House that has already been replaced but is not within the isolated tunnel shall be modified to incorporate an appropriate Under Ballast Mat.

9.3 Other Measures

9.3.1 The potential mitigation options outlined in Section 9.1 above are by no means considered to be exhaustive. LUL are the railway engineering specialists and we would welcome their views on alternative, and possibly more effective, measures that could be implemented.

1 http://www.pandrol.com/product/pandrol-under-ballast-mats/
2 https://www.getzner.com/en/products/rail-products/under-ballast-mats
3 http://www.tiflex.co.uk/brochures/trk_ballast.pdf

Conclusion

10 Summary

10.1 Measurements have been carried out to determine levels of noise and vibration generated at four properties on the Barbican Estate located above the LUL underground railway line. The measurements confirm subjective impressions that ground borne noise is clearly audible in three of the properties and/or vibration is perceptible in the tested properties.

10.2 The measurement results are broadly in line with those most recently recorded by LUL at each property. At Lambert Jones Mews, the CJ measurements indicate significantly higher levels than those measured by LUL in 2015 and the reasons for this should be the subject of further investigation.

10.3 The measured levels are also found to exceed objective criteria for transient noise and vibration events.

10.4 The measured levels, together with the character of the noise and vibration perceived by those affected, have been considered in relation to the following issues at each individual receptor:

- The location along the line of the LUL tracks running beneath the Barbican estate;
- The track form in the vicinity of each building;
- The relationship between the structure of the LUL tunnel and each of the Barbican buildings.

10.5 Full information is not available, and where additional input from LUL is considered important or necessary this is identified.

10.6 Nevertheless, we have attempted to identify the key factors that affect the level and character of the noise and vibration experienced at each receptor and what steps could be taken to mitigate these to levels consistent with acceptable thresholds.

End of Section

Glossary of Acoustic Terms

L_{Aeq}:

The notional steady sound level (in dB) which over a stated period of time, would have the same A-weighted acoustic energy as the A-weighted fluctuating noise measurement over that period. Values are sometimes written using the alternative expression dB(A) L_{eq}.

L_{Amax}:

The maximum A-weighted sound pressure level recorded over the period stated. L_{Amax} is sometimes used in assessing environmental noise when occasional loud noises occur, which may have little effect on the L_{Aeq} noise level. Unless described otherwise, L_{Amax} is measured using the “fast” sound level meter response.

L_{A10} & L_{A90}:

If non-steady noise is to be described, it is necessary to know both its level and degree of fluctuation. The L_{An} indices are used for this purpose. The term refers to the A-weighted level (in dB) exceeded for n% of the time specified. L_{A10} is the level exceeded for 10% of the time and as such gives an indication of the upper limit of fluctuating noise. Similarly, L_{A90} gives an indication of the lower levels of fluctuating noise. It is often used to define the background noise.

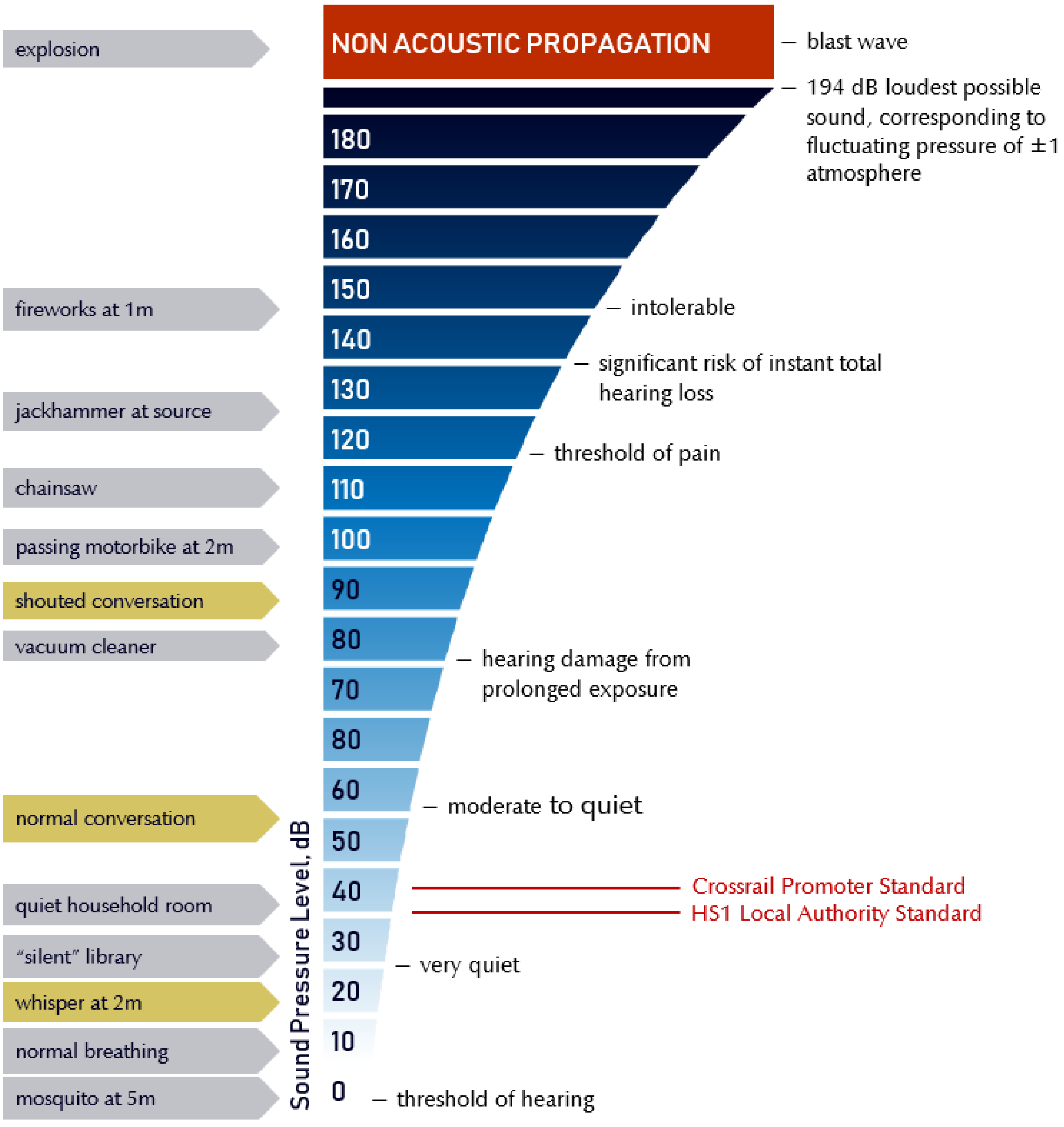
L_{A10} is commonly used to describe traffic noise. Values of dB L_{An} are sometimes written using the alternative expression dB(A) L_n.

L_{AX}, L_{AE} or SEL

The single event noise exposure level which, when maintained for 1 second, contains the same quantity of sound energy as the actual time varying level of one noise event. L_{AX} values for contributing noise sources can be considered as individual building blocks in the construction of a calculated value of L_{Aeq} for the total noise. The L_{AX} term can sometimes be referred to as Exposure Level (L_{AE}) or Single Event Level (SEL).

Measurements and Mitigation

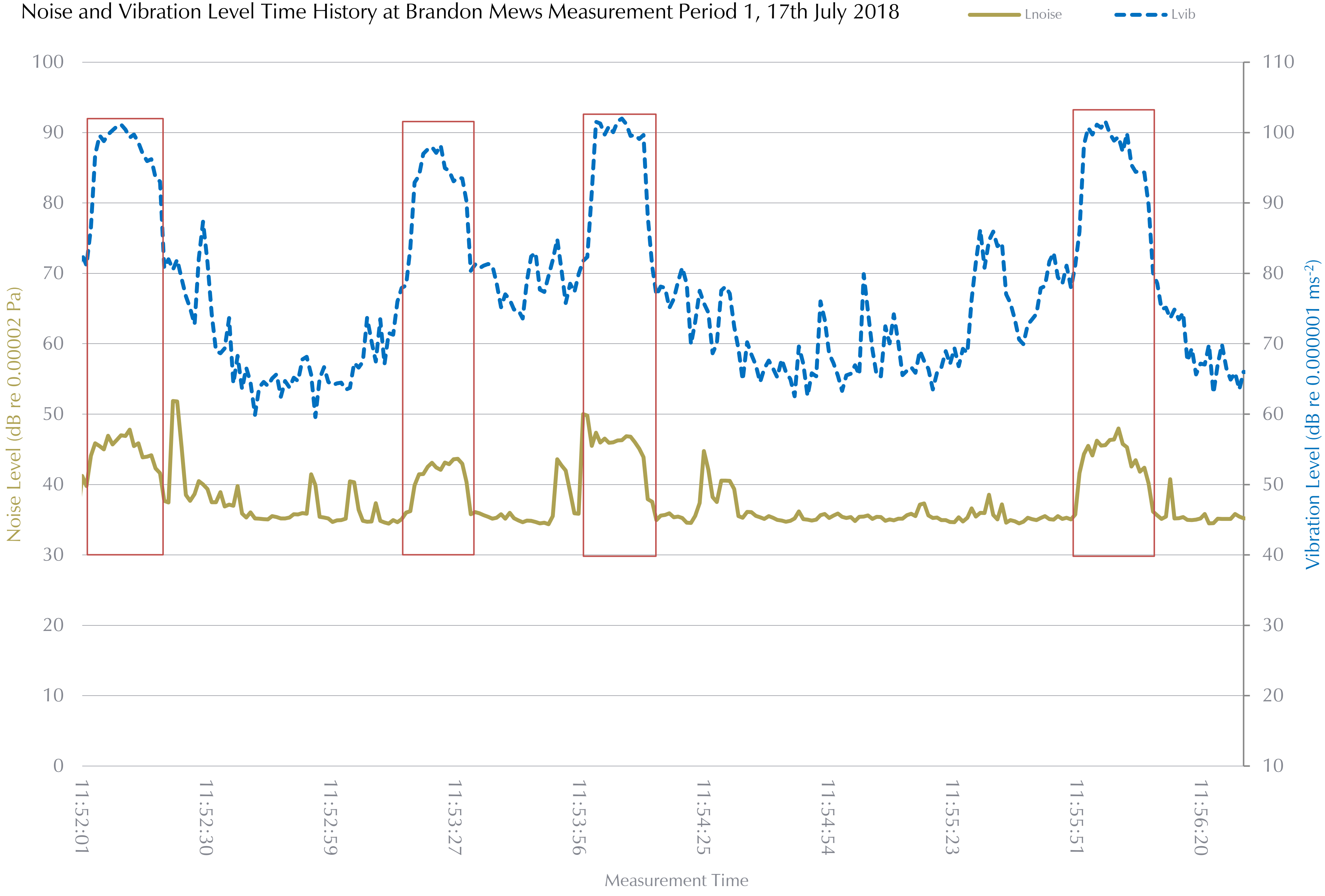
Noise Thermometer

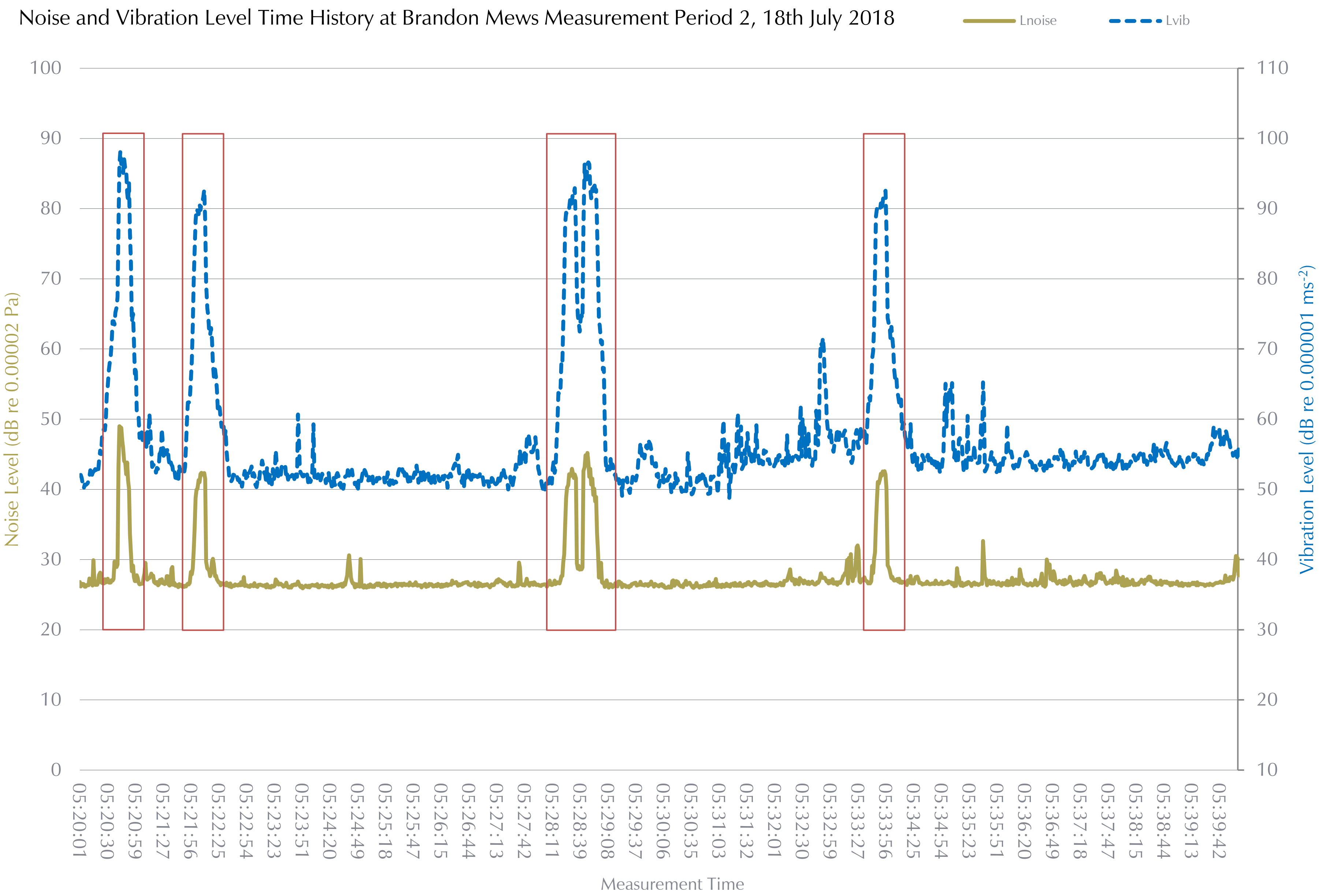


End of Section

Figure 18/0197/THNV.01

Noise and Vibration Level Time History at Brandon Mews Measurement Period 1, 17th July 2018




Noise and Vibration Level Time History at Brandon Mews Measurement Period 2, 18th July 2018
Lnoise
Lvib
Noise Level (dB re 0.00002 Pa)
Vibration Level (dB re 0.000001 ms-2)
Measurement Time
100
90
80
70
60
50
40
30
20
10
0
110
100
90
80
70
60
50
40
30
20
10
05:20:01
05:20:30
05:20:59
05:21:27
05:21:56
05:22:25
05:22:54
05:23:23
05:23:51
05:24:20
05:24:49
05:25:18
05:25:47
05:26:15
05:26:44
05:27:13
05:27:42
05:28:11
05:28:39
05:29:08
05:29:37
05:30:06
05:30:35
05:31:03
05:31:32
05:32:01
05:32:30
05:32:59
05:33:27
05:33:56
05:34:25
05:34:54
05:35:23
05:35:51
05:36:20
05:36:49
05:37:18
05:37:47
05:38:15
05:38:44
05:39:13
05:39:42

Noise and Vibration Level Time History at Brandon Mews Measurement Period 3, 18th July 2018

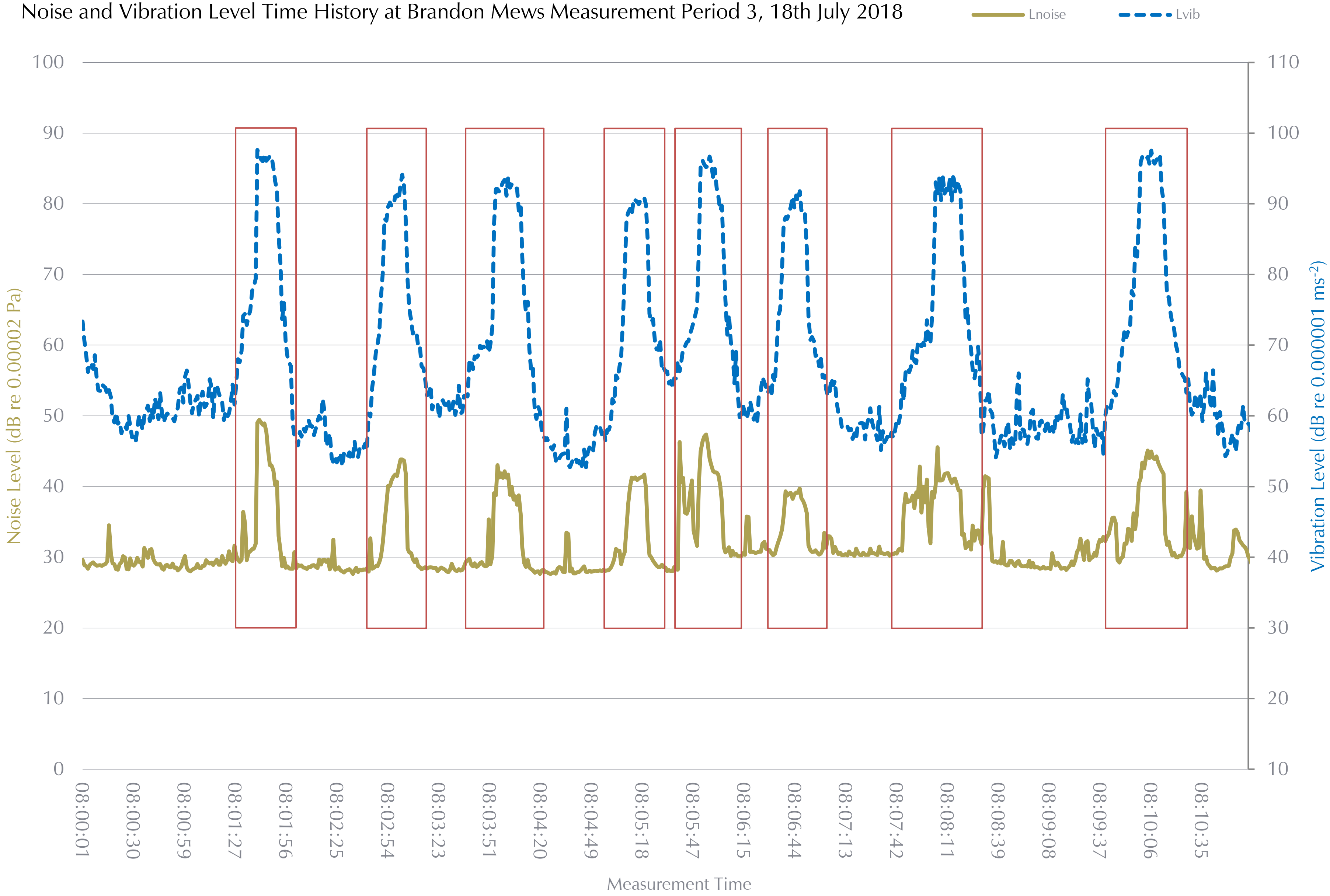
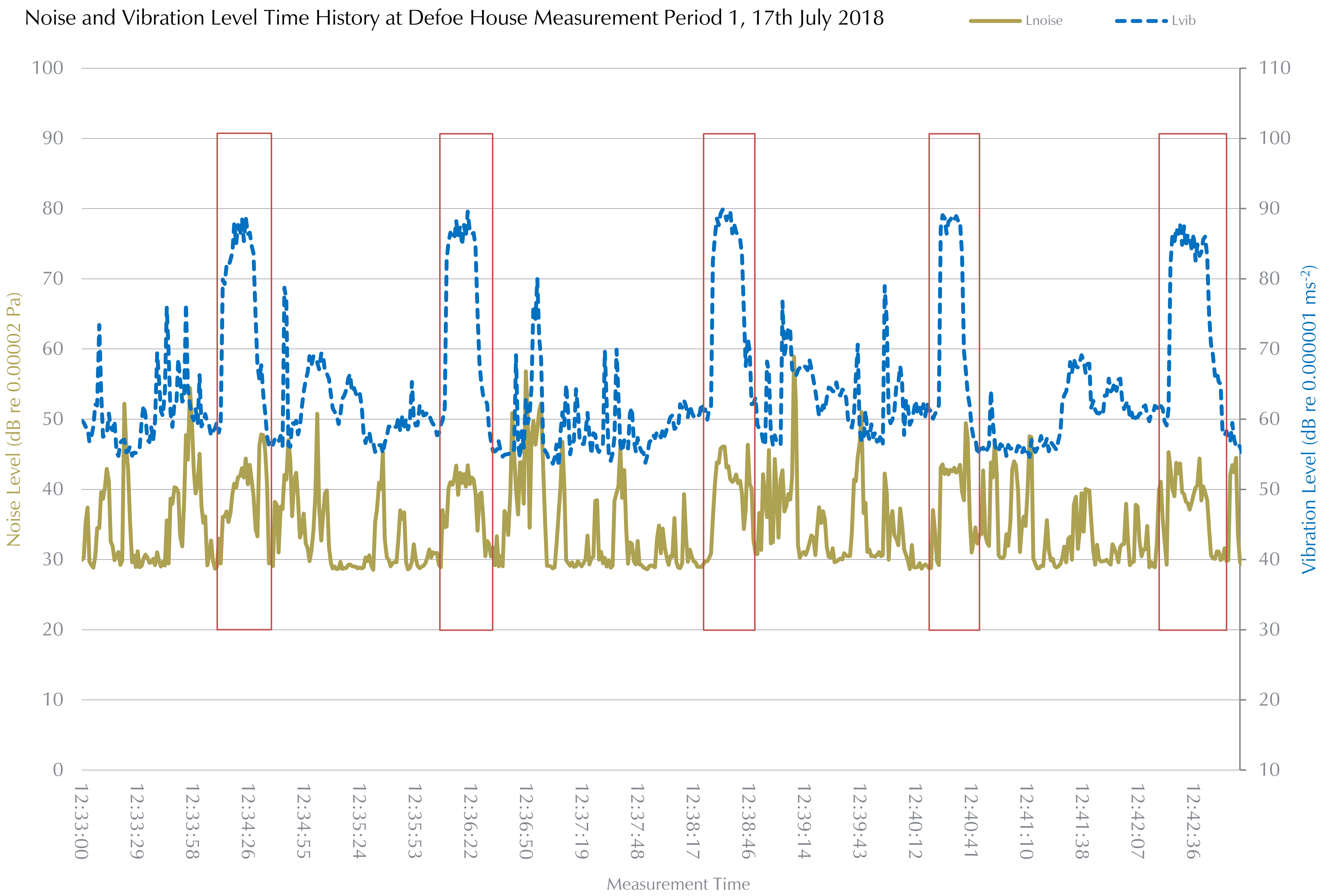


Figure 18/0197/THNV.04



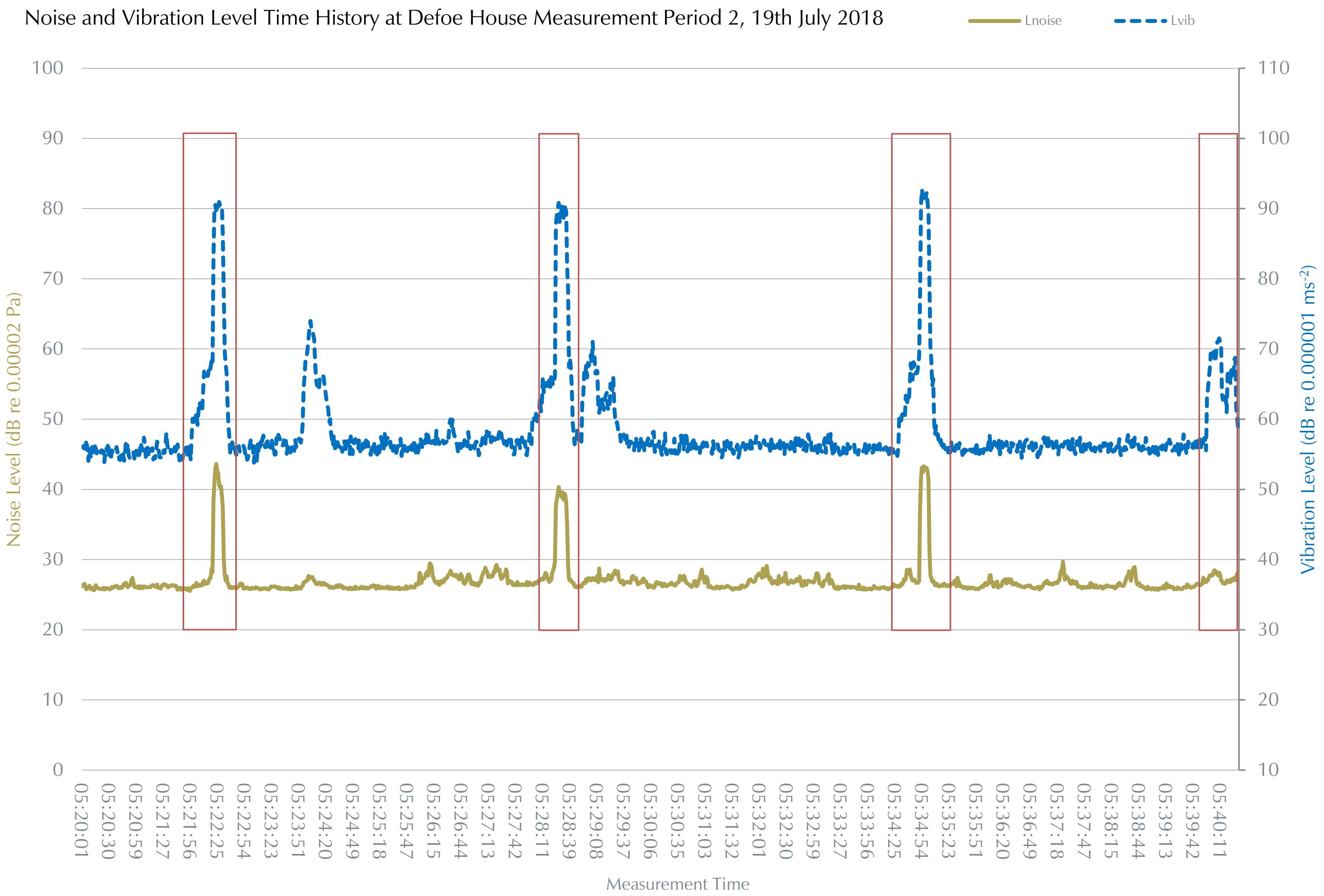
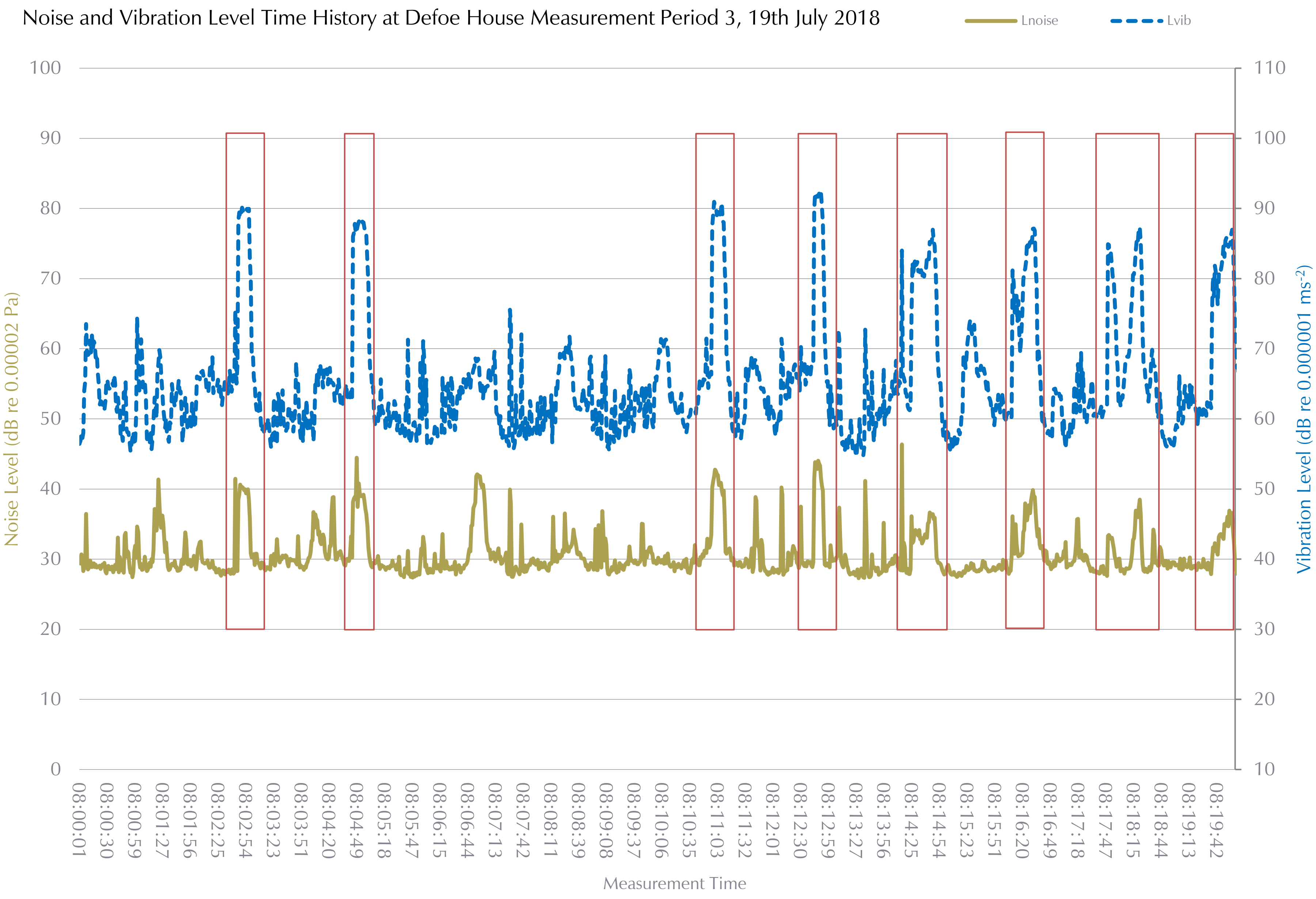
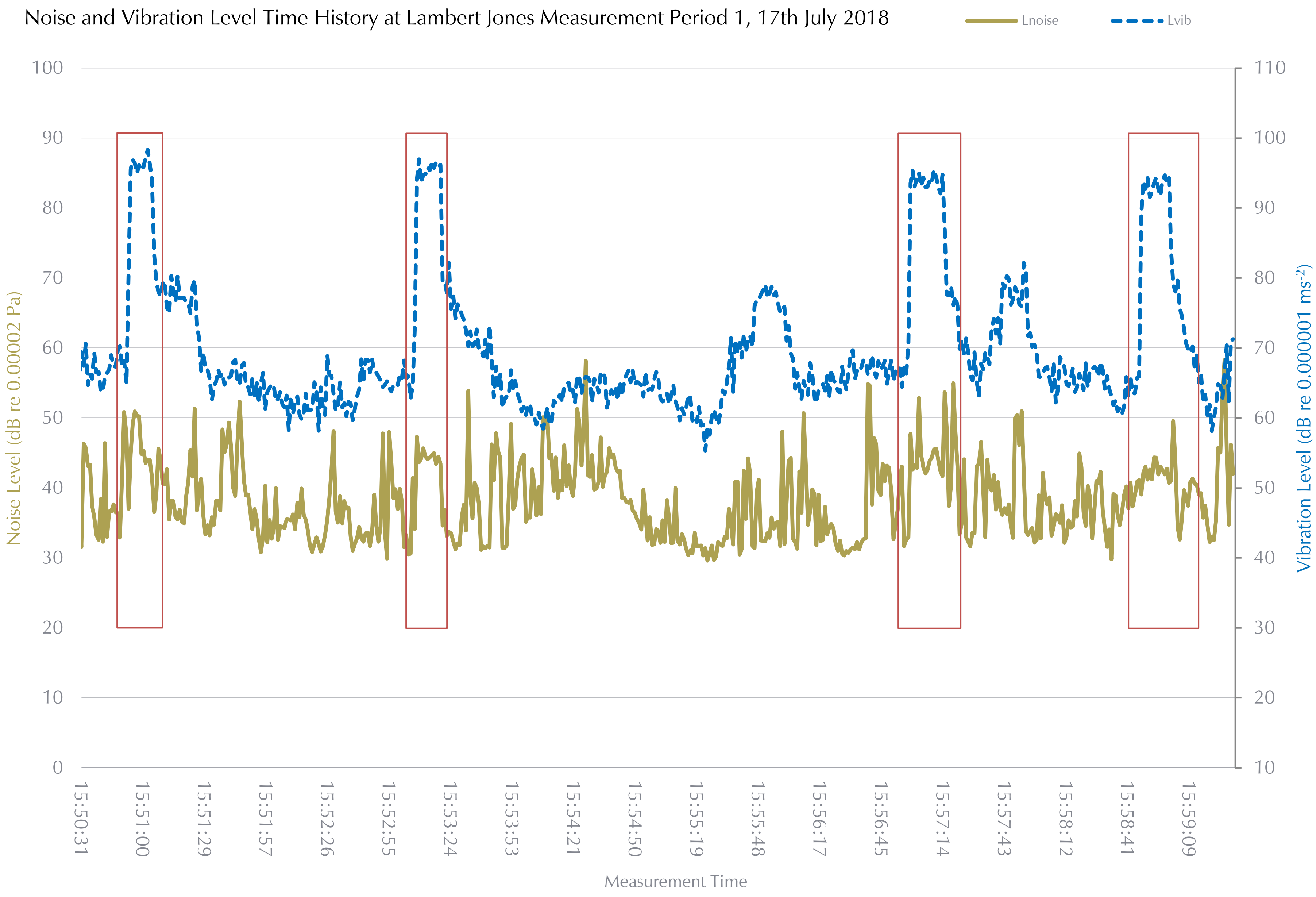


Figure 18/0197/THNV.05

Figure 18/0197/THNV.06




Noise and Vibration Level Time History at Lambert Jones Measurement Period 1, 17th July 2018
Lnoise
Lvib
Noise Level (dB re 0.00002 Pa)
Vibration Level (dB re 0.000001 ms-2)
Measurement Time
100
90
80
70
60
50
40
30
20
10
0
110
100
90
80
70
60
50
40
30
20
10
15:50:31
15:51:00
15:51:29
15:51:57
15:52:26
15:52:55
15:53:24
15:53:53
15:54:21
15:54:50
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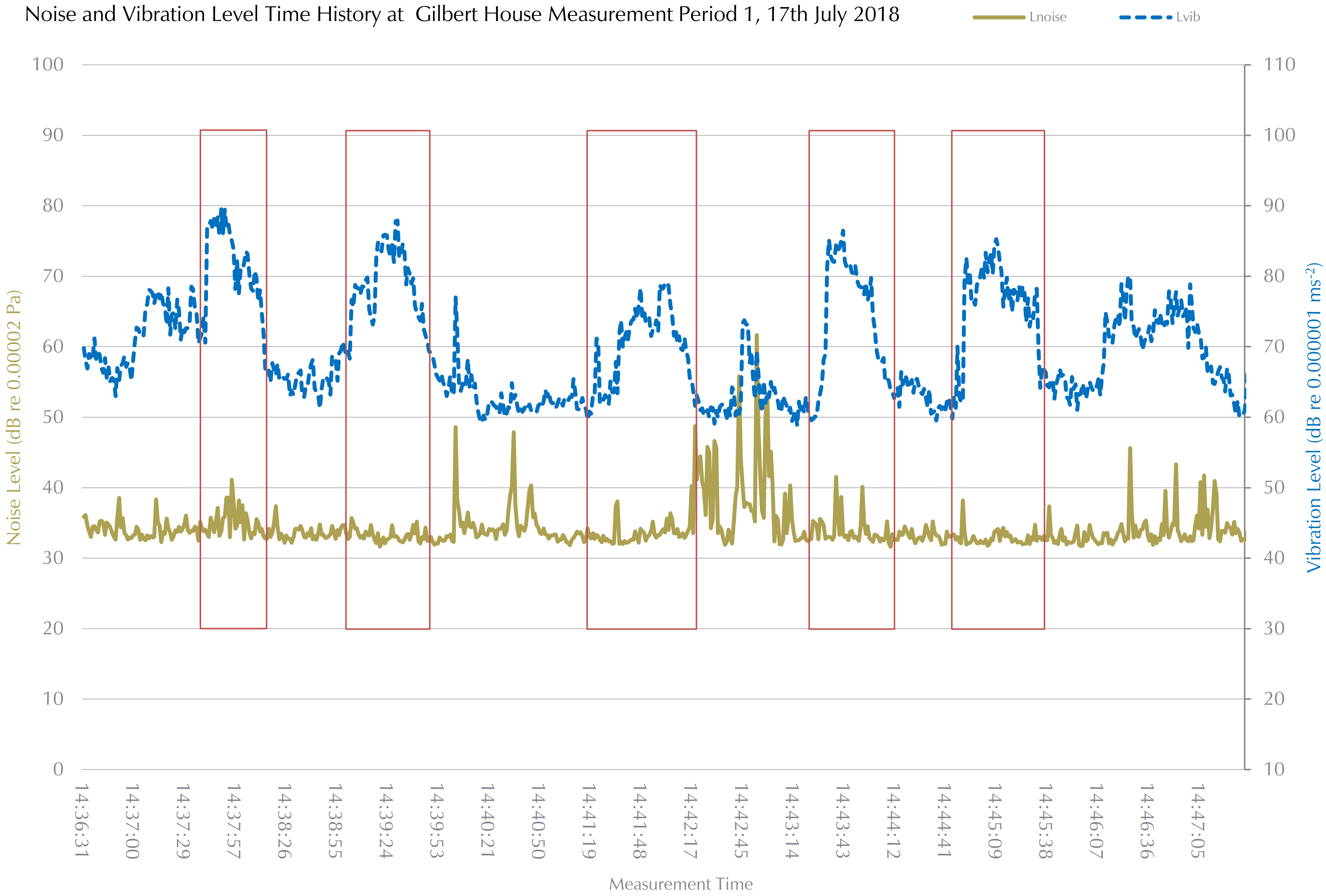
15:58:41
15:59:09


Noise and Vibration Level Time History at Gilbert House Measurement Period 1, 17th July 2018
Lnoise
Lvib
Noise Level (dB re 0.00002 Pa)
Vibration Level (dB re 0.000001 ms-2)
Measurement Time
100
90
80
70
60
50
40
30
20
10
0
110
100
90
80
70
60
50
40
30
20
10
14:36:31
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14:43:43
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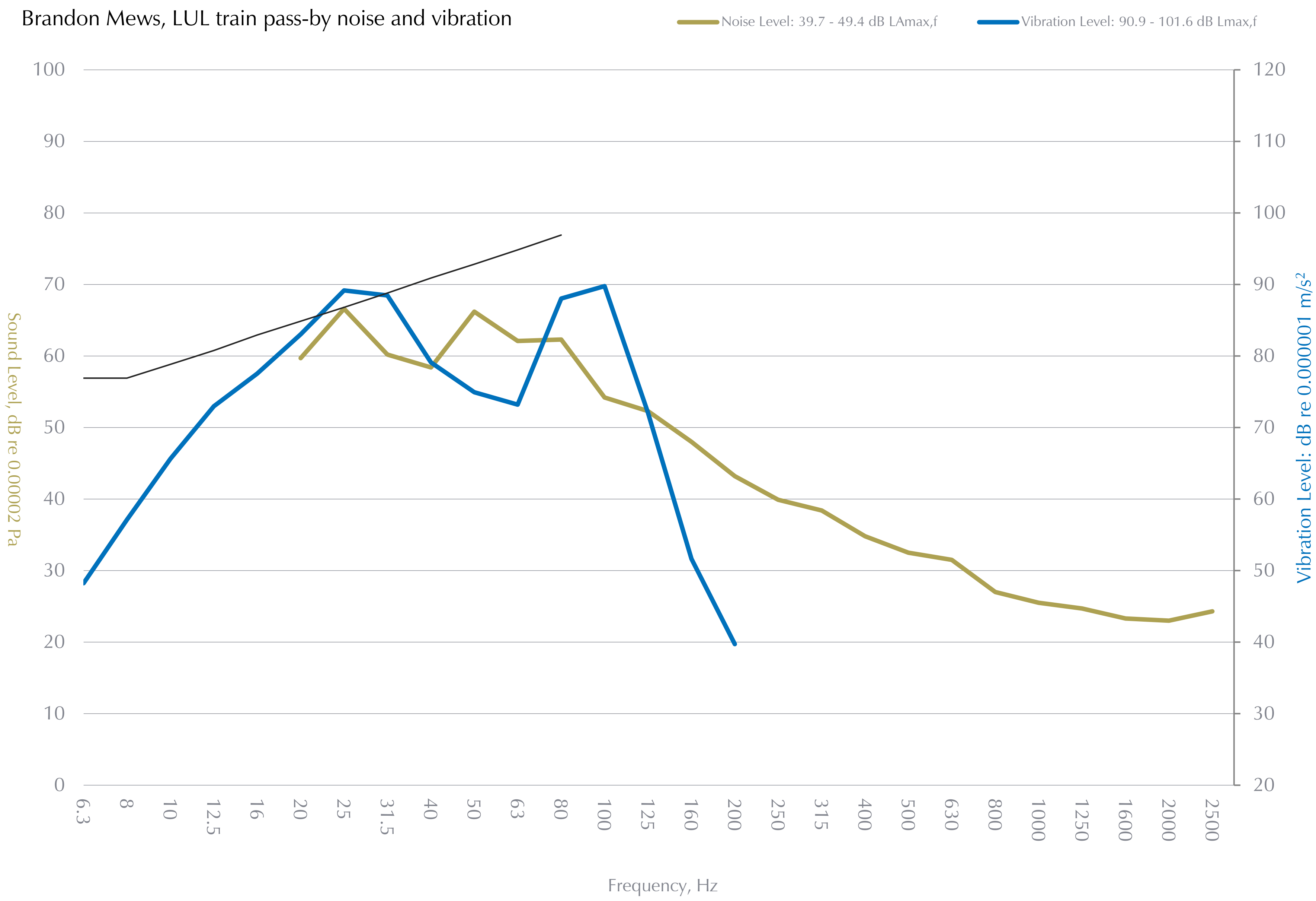
Figure 18/0197/TOB01



Defoe House, LUL train pass-by noise and vibration

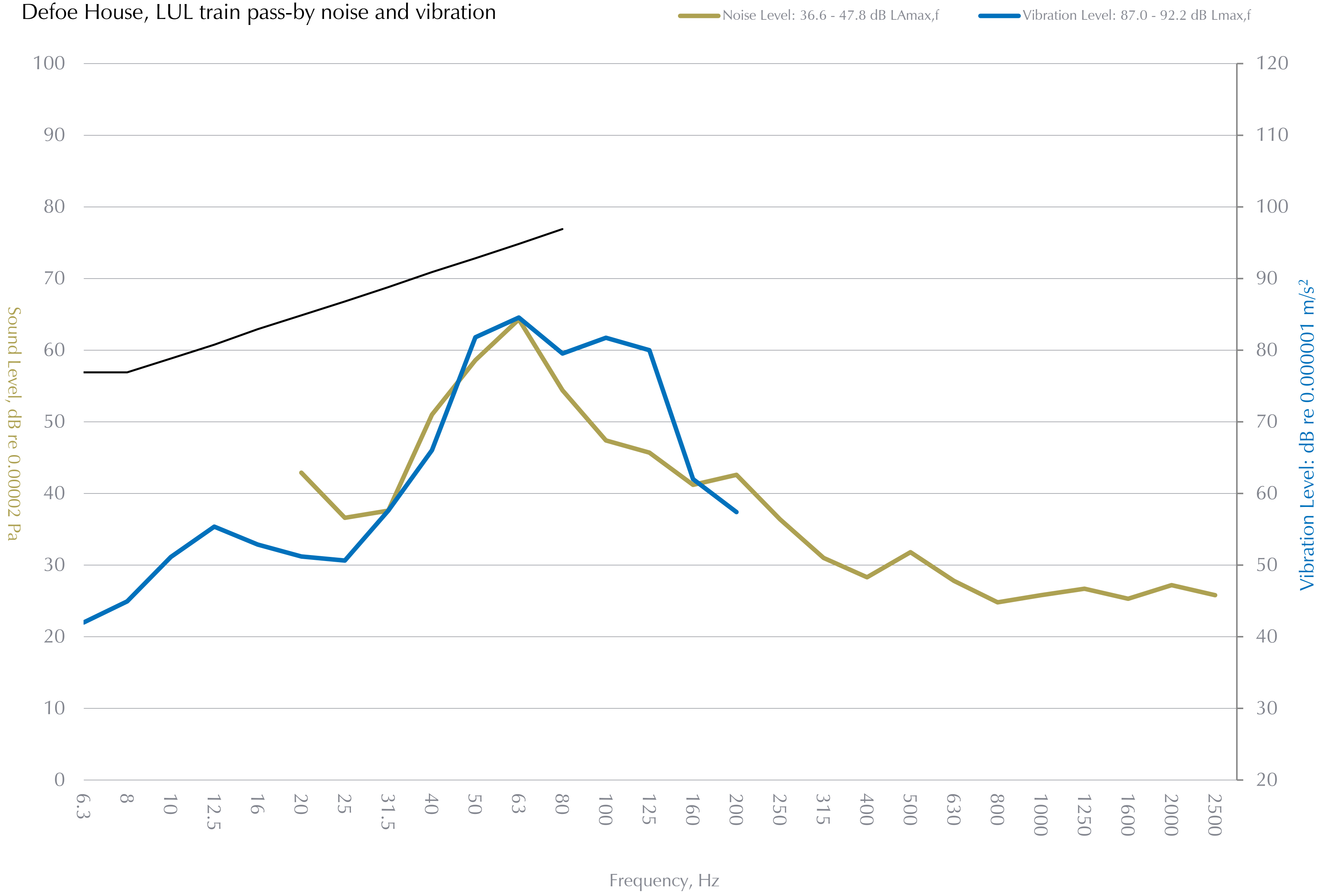
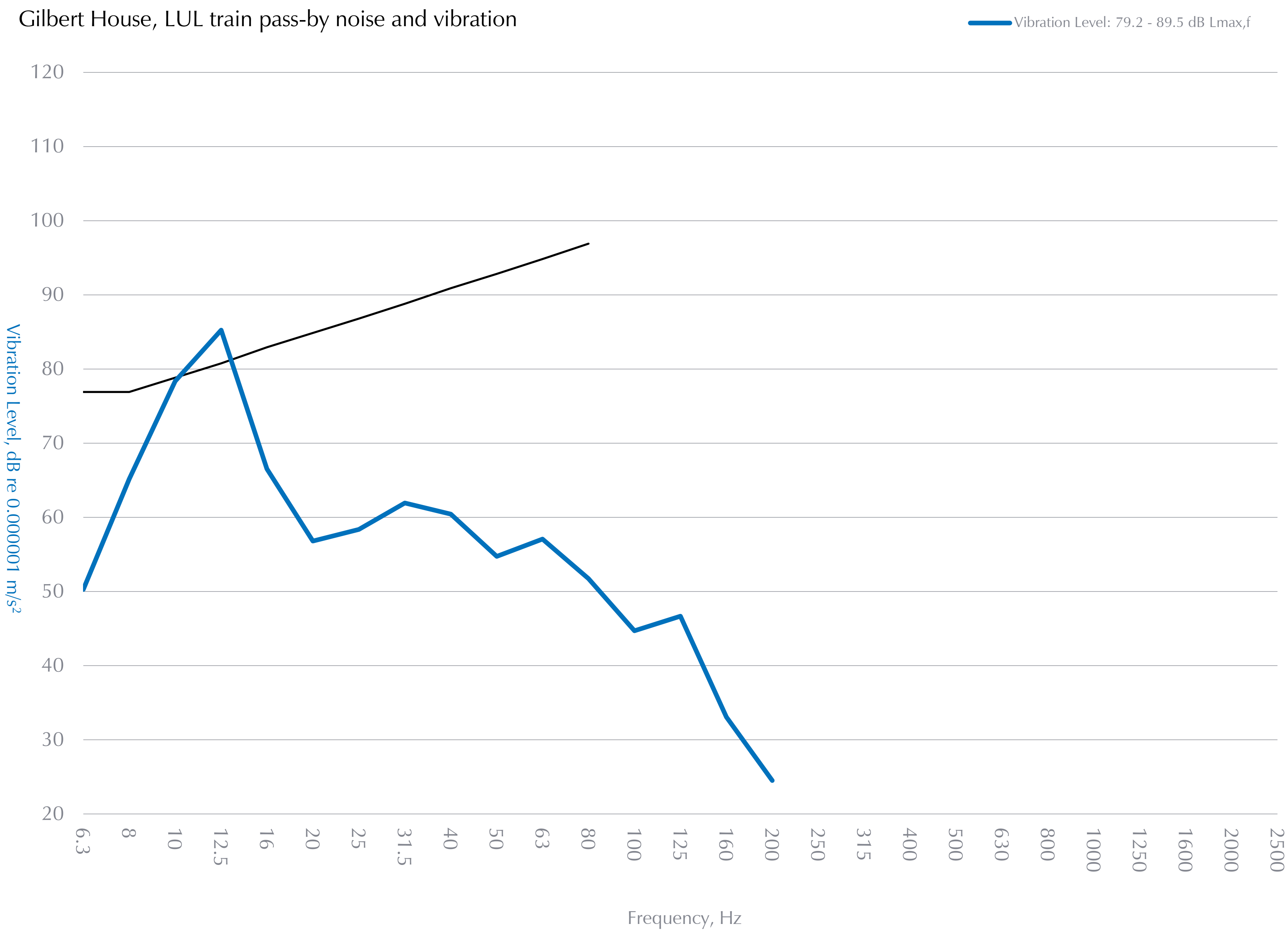


Figure 18/0197/TOB02

Figure 18/0197/TOB03



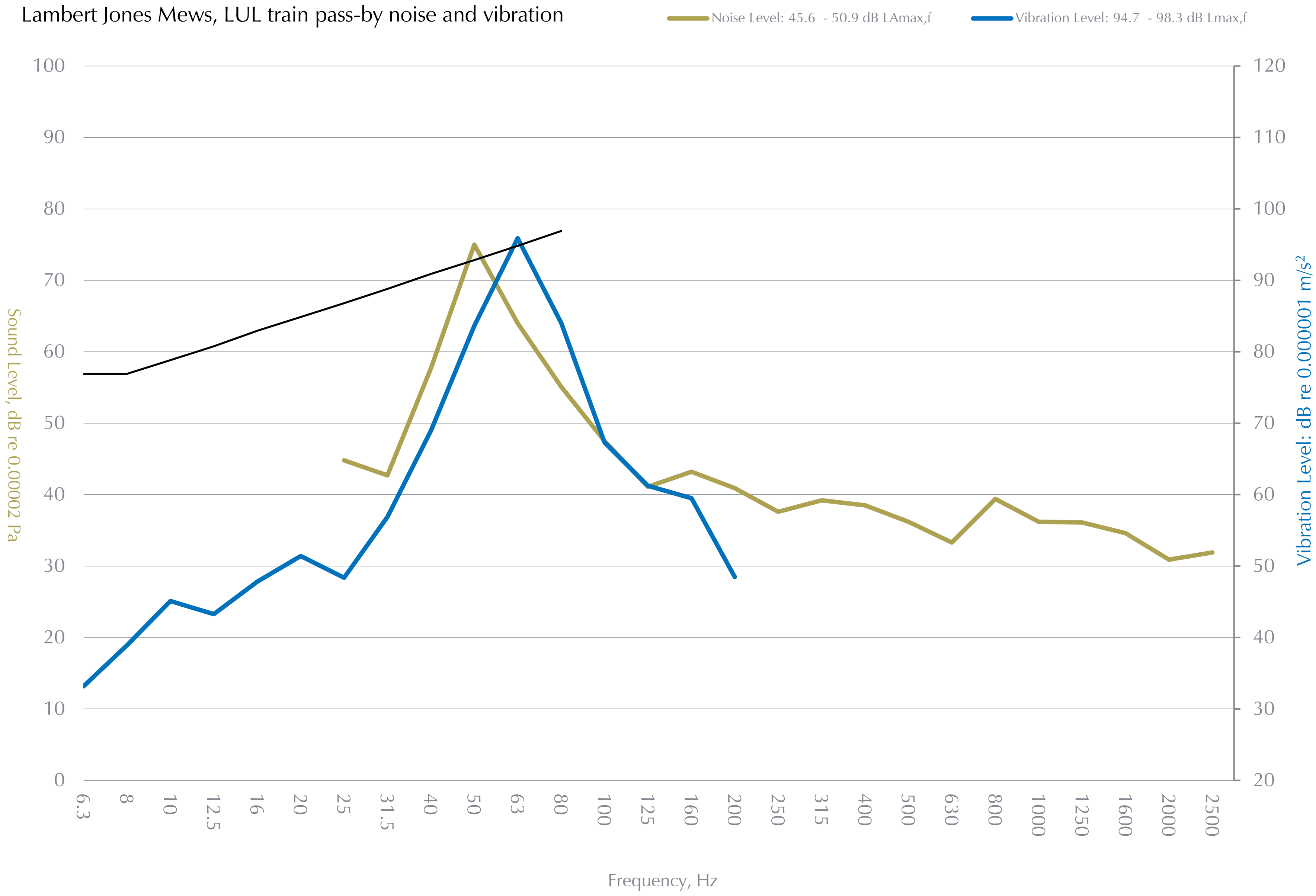


Figure 18/0197/TOB04

Appendix A

LUL Track Walk between Barbican and Moorgate Station

Technical Services
Noise & Vibration Section
Hearne House
3 Museum Way
London W3 9BQ

REVIEW OF TRACK WALK BETWEEN BARBICAN AND MOORGATE STATION

Issue Date: 4th September 2018

Prepared by: Martin Tonner

1. BACKGROUND

As part of noise and vibration investigation within the Barbican Estate, the City of London Environmental team requested TfL provide details of the track formation of the Circle, Hammersmith & City and Metropolitan line that runs between Barbican and Moorgate station. Particular emphasis is given on the location of the vibration isolation chambers, built in the 1960s in order to mitigate the transmission of ground-borne noise and vibration within the Barbican Arts and Conference Centre from passing London Underground trains. The chamber lies underneath the track ballast and contains rubber blocks to suspend the track and tunnel floor

A review the track walk within the tunnel between Barbican and Moorgate station was carried out by TfL Technical Services on the night of 30th August 2018.

2. OBSERVATIONS

From the tunnel entrance at Barbican station the formation of track on the Eastbound Outer line is ballasted track with flat-bottom rail on concrete sleepers for approximately the first 90m (figure 1). The track then changes to bullhead rail on timber sleepers (figure 2) for the next 410m, all the way to Platform 1 at Moorgate station.

Figure 1 – Flat-Bottom Rail on Concrete Sleepers

Figure 2 – Bullhead Rail on Timber Sleepers

On the Westbound Inner line the rail is also ballasted track with bullhead rail on timber sleepers for 390m from the tunnel entrance at platform 2 at Moorgate station and changes to flat-bottom rail on concrete sleepers for the next 110m, up to platforms at Barbican station.

There are sets of points and crossings on the track of the Eastbound line at approximately 300m (31b) and 480m (35a) from Barbican station (figure 3), and at 60m (35b) and 160m (31a) on the Westbound line from Moorgate station.

The track formation of the sidings from platforms 3 and 4 is flat-bottom rail on concrete sleepers (figure 4) which travels over set of points 32a/34 at approximately 67m from the platforms, before joining the Westbound line at set of points 31a/32b.


Figure 3 – Points 35 on both the Eastbound and Westbound Line


Figure 4 – Sidings Flat-bottom Rail on Concrete Sleepers from Platform 3

The location of the vibration isolation chamber (highlighted in yellow on the map in figure 5) was found to be between **140m to 450m** underneath the track ballast on the Eastbound line and **50m to 360m** on the Westbound. The chamber also runs underneath the entire length of the sidings track ending at platforms 3 and 4 at Moorgate station. This was determined by location of the metal grills on concrete that run parallel with sections of the track (figures 6-8) below.

The vibration isolation chamber is accessible via sections of removable metal grills, on the left hand side of the westbound road, and has attached ladders leading down into the chamber (figures 9 and 10).

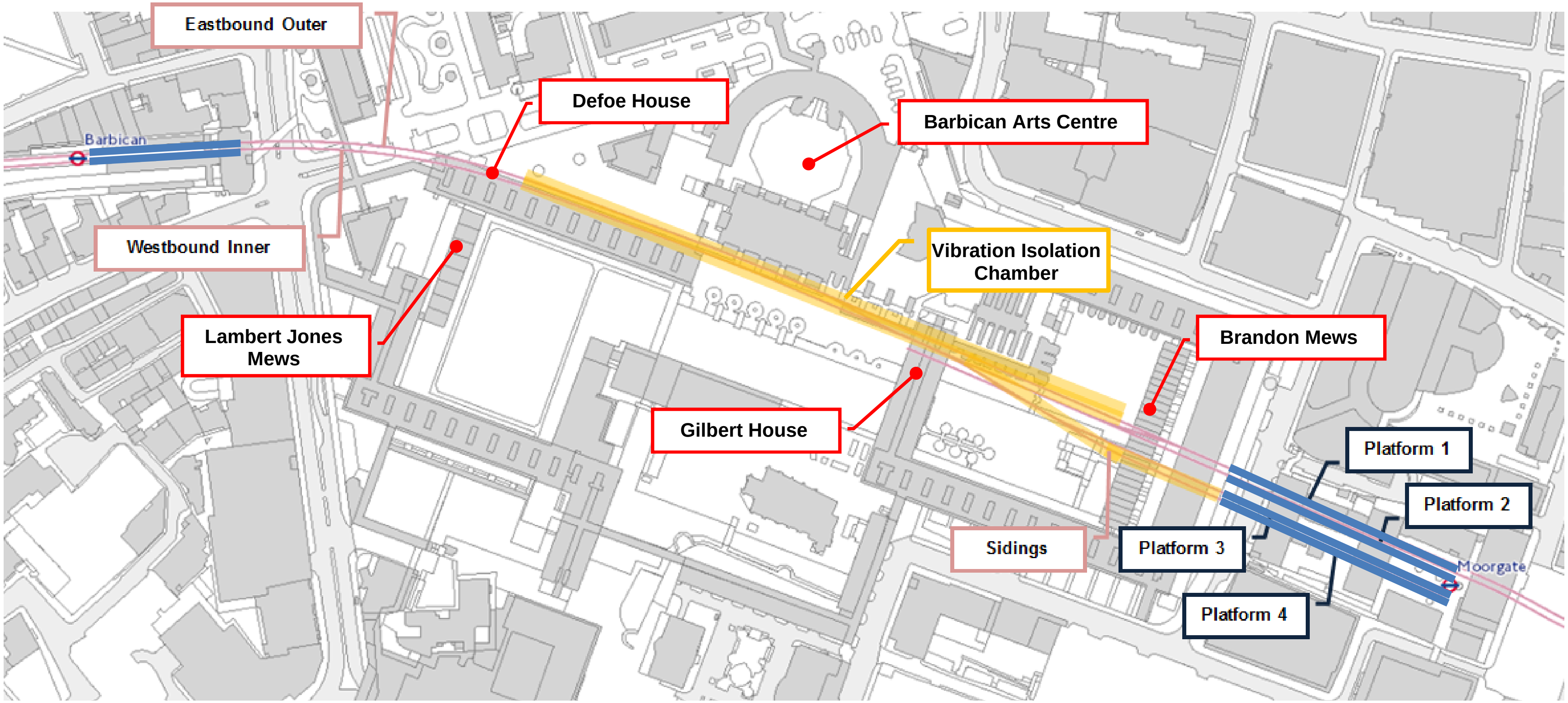


Figure 5 – Map Showing Location of the Hammersmith & City, Circle and Metropolitan Line between Barbican and Moorgate


Figure 6 – Metal Grills on Concrete Running Parallel with Rails


Figure 7 – Metal Grills on Concrete Running Parallel with Rails


Figure 8– Metal Grills on Concrete Running Parallel with Rails


Figure 9 – Removable Grills to Access Chamber

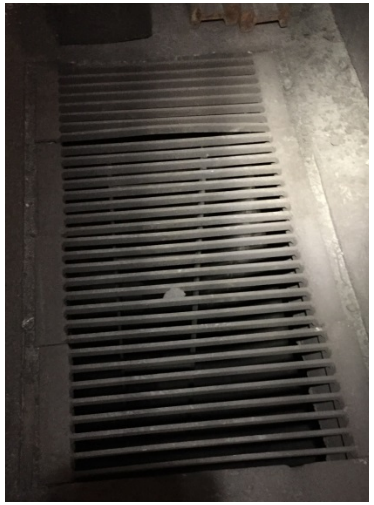


Figure 10 – Removable Grills to Access Chamber

Figure 11 and 12 below show inside of the vibration isolation chamber, which consists of a concrete structure supporting the suspended track with resilient rubber bearings in the centre (figures 13 and 14) isolating the direct contact between the chamber floor and ceiling.

The chamber ceiling is supported by brick columns with a concrete rod (figures 15 and 16) which is located outside of the chamber. They are not directly underneath the rail itself, but supporting the tunnel invert in the left hand side of the westbound line.

Figure 11 – Concrete Structure Supporting the Track

Figure 12– Concrete Structure Supporting the Track

Figure 13 – Resilient Rubber Bearings within the Concrete Structure

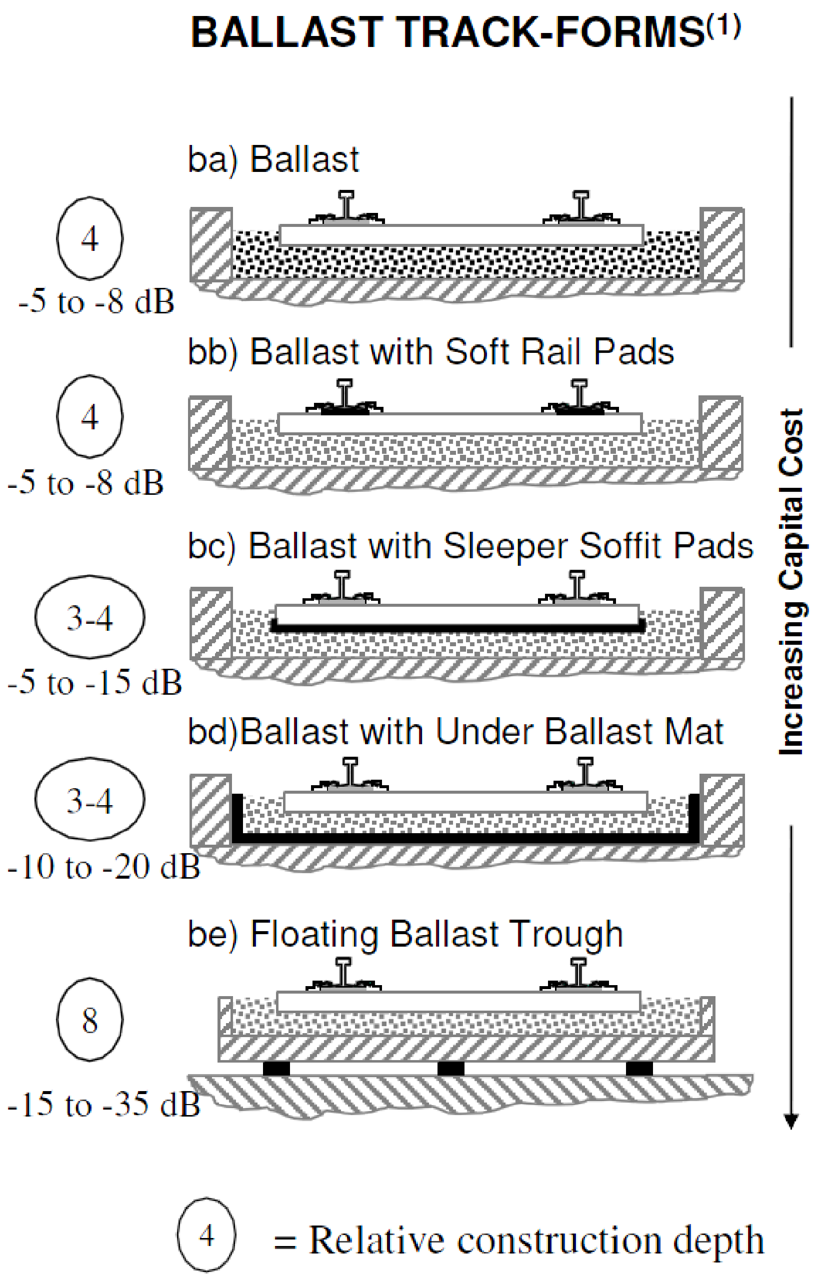
Figure 14 – Resilient Rubber Bearings within the Concrete Structure

Figure 15 – Supporting Brick Columns

Figure 16 – Supporting Brick Columns

Appendix B

Mitigation[4]



[4] Taken from Crossrail presentation to Corporation of London: *FTS Design for the Barbican*, 7th February 2013

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