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Noise and Vibration Guidance

CALL
0121 214 7107

EMAIL
info@lrssb.co.uk

WEB
www.lrssb.org

TWITTER
@LightRailSSB

LINKEDIN
@lightrailssb

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DESCRIPTION:

THIS DOCUMENT PROVIDES GUIDANCE IN RELATION TO THE MITIGATION AND MANAGEMENT OF NOISE AND VIBRATION DURING DESIGN, CONSTRUCTION AND OPERATION OF LIGHT RAIL SYSTEMS.

EXPLANATORY NOTE:

LRSSB is not a regulatory body and compliance with this guidance document is not mandatory. This document reflects good practice and is advisory only. Users are recommended to evaluate this guidance against their own arrangements in a structured and systematic way, noting that parts of this guidance may not be appropriate to their operations. It is recommended that this process of evaluation and any subsequent decision to adopt (or not adopt) elements of this guidance should be documented. Compliance with any or all of the contents herein, is entirely at an organisation's own discretion.

SOURCE / RELATED DOCUMENTS:

LRG 1.0 Tramway Principles and Guidance (TPG) (LRSSB)
LRG 16 Wheel Rail Interface Guidance (LRSSB)
LRG 28.0 Guidance on the Provision of Accessibility In Light Rail Systems (LRSSB)

RELATED TRAINING COURSES:	**RELATED LEGISLATION:**
N/A	Health & Safety at Work Act 1974 Railways and Other Guided Transport Systems (Safety) Regulations 2006 (as amended) (ROGS)

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NOISE AND VIBRATION GUIDANCE

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TERMS AND ABBREVIATIONS

Table A – Terms

Term	Definition
Carry-down	The distance from the point of application over which the lubricant remains effective.
Coefficient of Friction	A ratio of the frictional force resisting the motion of two surfaces and the normal force pressing the surfaces together. The higher the number, the more grip or adhesion between the surfaces.
dB(A)	Decibels measured on a sound level meter incorporating a frequency weighting which differentiates between sounds of different frequency (pitch) in a similar way to the human ear. Measurements in dB(A) broadly agree with people's assessment of loudness. A change of 3 dB(A) is the minimum perceptible under normal conditions, and a change of 10 dB(A) corresponds roughly to halving or doubling the loudness of a sound.
Decibel	The standard unit of measurement for sound pressure level and vibration level, it is derived from the logarithm of the ratio between the value of a quantity and a reference value. It is therefore a relative value not an absolute value and for sound pressure the reference (zero) value is usually 20 micro-Pascals which equates roughly to the lowest pressure the human ear can detect.
Free Field Conditions	Used to describe the conditions where sound measured at a point away from reflective surfaces other than the ground and with no significant contributions due to sound from other reflective surfaces. Typically outside and away from buildings. Buildings of a sensitive nature, for example, theatres or health centres doing audio diagnostics.
$L_{Aeq(1hr)}$	Used by the FTA for Light Rail noise impact assessments in high sensitivity areas, for example, schools, theatres and churches, but where night time sensitivity is not important. It is computed for the loudest hour of project related activity during hours of noise sensitivity.
$L_{Aeq\ 18hr}$	The LAeq over the period 0600 – 2400, local time. (Used for DEFRA strategic noise mapping as an annual average).
$L_{Aeq,T}$	The equivalent continuous sound level i.e. the sound level of a notionally steady sound having the same energy as a fluctuating sound over a specified measurement period (T). $L_{Aeq,T}$ is used to describe many types of noise and can be measured directly with an integrating sound level meter.
L_{Amax}	This is the maximum A-weighted sound pressure level recorded over a stated period. It is useful for assessing environmental noise where occasional loud noises occur which may have little effect on the overall L_{Aeq} level but will still be intrusive. Used in vehicle-noise specifications as L_{pAFmax} (sound pressure level

Term	Definition
	measured using a meter set to Fast time weighting as specified in BS EN ISO 3095).
Term	**Definition**
L_{den}	Used in WHO guidance. Describes day-evening-night-weighted sound pressure level measured over a year as defined in Section 3.6.4 of ISO 1996-1:2016.
L_{dn}	Used by the FTA to assess Light Rail noise for residential land uses. It describes a receiver's cumulative noise exposure from all events over 24 hours. Events between 2200 and 0700 are increased by 10 dB to account for humans' greater night time sensitivity to noise.
L_{night}	Used by the WHO to describe the night time noise indicator, which averages (continuous equivalent) sound pressure level over one year, focussing on the hours between 23:00 and 07:00 as defined by ISO 1996-1:2016.
$L_{pAeq,TP}$	From BS EN ISO 3095 and used to measure pass-by noise.
Pass-by Measurement	A measurement of time that is defined by commencing measurement when the sound pressure level is at least 10 dB lower than when the front of the Light Rail vehicle reaches the measuring point, and stopping 10 dB lower than when as the rear of the Light Rail vehicle passes the measuring point.
Peak Particle Velocity	Used to measure ground vibration, it is a measure of the peak velocity of a particle as it vibrates usually in mm/s.
Sound Exposure Level	An L_{eq} normalised to 1 second and is numerically equivalent to the total sound energy. For example, a noise level of 90 dBA lasting 1 second would have a SEL of 90 dBA but if the event lasted 2 seconds the SEL would be 93 dBA. SEL is a common metric since it can be used to compare the energy of noise events which have different time durations such as Light Rail vehicle pass-by events.
Tonal Sound	Sound characterised by a single frequency component or narrow band components that emerge audibly from the total sound (ISO 1996-1:2003).
Track Decay Rate	Rate of attenuation of vibration amplitude in the rail as a function of the distance along the rail. It is represented by a one-third octave spectrum of values expressed in decibels per metre (dB/m) representing attenuation over distance (ISO 3095:2013(EN)).
Vibration Dose Value	Used to evaluate the effect of building vibration on people. Derivation of Vibration Dose Value values is complex and the reader should refer to BS 6472-1:2008 for full details, but it is used to define acceptable levels of vibration for different types of building over 16hr (day) and 8hr (night) on a similar basis to that used for L_{eq} day / night for noise.

Table B – Abbreviations

Abbreviation	Definition
BS	British Standard
CEDR	Conference of European Directors of Roads
CEN/TS	European Committee for Standardisation/Technical Specification
CoF	Coefficient of Friction
dB	Decibel
dB(A)	Decibels measured with a frequency (A) weighting
dB/m	Decibels per Metre
DEFRA	Department for Environment, Food and Rural Affairs
EN	European Norm
EP	Extreme Pressure
EU	European Union
FAMOS	Factors Moderating People's Subjective reactions to road noise
FTA	Federal Transit Administration
GDU	Grease Dispenser Unit
GPS	Global Positioning System
HGV	Heavy Goods Vehicles
Hz	The SI unit of frequency
ISO	International Organisation for Standardisation
ISVR	Institute of Sound and Vibration Research
kg/m^2	Kilogramme force per square metre
Km/h	Kilometres per Hour
L_{Aeq}	Equivalent Continuous Sound Pressure Level
$L_{Aeq(1hr)}$	A-weighted sound pressure level of a continuous steady sound, within a 1 hour period
$L_{Aeq\ 18hr}$	The Laeq over 18 hours
$L_{Aeq,T}$	Equivalent Continuous Sound Pressure Level over a specified time
L_{Amax}	Maximum A-weighted sound pressure level recorded over a stated period
L_{den}	Day-evening-night-weighted sound pressure level
L_{dn}	Day-Night Average Sound Pressure Level
L_{night}	Night time noise indicator
$L_{pAeq,\ TP}$	Equivalent Continuous Sound Pressure Level over a specified time for pass-by measurement
LRSSB	Light Rail Safety and Standards Board
mm	Millimetres
mm/s	Millimetres per second
mph	Miles per hour

Abbreviation	Definition
N&V	Noise and Vibration
NPPF	National Planning Policy Framework
NPSE	Noise Policy Statement for England
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
ORR	Office of Rail and Road
PA	Public Address (System)
PAN	Planning Advice Note
PPE	Personal Protection Equipment
PPG	National Planning Practice Guidance
PPV	Peak Particle Velocity
ProPG	Professional Practice Guidance on Planning and Noise
RCF	Rolling Contact Fatigue
REFIS	Royal Environmental Health Institute of Scotland
ROGS	Railways and Other Guided Transport Systems (Safety) Regulations 2006 (as amended)
S&C	Switches and Crossings
SDS	Safety Data Sheets
SEL	Sound Exposure Level
STARDAMP	Standardisation of Damping Technologies for the Reduction of Railway Noise
TAN	Technical Advice Note
TDS	Technical Data Sheets
TfL	Transport for London
TP	Pass-by Measurement (Time)
TPG	Tramways and Principles Guidance
TS	Technical Specification
TSI	Technical Specifications for Interoperability
TWINS	Track-Wheel Interaction Noise Software
UIC	Union Internationale des Chemins de fer (International Union of Railways)
UK	United Kingdom
VDV	Verband Deutscher Verkehrsunternehmen
WHO	World Health Organisation
WRI	Wheel Rail Interface

1. Introduction

1.1. This guidance supports the high level principles set out in LRG 1.0 Tramway Principles and Guidance (TPG) published by the Light Rail Safety and Standards Board (LRSSB).

1.2. This document provides high level guidance in relation to the mitigation and management of noise and vibration for those operating a Light Rail (tram) vehicle based on 'line-of-sight' operations only. As with all guidance, this document is not prescriptive and is intended to give advice not to set a mandatory industry standard, and it is based upon goal setting principles as good practice.

1.3. Much of this guidance is based on the experience gained from good practice and risk assessment from existing UK and international Light Rail systems and other related industries and from publicly available documents. It does not endorse or prescribe particular arrangements adopted by any of these systems, and is intended to provide advice to those involved in the management of noise and vibration applicable to the operation of Light Rail systems in the UK.

1.4. This guidance is not intended to be applied retrospectively to existing Light Rail systems. However, owners and operators should consider and assess any implementation of this guidance and / or any subsequent revision to ensure continual improvement, so far as is reasonably practicable.

2. Scope

2.1. Light Rail systems can be a source of noise and vibration (N&V). With N&V widely recognised as potentially damaging to human health and wellbeing, managing its impact on the communities where these systems operate is an essential requirement.

2.2. This guidance aims to provide designers, owners, operators and maintainers with practical guidance for the management of N&V during Light Rail system design, construction and operation.

2.3. N&V management can be a highly technical; this guidance does not replicate in its entirety the detailed technical content of the numerous standards, documents and technical papers that exist on the topic. Instead, it aims to provide non-specialists who may have to deal with N&V issues as part of their wider management responsibilities with an easy to read overview. This includes the following:

- Background regulatory framework;
- Some basic N&V theory;
- Derivation of practical N&V limits;
- How to approach N&V management during both construction and operation of a Light Rail system; and
- The latest equipment and technologies for N&V mitigation.

2.4. This guidance also provides information on relevant standards and other useful documents for those who wish to dig deeper into the subject. It can be helpful to better understand the approach, advice and methodologies of the consultants and subject matter experts who are typically employed to provide specialist N&V advice and services.

2.5. Further to 1.4 above, it is acknowledged that some elements of N&V produced by an existing Light Rail system cannot be changed without fundamental redesign and reconstruction and / or the replacement of existing rolling stock and where this is the case, this guidance is not intended to be applied retrospectively to existing Light Rail systems. However, some of the guidance can be applied retrospectively, for example, installation of friction management equipment and such measures should be considered for implementation where guideline noise limits are being breached. Operational mitigation methods may also be relevant to meeting the requirements of DEFRA (Department for Environment, Food and the Rural Affairs) noise action plans, other local N&V management initiatives, and planning conditions for new lines and system extensions.

3. Regulatory Framework

3.1 In the UK there are no national legal limits to noise and vibration from existing railways (including Light Rail systems)[1] and in legal terms, noise and vibration are both regarded as statutory nuisance rather than a specific threat to health or safety. The Environmental Protection Act 1990[2], which is enforced by local authorities, is the appropriate legislation for dealing with nuisance noise and environmental pollution[3]. However, there are a range of national and international guidance documents that provide a framework for the management of N&V generated by Light Rail systems.

3.2 Requirements for the management of N&V on Light Rail systems as a place of work are health and safety responsibilities that sit outside the scope of this document and are enforced by the Office of Rail and Road (ORR) who act as the health and safety regulator for the rail industry. Regulations for rail safety, including Light Rail systems are published in the Railways and Other Guided Transport Systems (Safety) Regulations 2006 (as amended) (ROGS)[4] which were introduced to implement the then extant European Railway Safety Directive (2004/49/EC)[5] in the UK.

International Regulatory Framework

3.3 At an international level, current guidance starts with a 2019 document from the World Health Organisation (WHO) which provides recommendations for protecting human health from exposure to environmental noise originating from various sources including railways[6]. This document focusses on Europe and takes into account the existing EU directive (see below). The key recommendations for railway noise exposure are as follows:

- For average noise exposure, the WHO strongly recommends reducing noise levels produced by railway traffic below 54 dB L_{den}, as railway noise above this level is associated with adverse health effects; and
- For night noise exposure, the WHO strongly recommends reducing noise levels produced by railway traffic during night time below 44 dB L_{night}, as night-time railway noise above this level is associated with adverse effects on sleep.

3.4 EU Directive 2002/49/EC[7] is the main EU instrument to identify noise pollution levels and to trigger the necessary action both at member state and EU level. Its aim was to put in place a system which could be used to control the exposure of the EU's population to environmental noise from roads, airports, railways and industry[8]. It is subject to ongoing updates and revisions so care should be taken to refer to the latest version as it remains applicable in the UK unless or until it is replaced by national legislation or guidelines.

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1 https://www.gov.uk/noise-pollution-road-train-plane/railway-noise
2 https://www.legislation.gov.uk/ukpga/1990/43/data.pdf
3 ORR letter Sustainability Noise and Vibration dated 6 Feb 2015: https://www.orr.gov.uk/media/10616
4 https://www.legislation.gov.uk/uksi/2006/599/made/data.pdf
5 https://www.legislation.gov.uk/eudr/2004/49/contents
6 World Health Organisation Environmental Noise Guidelines for the European Region 2018: https://www.who.int/europe/publications/i/item/9789289053563
7 https://www.legislation.gov.uk/eudr/2002/49/contents
8 B Hemsworth. Environmental Noise Directive, Development of Action Plans for Railways 2008: https://uic.org/IMG/pdf/action_planning_paper_final-2.pdf

3.5 At the core of the Directive is a requirement for member states to prepare and publish every five years, noise maps and noise management action plans (which include public consultation) for areas that include the following:

- Agglomerations with more than 100,000 inhabitants; and
- Major railways (more than 30,000 trains a year).

3.6 The Directive does not set limit or target values and it leaves the measures to be included in the action plans up to competent member state authorities, DEFRA in the case of the UK. However, it does require EU member states to report noise above an L_{den} of 55 dB and L_{night} of 50 dB.

3.7 The Directive refers extensively to the L_{den} and L_{night} terminology also used by the WHO and is useful in providing a detailed breakdown of how these terms are derived. It is also worth noting that both terms refer to measurement or calculation of noise exposure at the most exposed outdoor façade, thereby reflecting long-term average exposure. There are no statutory EU noise limits for Light Rail vehicles. However, TSI 1304/2014[9] is understood to be used by some Light Rail vehicle OEMs for guidance, even though it is applicable to heavy rail rolling stock and generally proposes higher noise limits that would be expected on a Light Rail system.

National Regulatory Framework

3.8 In the UK, The Environmental Noise (England) Regulations 2006[10] provide the requirements and instructions for implementation of EU Directive 2002/49/EC including noise mapping and associated action plans. Alongside this, the Government's policy on noise is set out in the Noise Policy Statement for England (NPSE)[11] with its aim below:

> *'Promote good health and a good quality of life through the effective management of noise within the context of Government policy on sustainable development.'*

3.9 Whilst the NPSE is not legislation and local authorities are not legally bound by it, DEFRA has an expectation that local authorities will take it into account in relevant situations. Further information on the NPSE is given below in Section 3.18 and 3.19.

3.10 As stated above, as noise can constitute a statutory nuisance it is subject to the provisions of the Environmental Protection Act 1990 and local authorities have a duty to take such steps as are reasonably practicable to investigate a statutory nuisance complaint.

3.11 Noise is a devolved matter in the UK and similar documents have been produced and policies implemented in each of the devolved administrations. As a typical example in Scotland, Planning Advice Note (PAN) 1/2011[12] provides guidance on how the planning system helps to prevent and limit the adverse effects of noise. The Assessment of Noise Technical Advice Note[13] (TAN) provides guidance which may assist in the technical

9 COMMISSION REGULATION (EU) No 1304/2014 of 26 November 2014 on the technical specification for interoperability relating to the subsystem 'rolling stock — noise' amending Decision 2008/232/EC and repealing Decision 2011/229/EU: https://www.legislation.gov.uk/eur/2014/1304
10 https://www.legislation.gov.uk/uksi/2006/2238/made/data.pdf
11 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/69533/pb13750-noise-policy.pdf
12 https://www.gov.scot/publications/planning-advice-note-1-2011-planning-noise/
13 https://www.gov.scot/publications/technical-advice-note-assessment-noise/)

evaluation of noise assessment. Most Scottish local authorities also reference Royal Environmental Health Institute of Scotland[14] (REHIS) guidance.

3.12 In England, the outcome is a series of Noise Action Plan documents produced by DEFRA to meet these requirements including the following, which provide a framework for noise monitoring due to the operation of railways. These document the third iteration of strategic noise mapping and associated action plans since adoption of the EU Directive.

DEFRA Noise Action Plan: Railways [15]

3.13 This document is designed to address the management of noise issues and effects from railways in England. Although the DfT has ultimate responsibility for ensuring that the measures set out are implemented, in practice this is delegated to other rail industry experts including the Rail Safety and Standards Board (RSSB). Although this action plan is aimed primarily at heavy rail, some of its general provisions and comments on mitigation are relevant to Light Rail systems, including the process for identifying important areas (noise hotspots). For railways in agglomerations, the important areas are where the 1% of the population that are affected by the highest noise levels from those railways mapped in the agglomeration are located according to the results of the strategic noise mapping.

3.14 For each important area, this document states that DfT and the rail industry will identify proposed actions that will meet the Government's policy on noise unless they are satisfied that no further action can or needs to be taken. In this respect, it is unclear what the relevant stakeholders' responsibilities include when these principles are applied to Light Rail systems. In practice, Light Rail operators, relevant local authorities and potentially LRSSB should be involved in this process.

DEFRA Noise Action Plan: Agglomerations (Urban Areas[16])[17]

3.15 This action plan is designed to address the management of noise issues and effects from road and railways in the 65 agglomerations in England (see Table 2 of this action plan). It records the number of people within each agglomeration who are subject to railway noise measured in bands from 50 dB(A) upwards for L_{den}, L_{night} and $L_{Aeq\ 18hr}$.

3.16 The process used for identifying important areas with regard to railway noise in agglomerations is as detailed above in DEFRA Noise Action Plan: Railways, which also sets out the roles and responsibilities of the relevant authorities in the action planning process, potential mitigation measures, and gives further details on implementation and monitoring. It also includes provisions that aim to protect existing quiet areas and provides information on the process and criteria for identifying such quiet areas.

The Noise Insulation (Railways and Other Guided Transport Systems) Regulations 1996

14 https://rehis.com/

15 DEFRA Noise Action Plan: Railways - 2 July 2019: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/813664/noise-action-plan-2019-railways.pdf

16 With a population > 100,000 and population density equal to or greater than 500/km2

17 DEFRA Noise Action Plan: Agglomerations (Urban Areas) - 2 July 2019: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/813663/noise-action-plan-2019-agglomerations.pdf

3.17 A further set of noise constraints are specified in The Noise Insulation (Railways and Other Guided Transport Systems) Regulations 1996[18]. Although this document does not prescribe noise limits at source, it gives trigger levels where residential building noise insulation becomes mandatory at the levels identified below, measured at building facades. As provision of insulation in accordance with these requirements is expensive, these trigger levels have often been used as noise limits in UK Light Rail systems, even though they are not particularly demanding:

- 68 dB L_{Aeq}, 0600 – 0000 hours daytime; and
- 63 dB L_{Aeq}, 0000 – 0600 hours night.

National Planning Policy Framework (NPPF) and NPSE

3.18 In addition to the monitoring and management of operational noise, noise related to new Light Rail systems and extensions is managed through the associated planning process. Historically, the key government document in these scenarios was Planning Policy Guidance 24: Planning and Noise (PPG 24)[19] (and its devolved administration equivalents). This provided guidance to local authorities in England on the use of their planning powers to minimise the adverse impact of noise. It outlined the considerations to be taken into account in determining planning applications both for noise-sensitive developments and for those activities which generate noise. PPG 24 was withdrawn from official use in 2012 and replaced with the National Planning Policy Framework[20] (NPPF) and NPSE.

3.19 NPSE is a short top-level document that sets out the Government's vision and aims for noise management to:

> *'Provide the necessary clarity and direction to enable decisions to be made regarding what is an acceptable noise burden to place on society.'*

3.20 The NPPF 2021 sets out the Government's planning policies for England and how these should be applied with a strong focus on sustainable development. It is a material consideration in planning decisions and makes clear that planning policies and decisions shall also reflect relevant international obligations and statutory requirements. It does not cover N&V in any detail, although it does have a general section on transport infrastructure. It also states that planning policies and decisions should:

- Mitigate and reduce to a minimum potential adverse impacts resulting from noise from new development, and avoid noise giving rise to significant adverse impacts on health and the quality of life; and
- Identify and protect tranquil areas which have remained relatively undisturbed by noise and are prized for their recreational and amenity value for this reason.

3.21 Relevant to the implementation of NPPF is the Professional Practice Guidance on Planning and Noise[21] (ProPG) that has been produced by a working group of relevant professional bodies to provide guidance on the management of noise within the planning system in England. Although its scope is "*restricted to the consideration of new residential development that will be exposed predominantly to airborne noise from transport sources*"

18 The Noise Insulation (Railways and Other Guided Transport Systems) Regulations 1996
19 UK Planning Policy Guidance 24: Planning and Noise: PPG 24
20 National Planning Policy Framework - Guidance - GOV.UK (www.gov.uk)
21 https://www.ioa.org.uk/publications/propg

it does provide useful information such as guidelines for acceptable internal noise limits in residential buildings and broader guidance on the planning process.

3.22 NPPF is also supported by national Planning Practice Guidance[22] (PPG), a web-based resource launched by the government in 2014.

3.23 However, neither of these documents give the level of detailed guidance provided by PPG 24 and provide only qualitative descriptions of various levels of nuisance noise. In contrast, PPG 24 provides some numerical guidelines, albeit derived from those provided by the WHO at the time, one of the most important of which stated that noise needs to be considered for planning purposes above 55 dB(A) daytime and above 45 dB(A) night at a building façade. Guidelines for a series of higher noise level bands were also provided and, as a result, many local authorities in England still refer to PPG 24 when considering planning applications.

3.24 In general, local authorities should produce their own noise management guidance documents with a good example being the recent Manchester Planning and Noise Technical Guidance[23]. These can include local mandated noise limits, and will therefore be applicable to any transport infrastructure including Light Rail systems.

3.25 There is no single UK, European or international standard that covers the overall topic of N&V management on railways. However, there are numerous standards providing detailed guidance on specific aspects of N&V management, planning and measurement, for both construction and operational scenarios. Information on the key standards is included in this guidance where appropriate, so their relevance can be understood.

22 https://www.gov.uk/government/collections/planning-practice-guidance
23 Manchester City Council - Planning and Noise – Technical Guidance 2022: https://www.manchester.gov.uk/downloads/download/5199/information_for_developers

4. Sources of Operational Noise and Vibration

Noise Sources

4.1. There are two primary types of operational noise source from day-to-day operation of any Light Rail system.

- Noise from the rolling stock onboard systems which will be dominant when the vehicle is stationary and at low speeds; and
- Noise from the wheel rail interface (WRI) which includes rolling noise, noise from track discontinuities and irregularities, and curving noise (see Sections 4.6 to 4.11 for further information). On straight track, rolling noise typically becomes dominant above about 30 km/h depending on the system characteristics[24]. However, where wheel squeal occurs, it can be dominant at any speed but especially in tight curves and at low speed. Speed is critical to WRI noise, for example, doubling speed from 30 to 60 km/h can lead to an increase in the maximum level by up to 9 dB(A)[25].

4.2. Typical Frequency Bands for the main types of N&V discussed below are listed in Table 4.1.

Table 4.1: Typical Frequency Bands

Type of Noise	Typical Frequency Band (Hz)
Ground-Borne Vibration	40 - 200
Rolling	50 - 2500
Top of Rail Squeal	1000 - 5000
Flanging	5000 - 10000

Rolling Noise

4.3 Airborne noise caused by the steel wheel rolling on the steel rail increases with speed and is dependent on roughness at the contact patch that vibrates both wheel and rail, and can propagate through both rolling stock and track structures. Rolling noise consists of noise radiated by the track and noise radiated by the wheel, and a rough wheel can cause significant noise to be radiated mainly by the track vibration or vice versa. It is therefore difficult to assign noise contributions solely to the vehicle or infrastructure, so for any action plan aimed at reducing rolling noise, it is important to know if either the wheel or track is the dominant noise source. Specialist measurement and modelling techniques to achieve this are detailed in Environmental Noise Directive, Development of Action Plans for Railways 2008 (see as referred to above).

4.4 As a general indicator, sleepers (where used) are the most important low frequency noise source. In mid-frequencies the rails become the most significant and at high frequencies rolling stock wheels become the dominant noise source. As speed increases, the peak in the noise spectrum shifts towards higher frequencies leading to wheel condition and design becoming much more significant in terms of contribution to the total sound

24 UIC Railway Noise in Europe Sate of the Art Report Jan 2021 Section 3

25 VDV (Association of German Transport Undertakings) Paper 154 “Noise of railway vehicles for short-distance traffic – trams, light rail, metros” 2011

level[26]. The characteristics and strength of rolling noise will therefore be unique to any rolling stock / track combination, and will be affected by a range of variables including wheel and rail profiles, wheel design and the track system used.

Discontinuity Noise

4.5 Discontinuities such as switches and crossings (S&C), dipped welds and rail joints act as extreme, discrete examples of rail roughness and typically result in a short, sharp pulse of noise often referred to as 'impulsive' or 'impact' noise. A similar effect is caused by wheel flats, although the discrete event will repeat with each wheel revolution. It is also worth highlighting the link between discontinuities and some types of corrugation, with corrugation often initiated at poor welds which cause a sudden displacement of the vehicle's unsprung mass and subsequent vibration. Proactively addressing discontinuities will therefore mitigate noise both directly, and indirectly by helping to prevent noise-producing corrugation.

Curving Noise

4.6 Curving noise describes distinct types of noise emissions associated with rolling stock negotiating curves. In general, the better a bogie or wheelset 'steers', the lower the risk of curving noise. Although curving noise is more likely to occur with fixed axle wheelsets, it can occur on vehicles with independent wheels as there are still varying degrees of independence, especially on the very low radius curves common on Light Rail systems. There are three main types of curve noise that are detailed below.

Wheel Squeal

4.7 Wheel squeal can be a very loud tonal noise where up to 130 dB has been measured and >100 dB is common, which is typically dominated by a single frequency. Being so loud means squeal will often be the noise that emerges most clearly from other rail and ambient background noise.

4.8 Wheel squeal is most commonly (although not always) associated with wheel / rail contact between the rail head (top of rail), and the wheel tread, particularly for the leading inner wheel of a bogie. The WRI mechanics responsible for squeal are complex and whilst an established theoretical explanation has existed since the 1970s, other more recent mechanisms have been proposed and the topic is still subject to extensive research[27]. To summarise the established theory, frictional instability at the WRI leads to lateral stick-slip oscillations and the resulting high frequency vibration is emitted by the wheel, and potentially the adjacent rail, as the squealing sound heard.

4.9 The fact that conventional steel wheels can act as very efficient sound transmitters also contributes to the problem, and squeal has a number of characteristics such as its frequency range and tonality that can make it the most annoying type of Light Rail system noise. However, a common factor in all the main squeal theories is friction, and friction management is therefore one of the key means of mitigation.

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26 Wheel Rail Interface Handbook, Woodhead Publishing Ltd 2009, Chap 16, Noise and vibration from the wheel-rail interface, D. THOMPSON and C. JONES

27 A state-of-the-art review of curve squeal noise: phenomena, mechanisms, modelling and mitigation 2018. D.J. Thompson1 , G. Squicciarini1 , B. Ding1 and L. Baeza1

Flanging

4.10 This consists of a series of high frequency components sometimes described as an intermittent hissing or 'tching-tching' type of noise. Flanging noise is usually caused by the contact forces, and therefore friction between the wheel flange and the high rail gauge face / corner. It can also occur due to the back of the flange contacting the keeper on grooved rail or check rail on conventional track, usually when the high rail has seen significant wear'. In addition, flanging can be affected by top of rail friction on both high and low rails, as this can influence how well a bogie steers. Once again, friction is a common factor and friction management a key means of mitigation.

Graunching

4.11 Graunching tends to be a lower frequency rubbing sound. As it is rarely as loud as squeal or flanging, or indeed rolling noise, and has not been widely researched, it is not considered further in this document.

Noise From Onboard Systems

4.12 There are numerous items of primary and ancillary equipment on a Light Rail vehicle that emit noise, but because rolling noise typically becomes dominant at approximately 30 km/h, onboard system noise is of most interest when vehicles are stationary, as they accelerate from rest and during braking. The design of the various onboard systems is integral to the broader vehicle design so the associated noise levels should be known with pre-determined cumulative limits specified at the design stage.

4.13 Provided that the vehicle noise emissions meet the design specification, it therefore follows that as long as these systems are operating correctly and cumulative limits met, individual system noise is of little importance.

4.14 Where noise is caused by a defective component or system, this should be identified and rectified by routine maintenance and / or fault reporting and repair processes. With long intervals between Light Rail vehicle scheduled maintenance common, it is therefore essential that an effective process for defect reporting by drivers, other staff members and members of the public is in place to ensure noise related faults are rectified quickly.

4.15 Systems contributing to a vehicle's normal noise signature include the following:

- Traction Equipment and associated Cooling Fans;
- Electrical Control Equipment such as Inverters and Thyristors;
- Drivetrain and Gearing;
- Compressors;
- Audible warnings for doors;
- Public Address (PA) systems; and
- Air Conditioning Units.

4.16 Noise from other onboard systems can be variable but should be controllable, either by correct maintenance or operational procedures. Examples include the following:

- Brake squeal: modern Light Rail vehicles are braked electrically down to very low speeds so brake squeal should only be an issue in the final stage of braking. It can become significant due to the frequency of Light Rail services and the need to brake at every stop, but it should be manageable through routine maintenance and the use of suitable 'quiet' brake pad or shoe material;
- Pantograph: if rolling stock hardware is in good condition the main variable affecting pantograph system noise is vehicle speed so for Light Rail systems, rolling noise will normally dominate any noise from a serviceable pantograph system;
- Audible warning devices: EN 15153-4:2020 Part 4[28] defines the functional and technical requirements for exterior audible warning devices for urban rail vehicles including Light Rail systems. How these devices are used in practice and the sound levels involved may require careful operational planning to ensure they provide their design function including accessibility, without causing annoyance to members of the public and local residents (refer to LRG 28.0 Guidance on the Provision of Accessibility In LR Systems for further guidance). This includes the use of audible warnings in depots, especially during vehicle maintenance and preparation. Consideration should also be given to the use of horns in residential areas, especially at night where they are a common source of complaints;
- Door audible warnings: Rail Vehicle Accessibility Regulations (RVAR) 2010[29] specify the requirements for door audible warning devices that shall be fitted to each passenger doorway on a Light Rail vehicle. Again this can cause problems for people living close to stops. BS EN 17285:2020[30] also provides guidance; and
- Public Address systems: whether fixed at stations and stops, or on board the Light Rail vehicle, these can cause annoyance to people living in the vicinity, especially in residential areas with low ambient noise. Again, volumes and message frequency need to be managed to avoid annoyance and within the context of wider system noise limits.

Operational Ground-Borne Noise and Vibration

4.17 During normal operation, vibration from rolling stock is generated in a similar way to rolling noise by the combined roughness at the WRI, except that the relevant wavelengths are much longer than those responsible for airborne noise. Track vertical alignment (roughness) is a key factor in generating vibration, as any vertical displacement of the wheelset causes fluctuating forces that lead to vibration. The resulting vibration transmits through the ground and any connected structures to trackside buildings where it is manifested as vibration that is perceived by the occupants. Vibrating surfaces within the building may then radiate an audible low frequency noise and both noise and / or vibration may be perceived.

4.18 The resilience of the track system and its components will influence the transmission of vibration and although use of resilient components can attenuate higher frequencies, care should be taken because this approach creates a mass / spring system with its own resonant frequencies where amplification rather than attenuation can occur. However,

28 EN 15153-4:2020 Part 4 Railway applications - External visible and audible warning devices - Part 4: Audible warning devices for urban rail
29 https://www.legislation.gov.uk/uksi/2010/432/contents
30 BS EN 17285:2020 Railway applications. Acoustics. Measuring of door audible warnings

resilient floating slab track systems are an established means of reducing ground-borne N&V and these are discussed further in Section 6.

4.19 Similar to airborne noise, discontinuities can be considered as extreme, discrete examples of rail roughness and typically result in a short, sharp pulse of vibration. As well as the wheel and track roughness such as wheel flats, corrugation, and the general vertical track alignment that can affect vibration generation, vehicle unsprung mass is a critical factor with vehicle overall mass and suspension characteristics also relevant.

5. Noise and Vibration Measurement

5.1. Regular N&V measurements should be undertaken as and when required by the Light Rail system N&V Management Plan and should aim to capture information on the existing noise and vibration environment from a representative sample of the Light Rail vehicle fleet passing a number of defined locations. The results should then be assessed against previous survey results to check for negative trends, and compliance against the agreed limits or targets for the Light Rail system in question. This should lead to a noise mitigation action plan and it is good practice to use a scoring system to prioritise the actions needed.

5.2. A typical example of circumstances when noise measurements are required by a N&V Plan is as follows:

- During commissioning of the scheme a baseline benchmark needs to be established;
- Six months after commencement of passenger service (for each construction phase, where applicable);
- At six monthly intervals for the first three years of operation;
- Annually thereafter; and
- If requested by local or national regulatory bodies.

Measurement Locations

5.3. These should be chosen to represent a range of infrastructure types and environments including residential areas, business areas, a geographic spread, and incorporate locations such as tight radius curves, crossings and bridges, and both shared and segregated alignments.

5.4. For vibration measurement, consideration should be given to existing sources of vibration such as heavy industrial sites or railways, and proximity to vibration-sensitive facilities such as recording studios.

5.5. Input from local user groups, residents' associations or similar should also be considered to ensure local sensitivities are addressed.

5.6. Although it may be necessary to introduce new measurement locations in response to emerging issues or requirements, where possible, the same locations should be used as in previous assessments to allow comparison and trend monitoring over time.

5.7. Ideally the monitoring should cover the entire Light Rail vehicle fleet but where this is impractical, an agreed minimum number of pass-by events should be measured. Care should also be taken to ensure measurements are taken at distances representative of the nearest residential receiver to the tracks and measurement should cover Light Rail vehicles running in both directions where appropriate.

Noise Measurement

Equipment

5.8. Sound level meters should conform to the requirements of BS EN 61672-1: 2013[31]. This equipment calibration should also be checked before and after the measurement programme using a calibrator that conforms to the requirements of BS EN 60942: 2003[32].

5.9. The calibrator itself should be calibrated annually with a calibration history traceable to a certified calibration institution. Noise measurements should be taken in free field conditions with the microphone positioned away from reflecting surfaces as required by BS 7445-1:2003[33].

Measurement and Scoring Methodology

5.10. The following guidance is based on noise measurement methodology currently in use on some UK Light Rail networks. Measurements are typically used to calculate the $L_{Aeq,16h}$ dB rail noise level (07:00 – 23:00 hours) and the associated Sound Exposure Levels (SEL). An example of the type of scoring system which is then used to compare results with previous rounds of measurement, and then develop and prioritise a mitigation action plan is provided in Table 5.1 and 5.2 below. A key advantage of this approach is that it takes account of not just measured L_{Aeq} and L_{Amax} noise levels, but also the change in noise levels over time which helps indicate emerging issues.

Table 5.1 Assessment of Noise Levels

Score A	Daytime Light Rail vehicle Only Noise Level $L_{Aeq,16h}$ (dB)	Average Maximum Light Rail vehicle Noise Level in either direction L_{AFmax} (dB)
1	<55	<65
2	> or = 55	> or = 65
3	> or = 63	> or =80

Table 5.2 Assessment of Change in Noise Levels[34]

Score B	Change in noise from Previous Monitoring $L_{Aeq, 16hr}$ (dB)	Change in noise from Previous Monitoring L_{AFmax} (dB)
0	<0	<0
3	0 to +0.9	0 to +0.9
4	+1.0 to +2.9	+1.0 to +2.9
5	+3.0 to +4.9	+3.0 to +4.9
6	> +5.0	> +5.0

31 BS EN 61672-1: 2013 ‘Electroacoustics. Sound level meter, Specifications’
32 BS EN 60942: 2003 ‘Electroacoustics, Sound calibrators’
33 BS 7445-1:2003 'Description and measurement of environmental noise. Guide to quantities and procedures'
34 From lowest level recorded during past 3 years unless there has been a material change in measurement factors such as screening or tram configuration

5.11. Adding scores A and B can then be used to create a total score for each monitoring point which is used to prioritise future mitigation work.

5.12. More specific mitigation criteria may also be defined based on changes in noise levels rather than absolute limits, with the following approach already used on an existing UK Light Rail system. At any location, if the mean of the noise levels of all the vehicles measured on any one track is found to be 5 dB(A) or more greater than the mean measured on any previous occasion for an equivalent set of vehicles, then the track will be reground, or other appropriate work will be undertaken as soon as reasonably practicable, assuming noise from particular vehicles has not skewed either average.

5.13. Monitoring and scheduled maintenance will also be used to prevent any particular vehicle becoming excessively noisy as set out below. In the event that the maximum noise level of any vehicle is found to be 5 dB(A) or more over the mean, then the wheels of that vehicle will be scheduled for re-turning as soon as reasonably practicable.

Vibration Measurement

5.14. Key standards applicable to the measurement of vibration and what different levels of vibration mean to both humans and infrastructure are as follows:

- BS 7385-2:1993[35] provides guidance on the assessment of the possibility of vibration-induced damage in buildings due to a variety of sources, and identifies the factors which influence the vibration response of buildings. It is intended to provide a standard procedure for measuring, recording and analysing building vibration together with an accurate record of any damage occurring; and
- BS 6472-1:2008[36] provides guidance on predicting human response to vibration in buildings including the most important frequency range 0.5 Hz to 80 Hz. Frequency weighting curves for human beings exposed to whole-body vibration are included, together with advice on measurement methods to be employed. Methods of assessing continuous, intermittent and impulsive vibration are presented. The also describes how to determine Vibration Dose Value, which can be used to estimate the probability of adverse reaction from human beings experiencing vibration in buildings. Consideration is given to the time of day and use made of occupied space in buildings, whether residential, office or workshop.

5.15. Vibration meters used should conform to the following as appropriate:

- BS ISO 4866[37] requirements for Peak Particle Velocity (PPV) calculations, and have a current calibration certificate; and
- BS EN ISO 8041-1:2017[38] specifies the performance specifications and tolerance limits for instruments designed to measure vibration values for the purpose of assessing human response to vibration.

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35 Evaluation and measurement for vibration in buildings - Guide to damage levels from ground-borne vibration
36 BS 6472-1:2008 Guide to evaluation of human exposure to vibration in buildings
37 ISO 4866:2010 Mechanical vibration and shock — Vibration of fixed structures — Guidelines for the measurement of vibrations and evaluation of their effects on structures
38 ISO 8041-1:2017 Human response to vibration — Measuring instrumentation — Part 1: General purpose vibration meters

5.16. Vibration measurement should normally be carried out by specialist organisations. Although ground-borne vibration is typically a problem inside buildings, outdoor measurements may be preferred because equipment inside a building may cause significant vibration in its own right which should be documented separately, and the building's own structure and associated resonances can affect vibration in an unpredictable manner.

Vibration Measurement and Scoring Methodology

5.17. With Light Rail related vibration strongly related to track condition, identifying emerging track anomalies such as corrugation, worn S&C and rail joints, or other types of rail damage is again critical and measurements should be taken on as close to as new rail as possible to establish benchmarks. In addition to highlighting any deterioration, this will also help characterise the vibration caused by track irregularities where they exist. A similar methodology to that used for noise monitoring may therefore be adopted and an example of prioritisation with typical values from a UK system is provided in Table 5.3.

Table 5.3 Example of Prioritisation

Priority Rating	Assessment	Action
Low	PPV <0.3 mm/s and increasing over time	Review but immediate action may not be needed
Medium	PPV between 0.3 and 1.0 mm/s and increasing over time	Review and consider mitigation measures
High	PPV > or =to 1.0 mm/s and increasing over time	Review and consider mitigation measures

Continuous N&V Monitoring

5.18. The dependency on external specialists and their equipment for N&V monitoring means it is inherently reactive and can be inflexible in an operational context. Furthermore, operational N&V measurement or monitoring is generally implemented in response to a problem, perhaps initiated by a complaint, on a scheduled basis as required by a N&V Plan, or in response to a third-party requirement, for example, DEFRA. The tendency is therefore for existing problem N&V to be identified and / or confirmed and characterised, so this usually means action has to be taken to fix problems that already exist. As noise problems almost always relate to track or wheel damage, this means that costly damage may have already occurred before the problem is detected.

5.19. An alternative approach using recent technology already deployed in Europe uses onboard and / or trackside sensor equipment to pro-actively monitor N&V on a continuous basis. This allows emerging issues to be detected which in turn minimises the risk of N&V surprises and offers the benefits of preventative maintenance for both wheels and rail. Continuous fixed monitoring at particularly sensitive locations is in use on at least one UK system, but the technology discussed here applies continuous monitoring to a whole system.

5.20. Typically when using a service provision contract, the data collected is remotely communicated to a base server from where it is processed using special algorithms, and displayed in easy to use dashboard format via a dedicated web application. Such a system also has a safety benefit, for example, early detection of broken rails. A typical example of this type of technology works on the following principles:

- Using one or more fixed trackside monitoring units, the N&V signatures of passing vehicles can be constantly monitored. Individual vehicle data can be tracked via the dashboard and any vehicle-specific N&V trends identified; and
- Onboard N&V sensors with GPS (Global Positioning System) location tracking can also be fitted to existing rolling stock to create one or more control vehicles which allow constant network monitoring. In addition to recording key parameters such as vehicle speed, a range of WRI N&V monitoring options are available, including the ability to measure and differentiate between squeal and flanging noise, all with associated dashboards to present the information. This type of system can also detect corrugation at an early stage to allow grinding or other mitigation before it becomes a problem, with a further optional capability to monitor pantograph noise.

6. Noise and Vibration Management Through Design

6.1. This section outlines the N&V mitigation features that can be considered during the design stage for both infrastructure and rolling stock. In all cases when considering N&V mitigation, care should be taken to consider whole-life costs including not only capital costs, but maintenance, consumables and disposal with associated operational downtime.

6.2. One example is friction management systems where onboard stick lubricant systems require low initial capital expenditure but, depending on consumption rates, may have higher through-life costs compared to spray systems that are more expensive to install. Maintainability should also be considered, for example, the difficulty in welding encased grooved rail.

Wheel Rail Compatibility

6.3. WRI characteristics such as wheel and rail profiles and materials are critical to long-term performance, damage, wear and noise characteristics, and this is an area seeing increased focus and understanding. For new Light Rail systems and / or extensions, working with the track and vehicle designers at an early stage will pay dividends in the long term and opens the door to performance guarantees from some rolling stock manufacturers. However, materially changing the WRI on an existing system is understandably more controversial as it has the potential to alter the running behaviour of vehicles, increase wear and noise and increase resulting costs. The opposite is also true and if done properly, an optimised WRI can give significant benefits.

6.4. As an example, work on this topic by one of the major rolling stock OEMs[39] has led to a standardised process to develop an optimised wheel / rail-combination adapted to the customer's network. This uses complex analytics involving a range of factors such as rolling radii, curve characteristics and distribution across a network, track stiffness, loading, typical weather conditions (affecting friction) and gauge width. The key output of the process is to develop an optimum wheel profile for a specified rail profile which is agreed in liaison with the customer, and which is then validated using complex wear modelling. In a real world case study this work is claimed to have reduced wheel and rail wear by an order of magnitude. This approach is best applied at the design stage as although it can be effective for existing networks, the WRI must be reset through rail replacement, grinding and wheel re-profiling.

6.5. As WRI wear and noise often have the same root causes, this type of approach is also likely to reduce noise and should therefore be considered in cases where widespread chronic wear and noise issues occur.

6.6. Care should also be taken when introducing a new vehicle type for use on existing track where both infrastructure and vehicles may already have N&V attenuation devices tuned to the WRI. However, a different vehicle with different characteristics can de-tune and create noise and vibration across the system.

39 Jani Dede, Uwe Reimann and Marc Reimann Bombardier Wheel Rail Interface Study (WRIS)

Track System Design

6.7. As a general principle, track design should always ensure that curve radii are the maximum possible to minimise the risk of curve noise and associated wear and damage.

6.8. On Light Rail systems, the track support system is one of the major components that determines the levels of N&V. In a recent study[40], the following three different types of track on a single network were compared: slab track with embedded sleeper blocks, ballasted track, and a track with embedded rails in grass. This found that the overall level for slab track is 3–5 dB higher than for the ballasted track, mainly due to a higher noise level from the rail. The rail noise component was higher than the wheel noise in both cases, by 3 dB for the ballasted track and 5 dB for the slab track. For the embedded grass track, the overall level was 1–2 dB higher than for the slab track. Track rigidly attached to a concrete trackbed also results in the highest levels of vibration.

6.9. However, N&V can be much reduced by using specialist track systems which incorporate various resilient features and components such as resilient fasteners, ballast mats, and floating slabs. These specialist track systems do have costs, both financially and in terms of construction speed, and a mixture of systems may be needed. For example, the TfL Elizabeth Line uses four different track systems to achieve its ground-borne noise targets which vary depending on proximity to different types of noise-sensitive buildings. However, careful analysis at the design stage means that the vast majority of the line uses the cheapest of the four systems with the others only used for short distances where needed[41].

6.10. A similar approach has been used in UK Light Rail systems with a recent example involving three track system variants on a line extension. These were a standard system based on the existing reference system characteristics, a second variant which introduced an additional soft rail pad to reduce the vertical stiffness of the system and provide more dynamic insulation, and a third variant for the most sensitive areas using floating slab with the concrete slab supported by a continuous elastomeric mat covering both base and sides of the slab to ensure no mechanical coupling degrades the vibration isolation.

Resilient Track Systems and Components

6.11. The most effective approach to designing a track system is therefore to design the system to take account of local requirements within the wider regulatory framework and N&V limits discussed in this guidance document.

6.12. There are numerous components that can be sourced to mitigate N&V as part of a track system and an overview of the most common are detailed in the following paragraphs. However, at the design stage it is essential to use an integrated approach to system design as some of these components can also be retrofitted to address problems, but this should only be done with specialist advice and support. Most of these components primarily address vibration and ground-borne noise but, by improving track support characteristics such as load distribution and track deflection, they also reduce track wear and damage and can therefore reduce airborne rolling noise as a secondary benefit.

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40 Applied Acoustics 170 2020: The influence of track design on the rolling noise from trams, Sun, Thompson, Toward, Wiseman, Ntotsios and Byrne

41 https://learninglegacy.crossrail.co.uk/documents/control-of-railway-induced-groundborne-noise-and-vibration-from-the-uks-crossrail-project/

Resilient Fasteners

6.13. Resilient fasteners are used to fasten the rail to concrete track slabs. Standard resilient fasteners are very stiff in the vertical direction but special fasteners with reduced vertical stiffness may significantly reduce vibration at frequencies above 30 to 40 Hz. The Transit Noise and Vibration Impact Assessment Manual FTA Report No. 0123 provides an excellent reference for calculating existing noise levels from a variety of sources[42] ('transit' is US terminology for Light Rail). Resilient fasteners can be retrofitted if needed.

Resilient Baseplate Pads

6.14. Resilient baseplate pads can be used on slab track systems where they are installed between the rail mounting baseplate and the concrete support slab and, in addition to other benefits, can help reduce rolling N&V.

Sleeper Pads

6.15. Sleeper pads provide resilient support to concrete sleepers on ballast with a pad fitted to the bottom of the sleeper. Different pad materials such as rubber or foamed polyurethane are available depending on the application and they can typically mitigate vibration at frequencies above 25 Hz. They are also claimed to indirectly reduce airborne rolling noise by improving track stability which in turn reduces wear rates and surface roughness.

6.16. They can be installed during construction or retrofitted on-site but some manufacturers also offer the ability to install during sleeper manufacture to simplify construction work. Although more commonly used in higher speed applications they can also be useful where fittings such as S&C require optimum track stability and consistent deflection under load.

Floating Slab Track

6.17. There are numerous floating slab track systems and this approach can be very effective at controlling ground-borne vibration and noise. They work on the principle that the concrete slab itself rests on resilient components using rubber or other elastomeric materials.

6.18. Different configurations and materials allow these systems to be adapted to specific local requirements, and versions designed specifically for Light Rail system applications are available. Floating slab technology is, however, relatively expensive and can cost several times as much as conventional track.

Ballast Mat Systems

42 Transit Noise and Vibration Impact Assessment Manual FTA Report No. 0123, Federal Transit Administration: https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/118131/transit-noise-and-vibration-impact-assessment-manual-fta-report-no-0123_0.pdf

6.19. For ballasted sections of track, ballast mat systems offer a permanent means to mitigate ground-borne N&V. They operate on the basis that the track is elastically supported by a continuous resilient mat placed under the ballast and are most effective on a concrete base. By altering various mat properties such as material stiffness, mat thickness and number of layers it is possible to tune the mat system to different rolling stock and track system parameters.

6.20. These systems are typically designed to be fully water permeable so they do not affect drainage, have tough outer layers to protect against ballast damage and some types are fully recyclable.

Embedded Grooved Rail Systems

6.21. Increasing use is being made of resilient encapsulation systems for embedded grooved rail. Although not exclusive to grooved rail, this type of system is highly relevant to Light Rail systems where embedded rail requires continuous vertical and lateral support, vibration mitigation and stray current insulation. In these systems the rail is continuously supported and fastened by elastomeric material profiles with shape and stiffness characteristics tailored to individual project requirements, including vibration mitigation.

6.22. This type of system can be installed rapidly and may also be integrated in pre-fabricated slabs for even quicker installation. Manufacturers may also offer full encapsulation of S&C. However, maintainability does need to be considered, for example, welding can be problematic.

S&C Design

6.23. A major contribution to Light Rail system N&V comes from the impact noise due to S&C discontinuities and as even the best S&C components will generate some noise and vibration, system design should avoid their use in noise sensitive areas wherever possible. S&C design options for N&V mitigation include the following:

- Use of crossings designed for flange running are an effective N&V reduction option for grooved rail although care needs to be taken to ensure compatible wheel design. Care should also be taken to ensure any trackside lubricators in the vicinity are set up correctly and are not contaminating the wheel flange tip as this could affect braking. In addition, the bottom of the rail groove must be kept free of debris, especially sand, as this can increase rolling noise.
- Another option that can be used with switches is swing nose crossings that eliminate the gap inherent in conventional crossings and provide a near continuous running surface. Although more expensive than conventional crossings, by almost eliminating the discontinuity between running rails they can significantly reduce associated N&V. In the UK for example, they are used for switches in the noise sensitive area at Canary Wharf Station on the Docklands Light Railway.
- A further consideration is the use of unmotorised trailing switches, such as spring return points and free trailing points, which have been known to cause noise complaints in the UK due to the switch springing back. If this occurs it may be necessary to motorise the switch.
- An additional option where diverging routes are not in regular use (for example, emergency crossovers) is the lift-over frog. This gives an uninterrupted run for the

frequent normal traffic but at the expense of greater noise when using the emergency crossover.

Rail Dampers

6.24. Rail damping is characterised by track decay rate and in principle, high track decay rate reduces noise. Decay rates mainly depend on the stiffness of the elastic rail support because the damping inherent in the rail itself is very low.

6.25. Stiff rail pads therefore give significant reductions in rail noise and vibration compared to soft rail pads. However, they cause higher sleeper vibration and therefore higher sleeper noise radiation. Rail dampers are generally mass-spring absorber systems attached to the rail at mid span between the sleepers and they work by increasing track decay rate at certain frequencies, thereby reducing rail vibration without increasing sleeper vibration and noise. They have high internal damping and multiple tuning frequencies in order to be effective over a broad frequency range. Use of rail dampers is therefore typically more beneficial on a track with soft rail pads than on a track with stiffer ones[43].

6.26. Various types of rail damper are offered including elastomeric blocks and those using more sophisticated steel / elastomeric sandwich construction, with some tailored to rail profiles to ensure optimum performance. By reducing rail vibration, rail dampers may also reduce corrugation as a secondary benefit.

Trackside Equipment

6.27. Care also needs to be taken when designing and positioning trackside equipment and cabinets, for example, substations if these emit electrical noise or noise from ventilation or cooling systems. Wherever possible, these should be designed and located so that any noise emitted is not noticeable above existing background noise.

6.28. In a recent example from a UK Light Rail system, the contractor was required to assess noise levels from traction power substations and OLE installations according to BS 4142[44], and it was specified that in addition to meeting all planning conditions, noise shall not exceed extant background noise by more than 5 dB(A). However, this still gives a clear increase over ambient noise levels and LRSSB consider that the target should be an increase of no more than 3 dB(A) above the extant background noise.

6.29. A further benchmark for night time noise from trackside equipment is provided by the Yarra Light Rail system in Melbourne Australia where a limit of 42 dB(A) is specified and enforced.

Noise Barriers

6.30. Although it may not always be practical to use noise barriers on Light Rail systems due to space or visual impacts especially in congested areas where they are used, they can be very effective by breaking the line-of-sight between source and receiver with reductions of up to 10 dB(A) possible (refer to the FTA Transit Noise and Vibration Impact

43 The STARDAMP Software: An Assessment Tool for Wheel and Rail Damper Efficiency, Betgen, Bouvet, Squicciarini and Thompson
44 Methods for Rating and Assessing Industrial and Commercial Sound

Assessment Manual). They should therefore be considered at the design stage of any project.

6.31. It should be noted that the necessary height of a barrier depends on the source height and the distance from the source to the barrier and in general, the closer the barrier to the source, the lower and less intrusive it can be. Barriers located very close to a Light Rail vehicle, for example, may only need to be approximately 1 m above the top of the rail to be effective. Depending on the barrier design, effectiveness may be further improved by applying sound-absorbing material to the inner surface of the barrier.

6.32. The length of the barrier wall is also important and the detailed design shall ensure that noise from beyond the ends of the barrier does not compromise performance. The various types of noise barrier include the following:

- Simple reflecting barriers that provide a physical obstacle between source and receiver;
- Absorbing barriers are designed with absorbing materials on the side facing the noise. Commonly used to mitigate traffic noise, they can be effective but are also relatively expensive;
- Angled barriers reflect sound away from the receiver rather than block it; and
- Capped barriers have a specially designed top section to attenuate sound waves.

6.33. Noise barriers can be made from a range of materials including concrete and steel, but natural materials such as earth, wood and other material excavated during construction can also be effective.

6.34. While vegetation can be useful from a visual perspective to hide obtrusive barriers where there is room, and there is some evidence that visually hiding a noise source reduces associated annoyance, it has very little impact on noise levels with a number of studies citing only circa 1 dB(A) reduction from 10 m of vegetation.

6.35. On the broader topic of techniques to reduce perceived rather than actual noise, the Conference of European Directors of Roads (CEDR) have produced useful guidance on the use of non-acoustic interventions to reduce noise annoyance as part of their Moderating people's Subjective reactions to noise (FAMOS) project[45]. Although written primarily to address road noise, the associated guidebook[46] includes ideas and concepts that are also relevant to Light Rail.

6.36. Buildings themselves are also effective noise barriers and as part of wider infrastructure developments, placing insensitive commercial buildings between Light Rail systems and residential developments can be an effective approach to N&V management.

Rolling Stock Design

45 https://www.cedr.eu/docs/view/6373a7c267297-en
46 https://www.cedr.eu/docs/view/6266a30cbec0f-en

Weight and Suspension

6.37. Rolling stock specifications should include both static and 'pass-by' vehicle noise limits when tendering for new vehicles. Guidelines for these limits are discussed further below. In addition to designing the onboard equipment noise sources to meet cumulative static limits, the design should seek to minimise rolling noise and as one of the biggest contributing factors to Light Rail system N&V is unsprung vehicle mass, minimising this is a key part of vehicle design.

6.38. Primary suspension characteristics are also important, with a key principle being to control the transmission of vibration at audible frequencies (typically 20 Hz – 10 kHz) from the wheels in order to mitigate ground-borne N&V. Related to this, FTA recommend that a limit for the vertical resonance frequency of the primary suspension should therefore be included in the specifications for any new vehicle. They consider that a vertical resonance frequency of 12 Hz or less is adequate whist noting that some sources recommend this is reduced to less than 8 Hz.

Skirts and Shielding

6.39. By carrying their own noise barriers in the form of shielding around noisy components, skirts and / or underbody absorption materials, Light Rail vehicles can provide a significant level of inbuilt noise absorption with skirts on their own potentially offering 5 dB of mitigation by acting as close barriers to N&V propagation. However, their effect is limited as they do not shield the lower part of the wheel, the track and coupled structures. Aesthetics aside, they should be as continuous and close to the ground and wheels as possible, and preferably lined with acoustically absorbent material.

Resilient Wheels

6.40. Resilient wheels where rubber or plastic compression elements are mounted between, and thereby isolate the wheel web and rim are now widely used on Light Rail vehicles. Compared to a one-piece metal wheel, this type of wheel can mitigate squeal noise in tight turns with reductions of between 10 and 20 dB claimed by manufacturers in the related high frequency range, together with improved passenger comfort. Actual research is limited and results will vary by wheel design, system and rolling stock, however, a study on the Madrid Metro gave measurable improvements of over 7dB[47].

6.41. The effect of resilient wheels on ground-borne vibration is also less clear, although some studies including the Madrid Metro study referenced above, have shown a significant benefit. Again improvements in this respect are will vary depending on the actual wheel design and physical environment involved.

6.42. Rolling noise can also be slightly reduced with resilient wheels and according to the FTA, a 2 dB reduction on tangent track is typical. Although resilient wheels are more expensive than conventional steel wheels they can offer clear benefits and their fitment should be considered for urban Light Rail systems.

Wheel Dampers

47 Effectiveness of resilient wheels in reducing noise and vibrations B. Suarez, J. A. Chover, P. Rodríguez and F.J. González

6.43. Rolling stock wheels can be fitted with damping devices that work by damping the frequencies that cause wheel squeal and / or rolling noise. Wheel dampers are most effective on simple steel wheels, but some designs are compatible with and are claimed to be effective on resilient wheels. A key advantage of wheel dampers is that they can, subject to suitable clearances, be retrofitted if needed and are therefore one option to mitigate persistent squeal problems, particularly if they are occurring at multiple locations on a network.

6.44. There are two main types of wheel dampers[48], those that absorb energy across a continuous range of frequencies and those that target specific frequencies known as tuned absorbers.

6.45. The first type is typically configured as a ring clipped to the wheel rim, or as a series of visco-elastic plates held against the wheel disc by metal sheaths known as a constrained layer damper. These work by resisting or absorbing the vibration that causes noise, and then dissipating the resulting energy instead, usually as heat.

6.46. The second, tuned absorbers, rely on the fact that a rigid disk has one or more resonant frequencies and will therefore vibrate preferentially at certain frequencies, hence the tonality of wheel squeal. The device consists of several absorbers (sometimes known as blades) on each wheel that are tuned to one or more resonant frequencies. These are usually bolted to the inside of the rim or the outer part of the web and can be configured to address axial resonance which causes squeal, or the radial resonance responsible for rolling noise. In tight turns claimed reductions of up to 18 dB(A) are possible, together with up to 6 dB(A) reduction in rolling noise depending on the original wheel design[49]. These figures are generally supported by wider industry experience[50], although there is some evidence that this equipment may reduce wheel life, especially if not adequately maintained.

Noise and Vibration Modelling

6.47. With so many variables at play, the N&V characteristics of any Light Rail system will be unique, and will themselves vary throughout the network where different track-forms are used and as wear characteristics develop. This makes prediction of N&V behaviour, and diagnosis of recurring problems difficult and time consuming.

6.48. Therefore, an area of potential future interest is the use of computer modelling to predict N&V behaviour during system design and to model problems in service. Relevant models do exist but were developed originally for heavy rail with ballasted tracks and rolling stock with conventional steel wheels. For Light Rail systems, the main complications include resilient wheels and embedded tracks, which would require some adaptations to the models below, but discussion with relevant subject matter experts suggests this should be possible if required. In the UK, the University of Southampton has been heavily involved in this type of work and has previously utilised the TWINS model discussed below for research work involving at least one European Light Rail system. Other models do exist including non-commercial systems used by rolling stock OEMs, but the following are considered to have the most potential for use on the UK Light Rail systems.

48 The Contact Patch R.1610 The Wheelset. Christopher Wright rev 5 Aug 21
49 Shock, Vibration & Noise Control, Schrey & Veit GmbH
50 Reduction of Noise From Trams in Urban Areas. Report for the Federal Environment Agency, Germany, 115/2021. Ramboll Deutschland GmbH

TWINS (Track-Wheel Interaction Noise Software)

6.49. Perhaps the most well-known modelling system is TWINS which was developed in the 1990s in the Netherlands and funded by various UIC (International Union of Railways) and EU research and development projects. It is used to assess the acoustic effects of wheel and track design on railway rolling noise by calculating vibration levels and noise emissions from wheels, rails and sleepers during a train pass-by. Additional data including contact forces, wheel vibration and track decay rate can also be derived.

6.50. The design parameters that can be assessed include the following:

- Wheel and rail geometry;
- Materials;
- Effects of vehicle speed;
- Rail fastener system;
- Wheel / rail surface conditions;
- Damping of wheels and rails; and
- Shielding close to wheels and track.

STARDAMP (Standardisation of Damping Technologies for the Reduction of Railway Noise)

6.51. This modelling system was developed in a Franco-German project (2010-12) with the aim of developing a method to assess damping techniques and equipment, specifically wheel or rail dampers. In structural dynamics, a damper is a system that works by converting part of its vibration energy into heat and STARDAMP exclusively deals with rail and wheel dampers that correspond to this definition so does not cover shielding systems.

6.52. It is based on TWINS with more limited functionality, but with the ability to include the effect of damping treatments in a more automated way. This is useful because the performance of this type of equipment depends on track, rolling stock and operating variables that mean actual noise reduction will be specific to each application (refer to the Wheel Rail Interface Handbook).

Train Noise Expert

6.53. The Institute of Sound and Vibration Research (ISVR) at Southampton University have also been developing proprietary software to improve on TWINS and to extend capability to include pass-by noise effects including other sources in addition to rolling noise. This software is marketed as Train Noise Expert which is designed to be a 'one-stop' tool for accurately predicting noise from trains and railways. Optional capabilities include the following:

- Rolling noise: this calculation option allows rolling noise sound powers and pressures as well as track decay rates to be calculated for wheel and track designs. Calculations are based on the TWINS noise model approach; and
- External noise: As key partners in the ACOUTRAIN European research project, ISVR developed software that calculates exterior noise for trains, both stationary and during pass-by at either standard ISO positions or user defined positions.

7. Guideline Operational Noise and Vibration Limits

7.1. This section provides guidelines for N&V limits applicable during operation of UK Light Rail systems. These are derived from current UK best practice and policy, but also take into account the latest regulations and N&V management principles used on Light Rail systems in North America, Europe and Australia. Guideline values are summarised at Appendix A, with an overview of basic N&V propagation theory and more detail on the overseas information reviewed provided at Appendix B.

Operational Airborne Noise

7.2. Noise from the multiple sources that exist in any urban environment including road traffic combines with any Light Rail noise, and it is the cumulative noise levels that potentially interfere with activities and / or cause annoyance. In many urban environments the dominant noise is from road traffic so when considering the impact of Light Rail systems it is important to consider the difference in noise levels due to the Light Rail system, as well as Light Rail noise in isolation.

7.3. It is also important to understand that because noise is measured on a logarithmic scale dB(A), adding noise from two sources of similar strength can lead to a relatively small overall increase. For example, if a Light Rail system generates pass-by noise of 70 dB(A), adding this to existing road noise of 70 dB(A) will give a total of 73 dB(A) and the difference should only just be noticeable. However, if a stationary Light Rail vehicle at a stop is generating 50 dB(A), adding this to 70 dB(A) road noise gives only 70.04 dB(A) total, an increase that is imperceivable to humans.

7.4. This concept of taking noise difference into account when setting limits is widely reported in the UK and overseas. Notably, this includes the PPG 24 guidelines for local authorities wishing to set local noise limits for new developments and as discussed above, is also taken into account in existing UK Light Rail system N&V monitoring plans.

7.5. In the UK, historic Light Rail N&V management guidance has been based on the Noise Insulation for Railways Regulations 1996[51] that are still valid, together with PPG 24. This differentiates between design aims driven by the former document's trigger values for noise insulation, and design aspirations derived from PPG 24 for noise due to a Light Rail system in isolation. These are as follows.

7.6. The system should be designed taking into account the highest proposed traffic flows, to ensure that the levels listed below are never exceeded as a result of predicted Light Rail noise alone, 1 m from the façade of residential properties. (It should be noted that these values were rejected as inadequate for at least one existing UK Light Rail system.)

- L_{Aeq}, 0600 – 2400 hrs 68 dB (equates to DEFRA's $L_{Aeq\ (18hr)}$ for noise surveys); and
- L_{Aeq}, 0000 – 0600 hrs 63 dB;

7.7. The design aspiration should be not to exceed the free field levels listed below as a result of Light Rail noise alone in the vicinity of residential properties. Where this is not possible, their exceedance is an indication that mitigation should be considered. Although this

51 https://www.legislation.gov.uk/uksi/1996/428/made/data.pdf

guidance is several years old it closely reflects current WHO guidelines and is therefore still relevant.

- L_{Aeq}, 0700 - 2300 hrs 55 dB ($L_{Aeq\ (16hr)}$); and
- L_{Aeq}, 2300 – 0700 hrs 45 dB ($L_{Aeq\ (8hr)}$).

7.8. The above guidance is reflected in the noise management principles widely adopted in the UK as illustrated by the following very similar policy extracts from two existing UK systems that also apply the principle of noise difference as discussed above and in the following examples.

Example 1

7.9. Noise mitigation will start to be considered if the free-field noise level outside the window of any sensitive receiver exceeds either of the following noise target levels: daytime L_{Aeq} 0700-2300 hours 55 dB or night time L_{Aeq} 2300-0700 hours 45 dB.

7.10. In this example, noise sensitive receivers are defined to include all types of dwellings, schools, libraries, hospitals, theatres and concert halls, and places of worship bordering the route.

7.11. Where Light Rail noise is predicted to be more than 3 dB above either of the above thresholds, mitigation measures to reduce the adverse impact of noise will be considered according to the extent to which the pre-existing ambient ($L_{Aeq,\ 1\ hr}$) noise level is increased, as follows:

- Increase of 3-5 dB - mitigation considered on a case by case basis, and implemented if reasonably practicable and acceptable to affected parties; and
- Increase of greater than 5 dB – mitigation implemented if reasonably practicable and acceptable to affected parties.

Example 2

7.12. The threshold above which noise mitigation will be considered as the following:

- L_{Aeq} 0700-2300 hours 55 dB; and
- L_{Aeq} 2300-0700 hours 45 dB

7.13. With 3 dB(A) taken as the widely accepted limit of perception for change in environmental noise, where Light Rail noise is perceptibly above these thresholds (i.e. by at least 3 dB), mitigation measures to reduce the adverse impact of noise intrusion shall be considered depending on the extent to which pre-existing ambient ($L_{Aeq,\ 1\ hour}$) noise levels are increased, under the following criteria:

- Increase of less than 3 dB no mitigation required; and
- Increase of more than 3 dB mitigation considered on a case by case basis with increasing priority for greater noise increase.

7.14. Considering these examples alongside the information from other nations (in Appendix B) suggests that current UK guidelines as described in the above examples for the daytime and night time L_{Aeq} noise levels that trigger mitigation are still valid. If anything, experience in the US and Germany suggests that it may be possible to relax these limits in areas where there are no residential properties if these can be clearly defined, an approach that may offer cost savings for some systems.

Noise Events

7.15. Guidance based entirely on the various interpretations of $L_{Aeq,T}$ limits discussed above, or similar L_{den} and L_{night} values used by the WHO and DEFRA to measure the cumulative noise for a Light Rail system is insufficient. This is because averaging noise over a period of time does not capture the effect of potentially intrusive noise events linked to Light Rail vehicle 'pass-by' including wheel squeal and flanging, or more prolonged noise in one location emitted when a Light Rail vehicle is stationary. So although these metrics are useful for measuring the cumulative impact of noise and defining related limits, consideration also needs to be given to the maximum values or L_{Amax} from transient events.

7.16. Furthermore, at speeds below about 30 km/h, a Light Rail vehicle's onboard systems may be the dominant source of noise and are at their noisiest during acceleration from standstill and under braking. It is therefore necessary to consider pass-by noise at speed (maximum rolling noise), pass-by under acceleration and braking (maximum Light Rail system noise), and static noise at tramstops.

7.17. Measurement of both pass-by and static noise from Light Rail vehicle s is covered by BS EN ISO 3095:2013[52] where Annex D is specific to Light Rail vehicles. This Standard provides comprehensive details on measurement methods and conditions to obtain reproducible and comparable exterior noise emission levels and spectra for all kinds of rail vehicles including Light Rail vehicles. It provides the detailed methodology for measurement of pass-by and stationary noise for Light Rail vehicles and is a key reference for this topic.

7.18. Pass-by noise limits are not covered in detail in existing UK system policy and the guidance that does exist is consistent across multiple systems and seems to be derived from PPG 24 and the Noise Insulation Regulations with a typical example as follows:

> *'Where the tram free-field level exceeds* L_{Amax}*, slow (i.e. the meter is set to slow response) 82 dB more than twice an hour at night (2300-0700 hours), insulation will be offered provided the tram* L_{Amax}*, slow is above the pre-existing ambient* L_{Amax}*, slow by at least 5 dB (3 dB may be considered depending on frequency and local circumstances)'.*

7.19. Further to the above, one existing UK system is also known to have originally specified Light Rail vehicles not to exceed 76 dB(A) at 40 km/h and 82 dB(A) at 65 km/h, 7.5 m from the track centre.

7.20. Historically, one of the benchmarks for specifying UK noise limits has been the German guidance provided by VDV Paper 154. Although this document has been withdrawn and is currently under review, it still forms the basis for guidance in Germany, and the most recent version of VDV 154 apparently recommended the limit for pass-by noise as 81.7 dB(A) at 80 km/h and 7.5 m from the track centre.

52 ISO 3095:2013 Acoustics — Railway applications — Measurement of noise emitted by railbound vehicles

7.21. However, more detail on the latest targets applied to Light Rail systems in Germany is provided in the 2019 specification for new rolling stock in Berlin[53] where the following limits in Table 7.1 are specified and measured in accordance with BS EN ISO 3095. Note the use of limits and targets which should be considered as it can incentivise over-performance.

Table 7.1: Targets Applied to Light Rail Systems in Germany (Paper 115/2021)

Tram Movement	Limit	Target
Acceleration and Braking to / from 30 km/h	72 dB(A) L_{pAFmax} limit	65 dB(A) L_{pAFmax} target
Braking from 60 km/h	77 dB(A) L_{pAFmax} limit	70 dB(A) L_{pAFmax} target
Pass-by under acceleration from 20 km/h	72 dB(A) L_{pAFmax} limit	68 dB(A) L_{pAFmax} target
Pass-by at 60 km/h	76 dB(A) $L_{pAeq,\,TP}$ limit	73 dB(A) $L_{pAeq.\,TP}$ target

7.22. The above approach has been proposed for Berlin linked to a contract bonus scheme. In addition, the Berlin specification recognises that technical developments may allow the limit values to be reduced in future. The specification also includes some limits for noise in curves. However, with so many variables to consider, it is recommended that UK Light Rail systems adopt the principle that pass-by noise levels in curves should be no higher than on straight track.

7.23. Use of SEL rather than $L_{pAeq,\,TP}$ to compare Light Rail vehicle pass-by noise may also be considered, as it allows direct comparison of the sound energy resulting from each pass-by event, irrespective of the speed of the Light Rail vehicle or duration of the event. Because SEL normalises to 1 sec, SEL pass-by values will be higher than directly measured values.

7.24. The pass-by noise measurement criteria specified above are considered to be best practice and are recommended as part of the specification for new UK Light Rail vehicles. The values listed also provide useful guidance and both target and limit values should be achievable although higher pass-by speeds up to the maximum used on a system may be preferred. A ‘do not exceed’ overall limit of 82 dB(A) should also be considered to capture both higher speed pass-by up to 80 kmph, and to align with the existing PPG 24 derived limits for occasional transient noise.

Noise from Stationary Light Rail Vehicles

7.25. A further criterion for consideration is the noise created by Light Rail vehicles when stationary for significant periods such as at tramstops, depots or junctions as this can be important for people in the vicinity. Again, one of the historic benchmarks for specifying noise limits in this respect has been VDV Paper 154 and guidelines from the most recent version are still useful. In this case, VDV recommended a limit of 56 dB(A) at 7.5 m from the centre of the track with a vehicle at standstill with full air conditioning / heating

53 Reduction of Noise From Trams in Urban Areas. Report for the Federal Environment Agency, Germany, 115/2021. Ramboll Deutschland GmbH

active, and tested in accordance with BS ISO 3095. An example of how this is applied in practice is again provided by the proposed 2019 Berlin tram specification including the following:

- Stationary, all systems switched on with maximum heating: 50 dB(A) L_{Aeq}; and
- Stationary, all systems on with maximum aircon: 55 dB(A) L_{Aeq}.

7.26. This gives a useful benchmark, however, modern Light Rail vehicle designs can be significantly quieter than this with at least one major OEM claiming their designs can better the VDV requirements by almost 10 dB(A). If confirmed, this would mean some Light Rail vehicles can emit only half the specified noise level, so a guideline maximum stationary noise limit for new Light Rail vehicles of 50 dB(A) should be achievable. As with pass-by requirements, this would be written into the new vehicle specification prior to tender with a clear requirement to provide evidence of compliance from tests carried out in accordance with BS EN ISO 3095.

Operational Vibration Limits

7.27. BS 7385-2:1993 recommends that PPV is used to quantify vibration and this approach is recommended here although other methodologies are available such as the use of 'velocity decibels' to measure vibration in the North America.

7.28. BS 6472-1:2008 recommends that the effect of building vibration on people is best evaluated using Vibration Dose Value. A range of values for damage and perception thresholds can therefore be derived. However, calculation is complex with the results influenced by numerous variables including but not confined to the following:

- Type of vibration: continuous, transient or intermittent;
- The vertical, lateral and longitudinal components of the vibration;
- The receiver axis, i.e. for a human is the vibration felt vertically through the spine (z axis), front / rear (x axis) or side to side (y axis). Human sensitivity is greatest through the z axis[54];
- Height of building; and
- Building structure etc.

7.29. Acceptable vibration limits for a Light Rail system will also vary according to local route conditions, infrastructure and the type of buildings in close proximity. However, examples of current UK Light Rail system limits show a fairly consistent approach as below:

Example 1

7.30. Trackforms will be designed adjacent to sensitive receptor buildings using best practicable means to keep within the guideline levels of Vibration Dose Value given in BS 6472-1:2008 1992 below which the probability of adverse comments is low:

- Day (0700-2300 hours) 0.2 $m/s^{1.75}$;
- Night (2300-0700 hours) 0.13 $m/s^{1.75}$; and

54 Transport Research Laboratory Report 429 Groundborne vibration caused by mechanised construction works Prepared for Quality Services — Civil Engineering, Highways Agency, D M Hiller and G I Crabb

- In addition. the above specification for the design of the Light Rail system will include a Peak Particle Velocity (PPV) level no higher than 2 mm/s at 2 m from the rails.

Example 2

7.31. Trackforms will be designed adjacent to sensitive receptor buildings so as to endeavour to keep within the guideline levels of Vibration Dose Value given in BS 6472-1:2008 1992 below which the probability of adverse comments is low:

- Day (0700-2300 hours) 0.4 $m/s^{1.75}$; and
- Night (2300-0700 hours) 0.13 $m/s^{1.75}$.

Vibration Limits – Effect On Humans

7.32. The current version of BS 6472-1:2008 states the following values for low probability of adverse comment in residential buildings although lower limits may of course be justified. These values should be applicable on any floor in occupied buildings adjacent to the track and due to solely to Light Rail operations such as the following:

- Daytime (16hr) - 0.2 – 0.4 $m/s^{1.75}$; and
- Night time (8hr) – 0.1 – 0.2 $m/s^{1.75}$.

7.33. For offices and workshops the above values can be increased by two and four times respectively.

Vibration Limits – Building Damage

7.34. BS 7385-2:1993 defines guide values over a frequency range of 4 Hz to 250 Hz which covers the vast majority of likely scenarios and covers two types of buildings with limits as indicated below:

- Reinforced or framed structures. Industrial and heavy commercial buildings: 50 mm/s; and
- Un-reinforced or light framed structures. Residential or light commercial type buildings where PPV limits are more frequency dependent as follows:
  - 15 mm/s at 4 Hz rising to 20 mm/s at 15 Hz; and
  - 20 mm/s at 15 Hz rising to 50 mm/sat 40 Hz and above.

7.35. Typical vibration monitoring results from UK Light Rail systems show PPV values fall mostly within the 0.5 – 2 mm/s range so best practice is reflected in the design specification of the Light Rail system in Example 1 above, with the PPV limit no higher than 2 mm/s at 2 m from the rails.

Operational Ground-borne Noise Limits

7.36. For most Light Rail systems, low operating speeds and relatively light vehicle weight mean that ground-borne N&V is generally less of a problem than airborne noise.

7.37. Ground-borne noise is usually measured as L_{Amax} using a meter set to slow response and will ideally be measured at the point in a room where it is perceived to be most disturbing

(BS 6472-1:2008). A common alternative approach is to measure it at the centre of the floor.

7.38. In 2020 the Ontario Line Subway programme in Canada specified a maximum of 35 dB(A) inside residential buildings due to a train pass-by[55] and the TfL Elizabeth Line project adopted a similar approach using the term $L_{Amax\ S}$ which also refers to the maximum sound level during a sound event, i.e. a train pass-by. Here the design limit was specified as 40 dB for residential areas, schools and hospitals although lower limits are specified for certain other types of buildings and are as low as 25 dB in the vicinity of concert halls etc. Similar criteria were also specified during design of the Edinburgh Light Rail system.

7.39. For new construction, a ground-borne operational noise limit of 35 dB(A) inside residential buildings is recommended using the same $L_{Amax\ S}$ criteria as both TfL and Edinburgh Trams. A limit of 40 dB(A) is appropriate for other public buildings such as schools and hospitals but lower limits may be needed locally in particularly noise-sensitive buildings such as concert halls.

7.40. It is recognised that fundamentally changing the ground-borne N&V characteristics of existing systems is neither straightforward or cheap, but these guidelines should be considered during significant reconstruction work, during maintenance and if replacing relevant track components such as crossings.

55 Subway Programme – The Ontario Line - Noise and Vibration Management Approach Information Sheet 202

8. Practical Measures to Mitigate Operational Noise and Vibration

Wheel and Rail Maintenance

8.1. One of the most important principles of rolling noise reduction is to reduce the system excitation that causes noise and vibration which means maintenance of smooth wheels and rails.

Rail Grinding

8.2. The smoothness of the running surface is critical to minimise rolling noise and rail grinding is a key maintenance activity. Rail grinding has historically been carried out reactively in response to the need to restore worn rail profiles and, directly relevant to N&V, manage or remove rolling contact fatigue (RCF) damage, corrugation and other surface irregularities. Having effective N&V and rail condition monitoring programmes is therefore essential to ensure timely grinding interventions when needed. Rail milling may also be considered as an alternative to grinding with the ability to remove larger amounts of metal and with no sparks. Although most rail milling equipment is aimed at mainline applications, compact milling machines suitable for light rail are now available.

8.3. An alternative and / or complimentary approach is preventive grinding where rails are ground on a regular basis. This may have the advantage of eliminating RCF damage at the initiation stage, for example, crack depth <0.2 mm, and prevent some types of corrugation, for example, where they are triggered by a discontinuity such as a sunk weld. This approach can give an overall reduction in rail damage, wear rates and associated costs. For example, in Holland, a study by Pro Rail referenced by the WRI Handbook[56] indicated that every Euro invested in grinding gave a 3 Euro return.

8.4. Note that grinding can remove but not prevent low rail rutting corrugation in tight curves which should be addressed by other methods such as use of friction modifiers.

8.5. In addition, some rail manufacturers and infrastructure managers recommend pre-grinding new rail as this can remove any surface layer metallurgical or physical defects arising from production, transportation or construction. Research in the UK and Germany suggests pre-grinding also significantly delays the onset of some types of corrugation, which is consistent with corrugation being exacerbated by vertical vibration due to railhead roughness. If required by WRI analysis it can also be used to optimise the interface before use to minimise initial wear and damage, all of which mitigates N&V. Close liaison with rail and rolling stock OEMs together with grinding specialists is recommended to assess the applicability of pre-grinding, and the benefits and frequency of preventative grinding.

8.6. Grinding is a common cause of complaints and for Light Rail systems specialist mini grinders are available which also have the advantage of operating at relatively low noise levels circa 70 dB(A). Portable grinders can also be used for spot grinding, for example, local corrugation in tight curves.

56 Wheel-Rail Interface Handbook, Editors: R. Lewis, U Olofsson, September 2009 ISBN: 9781845694128 / 9781845696788. Page 796

8.7. A noise reduction of up to 15 dB can be achieved by grinding a heavily corrugated rail, whilst regular preventative grinding will typically give reductions of 3-6 dB (refer to the Report for the Federal Environment Agency, Germany, 115/2021).

8.8. Care should also be taken to ensure the surface left by grinding is smooth as a rough finish can lead to increased noise at higher frequencies even if overall levels are reduced.

General Rail Condition

8.9. Track condition surveys should also be used to identify potential noise sources such as rail damage and discontinuity monitoring, with the results used to inform noise monitoring requirements and correlate against any reported noise issues. This correlation works both ways with reported noise issues usually a clear indicator of a track defect and / or damage. An effective process to coordinate the results of both N&V and track condition monitoring is therefore essential.

Wheel Condition

8.10. Wheel condition is also critical with roughness, flats and polygonisation all significant sources of N&V, refer to 'A Good Practice Guide for Managing the Wheel-Rail Interface of Light Rail and Tramway Systems'[57] a document that has been produced for the ORR.

Friction Management

8.11. One of the main functions of WRI friction management is noise reduction and ideally the use of friction management systems should be considered at the design stage. However, they are often used reactively to mitigate problems. It is best practice to include onboard friction management systems as part of the specification for all new Light Rail vehicles with all the major vehicle OEMs offering this equipment. This section provides guidance on selecting the most appropriate type(s) of application system and consumables to be used in the management of WRI friction that include the following:

- Lubrication to reduce the coefficient of friction (CoF), typically to below 0.15;
- Friction modification or control to maintain CoF at a desired level, typically between 0.3 – 0.4; and
- Adhesion where products such as sand are applied to increase CoF.

8.12. Both lubrication and friction modification can significantly reduce noise and vibration, either directly by controlling the friction characteristics that lead to squeal and flanging, or indirectly by reducing the types of wear and damage such as corrugation that cause rolling noise and vibration.

8.13. For the purposes of noise control, friction management systems comprise consumable lubricants and / or friction modifiers and the means of applying them to the WRI.

8.14. The desired balance between cost and performance will vary by customer but in all cases it is good practice to assess the through-life costs and benefits of a system rather than capital costs in isolation.

57 https://uktram.com/wp-content/uploads/2018/07/Wheel-Rail-Interface-of-Light-Rail-and-Tramway-Systems.pdf

8.15. Historically there have been two relevant Standards covering this topic and although these are aimed at heavy rail, the contents are highly relevant to Light Rail systems with information on use, evaluation and testing for the various product and system types. These are:

- BS EN 15427:2008 Railway Applications. Wheel / rail friction management. Flange Lubrication; and
- BS EN 16028: 2013 Railway Applications. Wheel / rail friction management. Lubricants for trainborne and trackside applications.

8.16. Both of the above have now been replaced by a heavily revised EN 15427 which is in the process of being re-issued in six parts as listed below, with an accompanying technical guidance document also proposed. The CEN/TS documents will become full Standards in due course.

- BS EN 15427 1-1:2022 Equipment and Application – Flange Lubricants (released May 2022);
- CEN/TS 15427-1-2:2021 Railway Applications-Wheel / Rail Friction Management. Equipment and Application – Top of Rail Materials (released Jan 2021);
- Part 1-3: Equipment and Application – Adhesion Materials (not yet published expected early 2023);
- BS EN 15427 2-1:2022 Properties and Characteristics – Flange Lubricants (released July 2022);
- CEN/TS 15427-2-2:2021 Railway Applications-Wheel / Rail Friction Management. Properties and Characteristics – Top of Rail Materials (released Jan 2021); and
- Part 2-3: Properties and Characteristics – Adhesion Materials (not yet published, expected early 2023).

Trackside Friction Management Systems

8.17. There are two main types of trackside friction management systems that are potentially suitable for use on UK Light Rail systems, those using separate applicator bars attached to the rail, or those applying lubricant through specially drilled holes in the rail.

8.18. A third type used in some European markets for local regulatory reasons employ squirt dispensers set back from the rail are not considered in this guidance, as current systems offer no practical advantage over applicator bar or drilled rail options. However, proposed developments in this field may lead to future systems offering more accurate delivery of friction modifier than current applicator bars.

Applicator Bar Systems

8.19. In the UK, by far the most common type are systems that use an applicator bar or grease dispenser unit (GDU) which is attached to the rail and, for flange lubrication, distributes grease via multiple ports on to the rail gauge face and corner. A key limitation for Light Rail use is that they are not easily adapted for embedded rail, especially in shared infrastructure i.e. street running.

8.20. A similar approach is used for bars dispensing top of rail friction modifiers with the consumable dispensed through one or more ports to form puddles on the rail head allowing pickup by the wheel tread. Although flange grease can be accurately dispensed, the low viscosity of friction modifiers means that consistent and accurate application quantities using this type of system are difficult to achieve, and spillage / contamination of the surrounding area can be a problem. Nonetheless, more than one manufacturer has adapted this type of system for use on embedded Light Rail infrastructure.

8.21. There are three sub-types of applicator bar system: mechanical, hydraulic and electrical. All three can be used with flange lubricants but only electrical units can dispense friction modifier.

8.22. Mechanical and hydraulic systems are similar and are entirely self-contained with no external power supply. They rely on mechanical plungers depressed by each passing vehicle wheel to activate grease delivery from either a hydraulic grease pump, or a simple pump that relies on the grease tank itself to be pressurised. Both types of system have been widely used for many years and are still available due to their low cost, simplicity and small physical footprint, which in some cases means they can be installed in the four foot on standard gauge track.

8.23. The alternative is to use electric applicator systems that have been widely adopted over the last 20 years as they have a number of advantages despite much higher unit cost. Various power supply options are available including solar. They can cover two tracks from one unit and use non-contact wheel sensors to signal an electric pump to dispense consumables. Flange lubricant application rates can be accurately adjusted to minimise waste and mess, and newer systems offer various remote monitoring functions. With good quality grease or friction modifier, optimised application rates also mean one unit can protect multiple curves, thereby reducing the number needed. In a trial in the US[58], electric lubricators used 48% less grease to provide the same flange lubricant cover over the same distance of track compared to hydraulic units.

8.24. Importantly, electric lubricators have proved more reliable which, coupled to the ability to fit much larger consumable tanks and remote monitoring, allows them to offer reduced maintenance costs together with the safety benefits of reduced time on track for maintenance personnel.

Drilled Rail

8.25. This well proven type of system is widely used in Europe on Light Rail and metro systems where it has been refined over many years. The entire system can be mounted in a self-contained cabinet several meters from the dispensing point with some suppliers also offering systems that can be installed underground, below or alongside the track.

8.26. Drilled rail systems are electrically powered, can include remote monitoring and are suitable for all rail types including grooved where they can simultaneously lubricate the guide or check rail flank, gauge corner and, if required, the rail head. The latter technique, often referred to as rail wetting, can have safety implications and is discussed below (refer to Sections 8.38 and 8.39). By using precise application quantities tailored to each application, and precision-drilled lubrication channels to ensure the lubricant reaches the exact point it is needed, drilled rail solutions can deliver good results with minimum contamination and waste.

58 Canadian Pacific Railway's 100% effective lubrication initiative. Sroba P, Roney M, Dashko R and Magel E in Proceedings of the American Railway Engineering and Maintenance of Way Association conference, Chicago, Illinois, 9–12 September 2001

8.27. However, a note of caution with these systems is that some manufacturers will try and lock customers into long-term full-service provision contracts including lubricant supply, and these can prove expensive on a through-life basis. In addition, lubricants offered by these system manufacturers might not offer the best performance or environmental qualities.

Onboard Friction Management Systems

8.28. The objective of an onboard application system is to treat the network and not the vehicle. By building up a functional layer of friction management product across the network, all vehicles are protected and in some cases, especially for friction modifiers, only a portion of the fleet needs to be fitted. With the correct application points, protection for bi-directional running as also seamless in these circumstances. There are two types of onboard friction management system: spray and solid stick, both of which can dispense lubricant and / or friction modifier. These systems are further detailed below and they are compared below in Table 8.1.

Onboard Spray Systems

8.29. Onboard spray systems have been in use in Europe for over 30 years and if properly maintained are highly reliable, offering increasingly sophisticated application control features. Most systems consist of a consumable storage tank, a controller, pumping arrangements and, in most cases dispense through one or more pairs of nozzles, usually at or near the front of the vehicle. Longer vehicles such as the Elizabeth Line vehicles may have additional nozzles mid-vehicle. Flange lubricants are sprayed directly on to the wheel flange root although for aerodynamic reasons, friction modifiers are typically sprayed on to the rail head. In the latter case, an important design consideration is that nozzles should be close enough to the WRI to ensure that in tight curves the friction modifier does not spray to the side of the running band. Light Rail vehicles can be fitted with systems that apply lubricants and friction modifiers separately.

8.30. Most spray systems use compressed air from the vehicle’s onboard air systems but some manufacturers offer airless systems designed specifically for Light Rail vehicles with no onboard air supply. At least one manufacturer also offers a system with a built in compressor and air supply for Light Rail applications.

8.31. Basic systems continue to be offered with grease dispensed in fixed quantities at regular time or distance intervals across the entire network, but alternative application strategies now include the use of technology such as GPS, curve sensors and distance measurement to tailor application to specific requirements. Emerging technology includes the ability to easily re-programme these systems to adjust to new requirements such as a noise complaint.

8.32. Whilst use of intelligent systems in places such as the Toronto tram network and on TfL’s Elizabeth Line is becoming more common, the technology is not yet universally accepted by rolling stock OEMs with a legitimate concern that if friction management products are switched on and off too accurately, this can itself lead to rail damage where friction characteristics change consistently and abruptly. This is also a problem with trackside friction modifier systems on uni-directional track and supports the concept of network coverage.

Table 8.1 Comparison of the Key Features of Stick and Spray Systems

Criteria	Stick	Spray
Installation	Simple mechanical fittings, no interface with the vehicle's systems. Retrofit relatively simple with bespoke mounting brackets	More complex. Limited choice of systems that do not require compressed air supply. Bespoke retrofit possible but complex.
Lubricant Application	No control. Fixed rate lubrication is on when the vehicle is moving. May provide more or less than needed.	Variety of dumb and intelligent (for example, GPS) control options allow optimised application and minimum waste.
Cost and Efficiency	Can offer significant benefits but inflexible in use. Through life cost of sticks can be high but varies according to specific network characteristics.	High capital cost, usually integrated during vehicle design. Relatively low consumable cost. Optimised application may offer better performance than stick.
Environment	Most sticks use Thermoplastic or Thermo-resin to carry graphite or molybdenum dry lubricants. When consumed the residue is released as dust and debris. No stick to-date has formal Eco accreditation.	Flange lubricants can be eco labelled. So far friction modifiers are only eco-friendly due to solid content. Low quantities used minimise impact
Safety	Dust and microplastic residue, pieces can break off causing hazards, including potential to jam switches.	Use of Eco Label products minimises environmental and toxicity hazards. Flammability / fume hazards in tunnels mitigated by small quantities used.
Wheel and Rail Wear	Reduced wheel and rail wear by reducing friction at the WRI.	Reduced wheel and rail wear by reducing friction at the WRI. Ability to tailor application means benefits may be greater.
Noise	Can reduce WRI noise	Can reduce WRI noise. Tailored application offers greater potential noise reduction.
Maintenance	Simple but frequent stick changes but may not align with planned maintenance intervals. Easy to handle dry product requires only semi-skilled labour.	Lubricant refill infrequent and simple. But system requires regular routine inspection. Any repairs may need skilled labour.
Contamination	Performance may be compromised by extensive use of sand which contaminates the wheel / stick interface.	Sand may increase CoF by contaminating grease on flanges but this is mitigated by small quantities of grease used. The sand itself will also be lubricated by any grease it comes into contact with.

Stick Systems

8.33. These mainly use a either carbon sticks or a carrier material, usually thermoplastic, thermo-resin or similar impregnated with a solid lubricant such as graphite and / or molybdenum di-sulphide or other friction control materials. A third stick variant uses a vegetable fibre matrix to carry a vegetable oil component to reduce the amount of embedded thermoplastic and is the only type to carry a wet lubricant component. In addition, some stick types apply friction modifier rather than lubricant.

8.34. Sticks are mounted in simple spring-loaded applicator boxes which press the sticks directly against the wheel flange or tread depending on whether the stick compound used has lubrication or friction modifier properties. As the lubricant or friction modifier is applied and the stick consumed a product film is established to create the designed CoF at which point the stick is not only protecting the wheel and rail but also itself.

8.35. As the product is consumed the stick is no longer protected and will again wear and release more of the consumable. Actual wear rates vary widely depending on network characteristics (for example, number of tight curves) and care should be taken to validate stick consumption rates when considering through-life costs for a stick system. Some manufacturers offer different stick compounds to address this but users should note that lower wear rates are often achieved by harder sticks which may offer reduced lubricant performance. However, stick hardness is not in itself an indicator of stick consumption rates with some soft sticks performing well in this respect.

8.36. Although the applicators are simple they do need bespoke mounting brackets designed for each type of rolling stock. Other factors to consider are to ensure that stick life at least matches the planned maintenance interval of the vehicle, and because stick systems have a limited application rate, they may not provide adequate lubrication in some demanding scenarios and use of supplementary trackside systems may still be needed[59].

8.37. Although there is a clear trend towards onboard systems in many Light Rail vehicle markets, trackside and onboard systems also have different strengths and weaknesses. A key point to consider here is the need to treat any combination of onboard and / or trackside friction management equipment on a Light Rail system as a single system with a single coordinating mind.

8.38. Dealing with noise problems using friction management requires a fully integrated approach across track and rolling stock and this is not currently the case on some UK systems where track and rolling stock management silos exist. Table 8.2 below compares the main features of trackside and onboard systems.

Rail Wetting

8.39. Both onboard and drilled rail systems can be used to deliver flange lubricant to the railhead, a technique often referred to as rail wetting. Lubricating the railhead in this way can in some limited circumstances offer the same benefits as top of rail friction modifiers

59 Wheel Rail Interface Handbook, Woodhead Publishing Ltd 2009, Page 653, Managing the wheel-rail interface: Europe Metro experience on the London Underground Victoria Line

including noise reduction, but only with certain lubricants and very accurate application rates.

Table 8.2 Comparison of the Main Features of Trackside and Onboard Systems

Criteria	Onboard	Trackside
Cost	Typically in the region of £10,000 - £20,000 per vehicle depending on complexity. It is not always necessary to fit the whole fleet for example, only 50% of the recent Toronto Streetcar fleet is fitted.	Simple systems are a few £000 but complex Electric systems with remote monitoring can reach circa £30,000. Maintenance and refill costs for trackside much higher.
Performance	Inherently more flexible, each vehicle carries its own friction management protection wherever it goes. Intelligent systems offer a step change in efficiency and performance with product only applied where and when needed.	Each lubricator has limited coverage and flange lubricant pickup not always guaranteed. Optimum pickup point can change as WRI wears and electric systems difficult to move. Friction modifier bars can be wasteful and messy. Higher viscosity flange lubricant. Can be more robust than onboard and more tolerant of weather and temperature extremes.
Safety	Maintenance in safe depot environment. Low application quantities and, for friction modifiers, careful product selection minimise passer-by slip risk in street running areas.	On track maintenance teams. Systems positioned to avoid pedestrian slip risk but leaves parts of the network without friction management protection.
Environment	Eco Label flange lubricants available. Low application quantities of both lubricant and friction modifier minimise risk of product build-up and mess.	Eco Label flange lubricants available. Some grease products can build up over time causing mess and contamination. This can also be a significant problem with some friction modifiers.

8.40. However, the key risk is that the lubricant will reduce the railhead CoF to a point where braking performance is degraded. Although rail wetting using lubricants is not recommended, if used, it should only be considered in close consultation with both the application system and lubricant manufacturers. There could also be a risk to other highway users, as transfer of lubricant can occur over several kilometres. An inherently safer alternative is to use systems designed to separately apply flange lubricants and friction modifiers as commonly fitted to modern Light Rail vehicles.

Lubricant Selection

8.41. When selecting a WRI lubricating grease, the following characteristics need to be considered and evidence sought from the lubricant supplier to support any claims, for example, test results and references. EN 15427 Standards can be used for guidance.

8.42. In all cases, the grease to be used shall be compatible with the application system, and also compatible with any other WRI lubricants or friction modifiers already in use. All lubricants should have Technical Data Sheets (TDS) and Safety Data Sheets (SDS) to allow initial comparison, but these are not always comprehensive.

8.43. Key characteristics to look for in a flange lubricant include the following.

Low Coefficient of Friction

8.44. The lubricant should be tested to ensure low CoF at the WRI, typically less than 0.15 but ideally less than 0.1.

Operating Temperature Range

8.45. The lubricant should offer constant viscosity over the complete temperature range in which it will be used to ensure consistent application through common dispensing systems. Some products require different variants to be used on a seasonal basis due to operating temperature limitations, but this should not be necessary in the UK for a good quality product.

Carry-Down

8.46. Carry-down means the distance from the point of application over which the lubricant remains effective. Good carry-down can mean grease from one trackside applicator can protect multiple curves so less grease is used and fewer applicators needed. This is an area where using a cheap grease can be a false economy. Closely linked to carry-down is the application rate for a given product to achieve required performance. Good carry-down and lower application rates are desirable as this can result in the following:

- Reduce purchase quantities;
- Reduce the number of applicators needed over a given length of track;
- Reduce refill frequency and associated logistics and resource costs; and
- Improve safety by reducing on-track time for maintainers.

Good Adhesion and Cohesion

8.47. Adhesion in this context means the ability of the lubricant to stick to a wheel or track and cohesion refers to the ability of a lubricant to stick to itself. These are important as they relate to the amount of undesirable splash-off when a Light Rail vehicle initially picks up lubricant, and fling-off from the rotating wheels. Fling-off in particular can be a problem for some onboard lubricants, leading to waste and contamination of the underside of a Light Rail vehicle and test results should be available.

Product Separation

8.48. For both lubricants and friction modifiers, product constituents should not separate in storage or in applicator tanks. Some oil bleed is normal for greases but manufacturers should be able to advise how much to expect without affecting performance. Storage life can also vary between products with longer storage life desirable to reduce waste and save money.

Extreme Pressure (EP)

8.49. Good EP characteristics maximise the wear protection offered by a lubricant under heavy load and as wear causes noise, this is a key feature. EP performance is indicated by four ball weld and / or scar testing which should be available on the lubricant's TDS.

Wash-off

8.50. A further desirable characteristic is good resistance to water wash-off to ensure that the lubricant film is maintained in wet conditions. This should be covered on the TDS.

Easy Handling

8.51. Trackside lubricants usually require manual handling, often in difficult conditions, so they should be as simple to handle and use as possible without hazardous content such as skin irritants. Refer here to the product SDS as a starting point. Also consider colour, PPE requirements and ease of transport without the need for special handling or storage arrangements.

Environmental Factors

8.52. The fact that WRI friction management systems are total loss systems where all the lubricant or its residue enters the environment means eco credentials should be a major consideration, especially for Light Rail systems in urban environments. Globally there are a range of local or regional standards covering this topic, but the recommended benchmark is the EU Eco Label scheme. To be awarded EU Eco label, goods and services should meet high environmental standards throughout their entire life cycle from raw material extraction through production and distribution to disposal[60].

8.53. The Eco Label covers a number of product criteria including toxicity and packaging, but perhaps the best known is biodegradability with testing according to Organisation for Economic Co-operation and Development (OECD) 301 methods[61], most commonly OECD 301b[62] for WRI lubricants. Care should be taken to fully understand manufacturers' biodegradability claims with OECD 301 readily biodegradable indicating the fastest and most complete levels of product biodegradability, followed by inherently biodegradable. Other terms such bio based have no formal meaning in the UK and can be misleading as to how environmentally friendly a product really is.

Curved Rail Flange Lubricants

8.54. Curved Rail Flange Lubricants can be effective in mitigating flanging noise in curves and by reducing wheel and rail wear and damage due to friction at the WRI, rolling and impact noise caused by defects such as head checks, spalling and shells.

Friction Modifier Selection

8.55. As a relatively recent innovation (for example, first introduced to Network Rail in 2007), friction modifier technology is less advanced than lubricant technology. Broadly speaking there are two main types:

- Water-based drying products; and

60 https://environment.ec.europa.eu/topics/circular-economy/eu-ecolabel-home_en
61 OECD Test No. 301: Ready Biodegradability
62 OECD 301B – Biodegradation Test – CO2 Evolution

- Oil-based products.
- Some products try and combine the best features of both.

8.56. By definition, a true friction modifier is NOT a lubricant and should be able to maintain the WRI CoF at the desired value (0.3 – 0.4) in all normal operating conditions, wet or dry, and irrespective of excessive application quantities. This is safety critical due to the potential for increased braking distances, even with wheel slide protection systems if CoF is too low.

8.57. Independent testing has shown that some advertised friction modifiers can act as lubricants if over-applied, for example, inadvertently due to a system fault or damage. Although the chances of this happening are very low, it is no coincidence that Network Rail specify satisfactory brake testing as the first part of the approval process for any friction modifier. The recent CEN/TS 15427-1-2:2021 provides guidance on brake testing and advises consideration of over-application in this process.

8.58. Water-based friction modifiers use water as a carrier for the friction modifier and once applied, the water dries leaving a dry friction modifier film. The proprietary constituents may include metallic compounds and oxides, as well as elastomeric components such as latex. Problems with this approach can include poor carry down as the product dries quickly, wash off in rain, separation in applicator tanks and drying and clogging of applicator equipment.

8.59. Oil-based friction modifiers leave a wet film on the railhead and control friction using a range of solid additives, again including metallic compounds and oxides. Because they do not dry they can offer much longer carry-down than some water based products and are more resistant to rain. However, some oil-based products can act as lubricants if over applied. Some may also be tricky and unpleasant to handle and leave significant mess and contamination if used with trackside applicators. It is also best practice to rail-grind before introducing this type of friction modifier to a network because any existing rail surface cracking due to rolling contact fatigue can be accelerated by the hydraulic effect of a wet friction modifier being forced into the cracks by a passing wheel.

8.60. Some recent products seek to combine the best of both water and oil-based approaches. However, ongoing development by lubricant manufacturers suggests that the ideal friction modifier has yet to be invented and Light Rail users should watch for new developments in this field. In particular, friction modifiers are an area where fully representative field testing should be undertaken wherever possible to confirm that the product does not affect braking performance, even if over-applied.

8.61. It should also be possible to trial the noise reduction capabilities of different products using manual application and standard noise monitoring equipment, although practical experience suggests that noise reduction due to an effective friction modifier is very obvious to a human observer.

8.62. Friction modifiers can be effective in reducing noise, especially squeal, in tight curves by creating stable WRI friction conditions that prevent or reduce lateral stick / slip and associated vibration of inner wheels. They can also mitigate flanging noise in curves by improving steering and, in addition, can be effective in reducing roiling noise by preventing corrugation, especially low rail (rutting) corrugation in tight curves.

8.63. Extensive sanding in the vicinity of friction modifiers will compromise their performance. However, in theory unless low adhesion is due to external contamination such as leaves, sanding should not be needed where a genuine friction modifier is used as the designed CoF should ensure adequate braking and traction.

9. Mitigation of Noise and Vibration During Construction and Maintenance Work

9.1. Construction noise and vibration is a key source of N&V complaints and can be exacerbated by the night time work that may be scheduled to avoid disruption to extant road and rail traffic.

9.2. There are a wide range of potential N&V sources during a construction project ranging from plant and machinery to heavy goods vehicles (HGVs) and other support. The impact will not only be felt at the construction site but also along vehicle access routes.

9.3. Key Standards to consider include BS 7385-2:1993 as discussed above, as well as the following:

- BS 5228-1:2009[63] recommends basic methods to determine the local impact of noise from construction and open sites and provides guidance on how these effects can be mitigated. The legislative background is described and recommendations given for procedures covering liaison between relevant stakeholder;
- BS 5228-2:2009+A1:2014[64] gives recommendations for basic methods of vibration control where activities / operations generate significant vibration levels. The legislative background and liaison procedures are again covered and guidance provided on methods of measuring vibration and assessing its effects on the environment; and
- In addition, Transport Research Laboratory Report 429 is highly relevant and is particularly useful in giving a relatively easy to understand overview of this highly technical topic that is suitable for non-specialists. It covers basic vibration theory, gives advice on acceptable vibration thresholds, data measurement and covers the main sources of ground-borne vibration such as piling in detail. Note that Report 429 highlights a contradiction between BS 7385-2:1993 and the then extant BS 5228 Part 4[65] in vibration damage threshold values, but since Report 429 was published, BS 5228 Part 4 has been withdrawn so BS 7385-2:1993 should be used.

9.4. For any major construction project, the key to effective N&V mitigation is a comprehensive N&V Management Plan and this should be produced by the prime contractor using specialist sub-contractors as needed and approved by the customer.

9.5. Depending on the planned project length there should be a periodic review and update process for the N&V plan to capture practical experience, project changes, unforeseen circumstances and the planned use of equipment not originally envisaged.

9.6. The aim should be to predict any changes to N&V risk at sensitive receivers to allow pro-active mitigation as part of the ongoing planning process.

63 BS 5228-1:2009 Code of practice for noise and vibration control on construction and open sites. Noise

64 BS 5228-2:2009 Code of practice for noise and vibration control on construction and open sites. Vibration

65 BS 5228-4 Noise Control on Construction and Open Sites Part 4: Code of Practice for Noise and Vibration Control Applicable to Piling Operations

N&V Management Plan Requirements – Construction Projects

9.7. The plan should show how compliance with defined regulatory, legislative and / or project N&V requirements will be achieved, and should therefore state clearly what these requirements are and list any applicable standards and related guidance documents.

9.8. A pre-project noise monitoring plan should be included to establish baseline noise levels at sensitive locations. The dataset should include L_{max} and L_{Aeq} figures for day and night in order to enable the following:

- Provide a context for the project limits to be mandated;
- Allow an understanding of the change in noise due to construction; and
- Provide information that will be useful in the event of complaints.

9.9. If existing ambient noise levels are known to be high this may allow more flexibility when applying the above noise limits for particularly noisy tasks.

9.10. The N&V monitoring plan should outline the measurement and reporting methods that will be used to demonstrate compliance with the project noise limits. This should include the location of any fixed noise monitoring equipment and define the parameters to be measured. Best practice is to include the same locations as the pre-project baseline monitoring. In addition, sensitive receivers along the Light Rail system route should also be identified with additional monitoring and, where necessary, control measures adopted.

9.11. The plan should also indicate the methods to be used to control N&V including those outlined further below, with accountability for results and responsibilities for enforcement clearly defined.

9.12. Experience also shows that mitigation planning should not focus exclusively on noisy construction activity, with many complaints due to 'nuisance noise' such as constant low energy noise.

9.13. A communications plan should also be included with the objective of ensuring that local communities understand the following:

- What work is being done and why;
- The likely N&V impact;
- For how long and crucially;
- How the affected communities will benefit.

9.14. Where especially noisy activities are unavoidable, proactive communication with those effected is essential. The communications plan should also include a complaints mechanism and 24/7 contact details. It is also good practice to appoint a named individual to act as a liaison officer with local communities and provide a human face to the large organisations involved.

N&V Mitigation Methods – Construction

9.15. There are a number of ways to tackle N&V during a construction project including the following:

- When on site, equipment and plant should be positioned as far from sensitive receivers as possible;
- All vehicles, plant and machinery should be fitted with effective and properly maintained exhaust silencers;
- Careful positioning of static equipment (for example, pumps, compressors and generators), to ensure it is as far as possible from sensitive receivers such as residential property, with acoustic barriers installed where needed;
- Use silent solar power where possible;
- Use purpose-designed low-noise equipment such as sound reduced compressors and ensure any noise reduction design features are fully utilised and in good condition. Any pneumatic operated percussive tools should be fitted with approved silencers;
- Plant known to emit directional noise should be orientated so that noise is directed away from noise-sensitive areas;
- Machinery used intermittently should be shut down when not in use or, if this is impractical, throttled back to a minimum;
- Plan access routes to ensure HGVs or other heavy vehicle traffic avoid noise sensitive areas wherever possible. If sensitive areas are unavoidable, consider traffic timing and use of multiple routes to avoid constant noise in one place. Ensure access routes are in good condition and vehicles well maintained to minimise vehicle noise;
- Set and enforce an appropriate site speed limit. 10 mph has been used on recent UK projects;
- Plan activities so that several noisy activities are undertaken at the same time. As discussed above, the combined noise level produced will not be much higher than by undertaking these activities individually;
- Use temporary noise barriers between noise generating activities and sensitive receivers. These can be purpose designed but improvised barriers such as sandbags and piles of dirt or other excavated materials can also be effective. As a guideline, to attenuate noise effectively, the barrier material should have a mass per unit of surface area >7 kg/m^2;
- Use of specially designed sound attenuating working enclosures, and all-round enclosures for some types of noisy equipment is best practice from recent UK projects;
- Guidance on the design and installation of temporary noise barriers is provided by BS 5228 Part 1, 1997 but key points include the following:
  - On level sites, barriers should be as close as possible to either the noise source or the receiver(s);
  - Avoid gaps or openings in the barrier;
  - Ensure the barrier does not reflect sound to a different receiver;
  - As a guideline, the length of a barrier should be >5 times its height to minimise the risk of sound passing round the ends of the barrier. It is also good practice to curve a short barrier around a noise source;
  - Barrier height is also important and shall ensure that there is no direct line of sight between noise source and receiver;
  - Mobile screens may also be used but these need to be as close to the ground as possible with a gap <100 mm;
- Minimise night time activities, especially in residential areas;

- Where night working is undertaken, consider the location of staff welfare facilities to avoid conflict in residential areas;
- Consider construction (and demolition) methods with lower noise signatures. In particular, consider alternatives to impact pile driving such as silent piling techniques, hydraulic pile drivers and the use of non-metallic dollys between the hammer and the driving helmet; and
- Ensure that all staff are trained and competent to use the equipment as designed and in a way that minimises noise from site activities.

Vibration Monitoring and Control During Construction

9.16. The N&V Management Plan should include a specific section covering vibration with the key objectives of both reducing ground-borne noise to acceptable levels and minimising construction vibration damage using all reasonable and feasible means available. The plan should include the following components:

- Procedure for establishing threshold and limiting vibration values for potentially affected structures based on an assessment of each structure's ability to withstand the loads and displacements expected;
- Pre-works survey plan;
- Procedure for validating vibration assumptions made during the planning stage; and
- Compliance monitoring program during construction.

9.17. Pre-works surveys should include the following:

- Photos of existing structural damage;
- Details of existing cracks and their dimensions;
- Level and plumb surveys;
- Damp proof course condition and defects;
- Measurement of any tilting or bulging walls; and
- Other damage including cracked render, cracked plaster, cracked windows, broken pipes and roof damage including broken tiles or gullys, etc.

N&V Limits During Construction Projects

9.18. The following guidance is based on recent best practice from the UK taking into account the relevant standards and broader regulatory guidelines. For the purposes of these guidelines normal site working hours are assumed to be 0700 – 1900 hrs, Mon-Sat, so a 12 hr working day.

Airborne Noise

9.19. Airborne noise guidelines include the following airborne noise limits:

- During normal site working hours 75 dB $L_{Aeq\,(12hr)}$;
- Mon-Sat 1900 – 2200hrs evening 65 dB $L_{Aeq\,(3hr)}$;
- Sundays and Bank Hols 0800 – 2200hrs 65 dB $L_{Aeq\,(12hr)}$;
- For residential buildings at night 2200 – 0700hrs 55 dB $L_{Aeq\,(1hr)}$; and
- For schools and colleges whenever occupied 65 dB $L_{Aeq\,(1hr)}$.

9.20. For residential buildings, schools or similar, noise levels should be measured at no more than 1 m from the building façade. It is recommended that these noise levels should be treated as limits that are not to be exceeded except in exceptional circumstances. However, if essential planned work is expected to cause these limits to be exceeded.

9.21. The N&V Management Plan should include a formal application procedure so that the work such as the exceptional circumstances in 9.20 is specifically approved well in advance by the project manager or nominated deputy. Where this occurs, a specific mitigation plan should also be produced that details the measures taken to minimise impact and duration.

Ground-borne Noise and Vibration Limits

9.22. The principles for establishing ground-borne noise and vibration limits during construction are as defined above for operations. The inherent high levels of vibration in construction activities such as piling, as well as any associated demolition, may mean higher limits are needed than during system operation. In these circumstances careful planning and monitoring is required, especially around sensitive and / or listed buildings.

N&V During Major Maintenance Work

9.23. Major maintenance activities can be inherently noisy and are often carried out at night to avoid operational downtime. In addition, the mobile nature of work such as grinding and tamping makes N&V mitigation very difficult and specific limits are not practical in these circumstances. Nonetheless, reasonable efforts should be made to minimise the impact of this work wherever possible. Grinding in particular is a common cause of complaints and for Light Rail systems specialist low-noise (circa 70 dB(A) mini grinders are available.

9.24. In addition, with the exception of emergency works, as times and locations for such work are planned in advance, best practice is to consult with and inform local stakeholders including residents in good time. Critical to minimise the risk of complaints is good communication. This ensures residents in particular can plan ahead for unavoidable disturbance, as well as communicating the benefits of the work such as overall reduction in N&V, etc.

Depot N&V

9.25. BS 4142:2014 + A1:2019 methods for rating and assessing industrial and commercial sound provide a method of assessing the impact of a source of industrial or commercial sound, including sound from the following:

- Industrial and manufacturing processes;
- Fixed installations;
- The loading and unloading of goods; and
- Mobile plant and vehicles that is an intrinsic part of the overall sound emanating from premises or processes.

9.26. The Standard can be used to assess sound, including a change of sound, as a response to a complaint or as part of a planning application. It supports current UK planning guidance and Environment Agency requirements on noise impact assessments.

9.27. BS 4142 therefore provides a suitable basis for considering the potential impact of maintenance depots and their related static activities on local communities. It specifically excludes pass-by N&V from rail vehicles and the limits derived for operational use should be applied to Light Rail vehicle movements within depots.

APPENDIX A: SUMMARY GUIDELINES FOR LIGHT RAIL SYSTEM NOISE AND VIBRATION LIMITS

Recommended Average Airborne Noise Limits

WHO Noise Exposure Targets

1) As an overriding aim, mitigation should be considered where the following limits are exceeded due to Light Rail system noise:
   - Overall average noise level 54 dB L_{den}; and
   - Average night time noise level 44 dB L_{night}.

2) Trigger levels for mandatory residential building noise insulation:
   - 68 dB L_{Aeq}, 0600 - 0000 hours daytime; and
   - 63 dB L_{Aeq}, 0000 – 0600 hours night.

3) Trigger levels for Light Rail systems to consider noise mitigation:
   - 55 dB L_{Aeq}, 0700 – 2300 hours daytime;
   - 45 dB L_{Aeq}, 2300 – 0700 hours night; and
   - In addition, where extant ambient noise measured as L_{Aeq}, 1 hour is already perceptively (>3 dB) above these thresholds, any further increase of >3 dB due to Light Rail system operation should require mitigation to be considered.

Vehicle Specification Stationary Noise Limits

4) The noise limit for all systems switched on with maximum heating or air conditioning as applicable should be 50 dB(A). This should be included in all new UK Light Rail vehicle specifications with measurement in accordance with BS EN ISO 3095.

Existing Vehicle Stationary Noise Limits

5) As older vehicles may struggle to meet these new vehicle limits, mitigation should be based on noise increases against the original vehicle specification if this includes designed noise values, or against benchmark values determined by measurement of a representative fleet sample. In this case mitigation should be considered in the event of any increase >5 dB(A) from the specification or benchmark values.

Recommended Limits for Short Period Airborne Noise Events

Vehicle Specification Pass-by Noise Limits

6) The following pass-by noise limits should be included in all new UK Light Rail vehicle specifications with measurement in accordance with BS EN ISO 3095:
   - Acceleration and braking to / from 30 km/h 72 dB(A) L_{pAFmax};
   - Braking from 60 km/h 77 dB(A) L_{pAFmax};
   - Pass-by under acceleration from 20 km/h 72 dB(A) L_{pAFmax}; and
   - Pass-by at 60 km/h 76 dB(A) $L_{pAeq,\,TP}$.

Vehicle Specification Pass-by Noise Targets

7) Consideration should also be given to requiring more demanding targets as below with appropriate incentivisation:

- Acceleration and braking to / from 30 km/h 65 dB(A) L_{pAFmax};
- Braking from 60 km/h 70 dB(A) L_{pAFmax};
- Pass-by under acceleration from 20 km/h 68 dB(A) L_{pAFmax}; and
- Pass-by at 60 km/h 73 dB(A) $L_{pAeq, TP}$.

Existing Vehicle Pass-by Noise

8) As older vehicles are likely to be noisier than new designs, transient vehicle noise management for existing fleets should be based on responding to noise increases using the principles described in Section 5. Any increase of >5 dB L_{AFmax}, either compared to fleet pass-by average or previous survey values at the same location should lead to mitigation. Ideally action should be considered for an increase of >3 dB.

Maximum Allowable Transient Noise

9) A hard limit for transient noise applicable to Light Rail vehicles at speeds above 60 km/h at any time, and for noise events no more than twice per hour at night should be specified to exceed a transient noise limit of 82 dB L_{ASmax}.

Recommended Vibration Limits

10) For new construction or where existing trackforms are completely replaced, the design specification should include the following maximum vibration dose level values where the track is adjacent to sensitive receptor buildings:

- Day (0700 – 2300 hours) 0.2 $m/s^{1.75}$;
- Night (2300 – 0700 hours) 0.4 $m/s^{1.75}$; and
- In addition, the design specification should also include a maximum PPV of 2 mm/s at 2 m from the rails.

11) For existing systems best practice is to use regular system monitoring to identify increases in vibration that will indicate emerging problems. Section 5.17 provides an example of an appropriate methodology.

Recommended Ground-Borne Noise Limits

12) For new construction, it is recommended that the following ground-borne noise limits are specified as system design requirements, noting that if track passes close to particularly noise sensitive buildings lower limits may be needed (see Section 7.39).

- Inside residential buildings 35 dB L_{Amax} S; and
- For public buildings such as schools and hospitals 40 dB L_{Amax}.

13) Although fundamentally changing, the ground-borne N&V characteristics of existing systems is neither straightforward or cheap, as such, the above guidelines should be considered during significant reconstruction work, during maintenance and if replacing relevant track components such as crossings.

Recommended Airborne Noise Limits During Construction

14) The following airborne noise limit values are considered best practice in the UK:

- During normal site working hours 75 dB $L_{Aeq\ (12hr)}$;
- Mon-Sat 1900 – 2200hrs evening 65 dB $L_{Aeq\ (3hr)}$;
- Sundays and Bank Holidays 0800 – 2200hrs 65 dB $L_{Aeq\ (12hr)}$;
- For residential buildings at night 2200 – 0700hrs 55 dB $L_{Aeq\ (1hr)}$; and
- For schools and colleges whenever occupied 65 dB $L_{Aeq\ (1hr)}$.

APPENDIX B: DERIVATION OF OPERATIONAL NOISE AND VIBRATION GUIDELINE LIMITS

1. This Appendix is included to provide more background on how the guideline values in Section 7 were derived for those readers who may be interested. It therefore includes some basic principles of N&V transmission theory, but also includes broader background information from the research carried out which covered current practice across Light Rail systems in Europe, North America and Australia as well as in the UK.

2. Where relevant, this information has been used to help derive the values given. The research also highlighted different approaches to setting noise limits, which although not used in the core guidelines, offer alternative ideas that may be of use in deriving innovative approaches to this topic in the future.

Derivation of Guideline Noise and Vibration Limits

3. When considering the environmental impact of N&V from a Light Rail vehicle, it is helpful to understand the basics of noise propagation. A common concept used to explain this is source-path-receiver where N&V is generated at a source, and then propagates along a line of sight path to a receiver. In doing so, N&V energy is expended in passing through whatever medium lies between the source and receiver, and the rate at which the energy is dissipated depends on the material(s) along the N&V path. This is why airborne noise is usually dominant as noise transmits easily through air, and why noise can be effectively blocked by noise barriers or other dense objects which absorb the sound energy.

4. In addition, because the N&V energy is finite at source, the energy reaching a receiver also reduces with distance as it spreads out over an increasingly wider area. So whatever the N&V energy has to pass through from source to receiver and how far the receiver is from the source are critical to the N&V perceived at any point.

5. The source-path-receiver framework for ground-borne N&V also sits at the heart of environmental vibration study and management. The rolling action of Light Rail vehicle wheels on the rails create vibrations that are transmitted through the track support system into the underlying base structure. Vibration of this structure then excites the adjacent substrate and this vibration in turn propagates through the ground and into adjacent infrastructure and buildings. The type of substrate, for example, soil, rock or clay has a significant effect on how the vibration propagates.

6. Problems caused by ground-borne vibration typically take one of three forms[66]. Severe vibration may cause actual damage to existing structures. The two more common sources of complaint are direct vibration disturbance (perceptible intrusion) to occupants of buildings, and audible intrusion due to ground-borne noise radiated from elements of a structure which are caused to vibrate.

7. Intrusion is more common than damage because the levels of vibration that are perceptible are usually at least an order of magnitude smaller than those which may cause damage. Vibration impacts may therefore be classified according to whether the levels are sufficient to be damaging or merely intrusive.

66 Transport Research Laboratory Report 429 Groundborne vibration caused by mechanised construction works D M Hiller and G I Crabb published 2000

Operational Airborne Noise

8. As discussed above, Light Rail systems have a number of different airborne noise sources and the noise generated by each source has different characteristics. The noise from each source propagates along a line of sight path to a receiver, and along the path, noise levels can be reduced (attenuated) with the degree of reduction dependant on distance and any intervening obstacles.

9. Noise from the multiple sources that exist in any urban environment including road traffic then combine with any Light Rail vehicle sourced noise at the receiver, and its strength and how it is perceived potentially interferes with activities and / or causes annoyance at that location. In many urban environments the dominant noise is from road traffic, so when considering the impact of Light Rail systems it is important to consider the difference that the Light Rail system makes to extant noise levels, as well as Light Rail noise in isolation.

10. This concept of taking noise difference into account when setting limits is widely reported, including in the PPG 24 guidelines for local authorities wishing to set local noise limits for new developments and as discussed above, is also taken into account in existing UK Light Rail system N&V monitoring plans.

11. In the US, this principle is also covered at length in current FTA guidance (see the FTA Transit Noise and Vibration Impact Assessment Manual). This differentiates between projects where a Light Rail project is introducing a new dominant noise source and projects where a new Light Rail system is adding to an existing dominant noise source (typically road noise).

12. FTA provide very detailed guidance for Light Rail project N&V assessment and management, including calculation of noise exposure values, and their approach is based on calculating the increase from existing noise levels and defining what level of increase is acceptable during system operation. To achieve this they define the impact of increased noise levels as either Moderate (the threshold of measurable annoyance where mitigation should be considered), or Severe (likely to cause a high level of community annoyance where mitigation is essential).

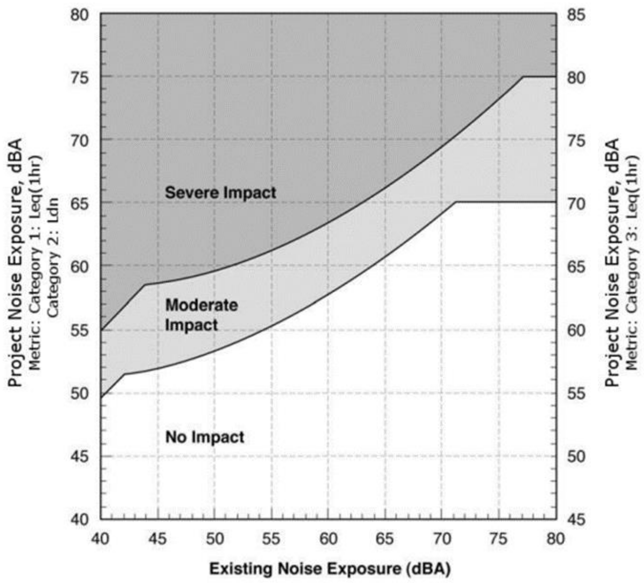
13. Ideally the Light Rail system will design out the problem, for example, re-routing, but if this is not possible, effective mitigation should be provided. FTA also apply three land use categories to capture overall noise sensitivity and the noise-sensitive time of day. For Categories 1 and 3 the noise metric, $L_{eq(1hr)}$ is applied to land uses where night time sensitivity is not a factor, with Category 3 land uses less noise-sensitive than Category 1. For Light Rail system analyses, $L_{eq(1hr)}$ is computed for the noisiest hour of operation. For Category 2, the noise metric L_{dn} is used where night time sensitivity is a factor. It includes residential areas and includes a 10 dB penalty for night time noise.

14. FTA guidelines for acceptable noise increases are summarised by the graph in Figure App B1 FTA taken from their Noise and Vibration Impact Assessment Manual.

15. The principle adopted is that people already exposed to high levels of noise should be expected to tolerate only a small increase in noise but if the existing noise levels are quite low, it is reasonable to allow a greater change in the community noise for the equivalent difference in annoyance.

16. For noisy urban areas, the absolute tolerable limit is 80 dB(A) $L_{eq,\,1hr}$ reducing to a limit of 75 dB(A)L_{dn} in residential areas. A higher limit is considered to give unacceptable living standards. The limit before mitigation of 65 dB(A) L_{dn} for residential areas is aligned with other federal agencies noise limits. Where the Light Rail system is the main source of noise in otherwise quiet areas, the residential limits before mitigation are considered to drop as low as 50 dB(A)L_{dn}.

Figure App B1 FTA Guidelines for Acceptable Noise Increases



17. In Germany, cumulative limits for traffic noise (road and rail including Light Rail) are also differentiated by the type of environment ranging from 59 dB(A) daytime for residential areas to 69 dB(A) in commercial areas with a further 10 dB(A) reduction at night. These values are measured over a 16hr day period (0600 – 2200) and 8hr night period (2200 – 0600) so are effectively $L_{Aeq\ (16hr)}$ and $L_{Aeq\ (8hr)}$ values respectively. These limits are applicable to all new developments and the document provides comprehensive details on calculating the appropriate limits for different locations on a network, and how to account for the numerous variables involved. Although the measurement units are different, these values are broadly similar to the US limits, especially for residential areas and at night. This also includes a specific section on measuring noise emissions from Light Rail vehicles.

18. An alternative approach is taken in Australia with the Yarra Light Rail system in Melbourne, that specifies internal noise limits for residential properties as follows:

- Not greater than 35 dB(A) $L_{eq\ 8hr}$ for bedrooms, assessed from 2200 to 0600;
- Not greater than 40 dB(A) $L_{eq\ 16hr}$ for habitable rooms 0600 to 2200; and
- The loudest hour of traffic noise should not exceed:
  - o 45 dB(A) $L_{eq\ 1h}$ in habitable rooms from 0700 to 2200; or
  - o 40 dBA $L_{eq,\,1h}$ in bedrooms from 2200 to 0700.

19. However, as a single glazed window attenuates noise by about 30 dB(A) (refer to PPG 24), these values are again similar to the upper FTA limits, and UK noise insulation trigger values recommended above.

Vibration and Ground-borne Noise

20. The source-path-receiver framework mentioned above also sits at the heart of environmental vibration study and management. The rolling action of Light Rail vehicle wheels on the rails create vibrations that are transmitted through the track support system into the underlying base structure. Vibration of this structure then excites the adjacent substrate and this vibration in turn propagates through the ground and into adjacent infrastructure and buildings. The type of substrate, for example, soil, rock or clay has a significant effect on how the vibration propagates.

21. Problems caused by ground-borne vibration typically take one of three forms . Severe vibration may cause actual damage to existing structures. The two more common sources of complaint are direct vibration disturbance (perceptible intrusion) to occupants of buildings, and audible intrusion due to ground-borne noise radiated from elements of a structure which are caused to vibrate.

22. Intrusion is more common than damage because the levels of vibration that are perceptible are usually at least an order of magnitude smaller than those which may cause damage. Vibration impacts may therefore be classified according to whether the levels are sufficient to be damaging or merely intrusive.

Operational Vibration Limits

23. Vibration is considered in its effects on both humans and on buildings, and guidelines need to take account of both aspects. There is, however, no real international consensus on this topic and a range of national threshold values exist for both damaging and perceived vibration depending on the derivation methodology used.

24. In addition to the Standards quoted in Section 7, DIN 4150-3 is the German equivalent of BS 7385-2:1993 and gives useful alternative guidelines on the appropriate PPV limits to avoid structural damage. These vary depending on the building types in a frequency measurement range from 1 Hz to 100 Hz as below:

    - 20 mm/s to 50 mm/s – commercial and industrial buildings;
    - 4mm/s to 20 mm/s for residential buildings; and
    - 3mm/s to 10 mm/s for buildings sensitive to vibration and / or has great intrinsic value i.e. listed buildings.

Operational Ground-borne Noise Limits

25. Ground-borne (also referred to as structure-borne) noise is typically low frequency, often perceived as a rumbling sound. Because human hearing perceives specific low frequency sounds as louder than broadband sounds (a mix of frequencies with none dominant, such as on a busy street), for a given dB(A) level, ground-borne noise can sound louder than broadband noise. For this reason ground-borne noise targets should generally be lower than those for broadband (usually airborne) noise.