UK Tram

Support to UKTram Activity 4
"Operational Noise and Vibration"
Phase 2 Reports

Best practice guidance design and specification for minimum noise and vibration impact

Mitigation and avoidance of emerging problems during operation

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30 July 2007

Support to UK Tram Activity 4
"Operational Noise and Vibration"

Consisting

Phase 2a

Systems and Components Guidance on acceptable levels of noise and vibration

Phase 2b Report 1

Best practice guidance Noise & vibration generation, standards and monitoring

Phase 2b Report 2

Best practice guidance Design and specification for minimum noise & vibration impact Mitigation and avoidance of emerging problems during operation

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Support to UK Tram Activity 4
"Operational Noise and Vibration"

Phase 2a

Systems and Components
Guidance on acceptable levels of noise & vibration

November 2007

Title	Support to UK Tram Activity 4 “Operational Noise and Vibration” Phase 2a – Systems and Components - Guidance on acceptable levels of environmental noise & vibration
Customer	UK Tram via Faber Maunsell and Centro
Customer reference	FMJ-5W-1048
Confidentiality, copyright and reproduction	Copyright DeltaRail Group Limited Distribution only on the basis of strict confidentiality. Confidentiality to be maintained. Enquiries about copyright and reproduction should be addressed to the Head of Business Risk Services, DeltaRail Group Limited.
File reference	CD 47211
Report number	DeltaRail-ES-2007-120
Issue number	Draft 4.1

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1 Introduction

This report is the first output from Phase 2 of the UK Tram Activity Group 4 Operational Noise and Vibration project. It takes account of the output of Phase 1 of the study, ie the reports "Phase 1a Information Gathering – Peer Review of Existing and Proposed UK Schemes" and "Phase 1b – Peer Review of Existing Noise and Vibration Legislation, Standards and Guidelines", and presents the basis for the Phase 2b Best Practice Guides on environmental noise and vibration. The elements of tramway systems responsible for noise and vibration emission are identified, followed by a schedule of acceptable levels of noise and vibration emission by system and, where appropriate, sub-system.

2 Definitions of noise and vibration terms

A-weighting:
An adjustment to sound pressure levels to take account of the fact that human hearing is not equally sensitive to all frequencies

Decibel scale (dB):
A linear numbering scale used to define a logarithmic amplitude scale, thereby compressing a wide range of amplitude values to a small set of numbers

Ground-borne noise:
Low frequency sound (rumble) within buildings that results from vibration-excitation of the inner surfaces of buildings as trams pass

Ground-borne vibration:
Vibration caused by the passage of a tram, felt as a sensation of movement

L_{eq}:
The level of a notional steady sound which, at a given position and over a defined period of time, has the same acoustic energy as the actual fluctuating sound

L_{Aeq}:
The L_{eq} of an A-weighted sound level

$L_{Amax, slow}$:
The maximum A-weighted sound level measured during a defined time period with a meter set to "Slow" response

L_{Afmax}:

The maximum sound level with the meter set to “Fast” response

Vibration Dose Value (VDV):
The time-integrated 4th power of vibration acceleration, normally in units of $m/s^{1.75}$. A means of calculating the vibration “dose” received by a person over a defined time period

Peak Particle Velocity (ppv):
The maximum instantaneous velocity of a particle at a point during a given time interval, normally measured in units of mm/s

3 Elements of tramway systems responsible for noise and vibration emission

3.1 Operational Airborne Noise

3.1.1 Wheel rail interaction

The rolling noise from trams results from vibration excitation of wheels and rails by the combined roughness at their interface, ie at the contact patch, as the wheel rotates. This vibration, which propagates to other connected structures such as bogie frames, street surfaces, sleepers etc, results in the radiation of sound to the environment. The character and level of this radiated sound is predominantly a function of the wheel and track shape, size and construction, the vehicle speed and the number of wheels per tram.

Discontinuities in the track such as rail joints, switches and crossings, can be considered as extreme, transient, examples of rail roughness leading to impulsive noise as the tram passes.

A second interaction effect is that of “Curving Noise” caused when vehicles are unable to negotiate curves of small radius by pure rolling, because of incompatibilities between vehicle dynamics and track geometry. It can take the form of one or more high level, high frequency pure tones (curve squeal) but can also have a lower frequency characteristic, sometimes known as “graunching”. Although curving noise is more likely to occur with rigid wheelsets, squeal and graunching has nevertheless been reported on vehicles with independent wheels. There is always a compromise between the requirement for high speed stability from vehicle suspensions and the ability to conform to tight track geometry.

3.1.2 Traction equipment

Wheel rail noise tends to be the dominant running noise element from conventional railway vehicles over a wide speed range, and will therefore be similarly dominant for trams operating on conventional ballasted track at higher speeds. However, at lower speeds, both for street running and on ballasted track, a range of equipment and components associated with delivering traction can be the dominant noise sources. Two traction equipment sources that can have a particular impact are gears and fans. Gears can produce high levels of tonal noise, depending on the degree of continuous contact provided by the meshing geometry, so that straight-cut, simple spur gears etc are more prone to producing tonal noise than helical or hypoid arrangements.

Fans for the cooling of traction equipment such as inverters and traction motors can produce high levels of broadband sound (containing many frequencies), or tonal sound, the latter often being a function of the “siren” effect as fan blades pass a fixed component.

Compressors for air systems or air conditioning units can be the cause of wayside noise, especially if they are of the reciprocating type.

When friction brakes are used, they can generate additional noise by squealing, but they can also short across suspension elements leading to additional vibration, and hence noise radiation, from vehicle components.

3.1.3 Electrical control equipment

A specific item of traction noise that can be the cause of a potentially very annoying element of tram noise is the electrical control equipment. Inverters, thyristors and choppers can all be the cause of tonal noise ranging in frequency from 100 Hz (a “hum”) to several kHz (a “whistle”), either of constant or variable frequency, the latter either being speed-dependent or performing a series of ramps of increasing or decreasing frequency as the vehicle accelerates or decelerates respectively.

All these phenomena result from magnetostrictive vibration excitation of the electrical control equipment, and hence sound radiation, with frequency characteristics that are a function of the electro-mechanical forces being generated, eg the residual AC ripple on a nominally DC supply.

3.1.4 Bells, horns and other audible warning devices

The audible warning devices fitted on trams to alert pedestrians and road users, and also track workers, can be a cause of disturbance and complaint for residents in the vicinity of the tracks. The manner (duration and frequency) in which such devices are sounded by the driver can be as important a factor as the absolute level.

3.1.5 PA systems

Public Address systems, either fixed at stations and stops, or on board the tram, can cause annoyance, especially when background levels are low.

Rail Vehicle Accessibility Regulations (RVAR) 1998 require that an audible warning device shall be fitted to each passenger doorway in the side of a tram and that a warning sound be emitted when the doors of a vehicle can be opened by a passenger and also when they are about to close. The enabling sound must emit for at least three seconds once vehicle doors are enabled and the closure sound must commence no less than three seconds prior to door closure. This requirement has the potential to increase the environmental noise from trams at stops.

3.1.6 Air conditioning or ventilation equipment

External openings for the air inlet or exhaust elements of air conditioning or ventilation systems can emit fan noise and air turbulence noise.

3.1.7 Substations and trackside cabinets

Substations and trackside cabinets will have the potential to emit noise of a similar character to on-board electrical equipment, as well as fan and air turbulence noise from ventilation systems.

3.2 Operational Ground-Borne Noise and Vibration

3.2.1 Street running

Tram vibration is generated, as with rolling noise, by the combined roughness at the wheel/rail interface, except that the roughness wavelengths of relevance are considerably longer than those that generate audible airborne noise. The vibration transmits via connected structures to trackside buildings and is manifested as vibration that is felt by the occupants and/or as an audible low frequency rumble caused by vibrating surfaces radiating sound. As with sound, discontinuities can be considered as an extreme, transient, roughness event.

As well as the wheel and track “roughness”, in the form of wheel out-of-roundness and eccentricity, and the general vertical track alignment, other factors that can affect vibration generation are the vehicle unsprung mass, the vehicle overall mass, vehicle suspension characteristics, the degree of resilience, if any, in the rail fixing, the nature of the ground between track and building, and the vibration response of the building.

3.2.2 Non-street running

On conventional ballasted track, the vibration-generating mechanism is similar to that discussed in 3.2.1, with higher frequency vibration possible because of greater operating speeds. Slab track can reduce ground vibration but can lead to increased levels of ground-borne noise.

3.3 Maintenance Activity

3.3.1 Maintenance of track

Routine and emergency maintenance of the track sometimes has the potential to cause disturbing levels of noise and vibration, especially as this will tend to take place at night. Track grinding is a major example of this, but the excavation and replacement of embedded street-running rail is another potential problem.

3.3.2 Maintenance of vehicles at depots

There is a wide range of possible noise and vibration sources that might arise during maintenance activity at depots, often at night where the potential for disturbance is at its greatest. These can include tram movements, tram wash and sand filling, wheel lathes, bells, horns, curving noise, braking noise, public address systems, road vehicle activity, reversing alarms on road vehicles, audible warnings of tram movement, road vehicle movements, personnel shouting, and radios.

4 The process of determining recommended acceptable noise and vibration levels from trams

UK Tram has referred to the experience and aspirations of all existing and currently-proposed tram systems, and to best practice internationally, to recommend acceptable noise and vibration levels both from tram systems overall and from their component parts.

This has led to the formulation of a set of recommendations presented in Section 5, which are designed to ensure that by the application of current best cost-effective practice, tram operations do not lead to unacceptable environmental noise and vibration impact.

5 Acceptable noise levels from the system

5.1 System Running Noise – Design Aims and Aspirations, Ballasted Track and Street Running

The system should be designed, taking into account the highest proposed traffic flows, to ensure that the following levels (from the Noise Insulation Regulations for Railways, 1996) are never exceeded as a result of predicted tram noise alone, 1m from the façade of residential properties:

$L_{Aeq,\ 0600\ –\ 2400\ hrs}$	68 dB
$L_{Aeq,\ 0000\ –\ 0600\ hrs}$	63 dB

The design aspiration should be not to exceed the following free field (ie away from reflecting surfaces) levels (from Planning Policy Guidance [PPG] 24), as a result of tram noise alone, in the vicinity of residential properties, but where this is not possible, to use their exceedance as an indication that mitigation should be considered:

$L_{Aeq,\ 0700\ -\ 2300\ hrs}$	55 dB
$L_{Aeq,\ 2300\ –\ 0700\ hrs}$	45 dB

$L_{Amax, slow, 2300 – 0700 hrs}$ 82 dB no more than twice/hour

The last of these criteria will pick up short term, high noise level, events such as squeal, which may not register significantly in an L_{Aeq} measurement but which can still create dissatisfaction for residents.

In addition, the ambient noise level, measured in terms of L_{eq} in the vicinity of residential properties during any continuous 1 hour period, shall not be increased by more than 5 dB(A) by the introduction of tram operations.

5.2 Running Noise – Vehicle specification

The running noise specification shall be based on the pass-by requirements of VDV 154 (2002), and testing must always be carried out on conventional ballasted track to remove the uncertainty associated with the performance of various configurations of buried/embedded rail.

In VDV 154, the roughness of the test track and the local acoustic environment is required to follow that specified in pr EN ISO 3095 (2001). This ISO states that "For conventional vehicles, the measurements shall be made with ballast bed and wooden or reinforced concrete sleepers, or with the track normally used by the train." It is recognised that, when acceptance testing is to be carried out to assess compliance with this standard, it is likely to be impossible to have access to a suitable section of test track with the low roughness specified in ISO 3095. Where it is not possible, therefore, to set up for testing on ISO-compliant section of track, it is recommended that it is acceptable to test on a ballasted section of track where the rail head is, from visual inspection, of good quality and without any obvious rail head roughness or pitting, and no joints or other discontinuities for 50m either side of the measurement location. In this case, pass-by levels may be raised by **3 dB(A).**

The pass by noise shall be measured 7.5m from the track centre line, 1.2m above the rail head, in terms of L_{Afmax} (the maximum level with the meter set to "Fast" response") at 60 km/h, if that speed is achievable, or at the maximum speed of the tram if that is lower. For a speed V other than 60 km/h the value should be adjusted by the factor $30 \log_{10} (V/60)$ to provide the value at 60 km/h.

On ISO 3095-compliant track the pass-by level at 60 km/h shall not exceed **79 dB(A)**. If the test section of track has not been set up to be ISO-compliant, but has been approved via visual inspection, then the pass-by level shall not exceed **82 dB(A)**.

5.3 System Ground-Borne Noise – Design, for Ballasted Track And Street Running

Although it is not always possible to measure ground-borne noise in the presence of airborne sound either from the tram or from general ambient background noise, unless specialised techniques are applied, it is recommended that the system shall be specified not to generate ground-borne noise within neighbouring properties, where it is measurable, greater than 40 dB(A) on a meter with “Slow” response for any individual tram pass-by event.

5.4 Stationary Noise – Design And Specification

Specified stationary levels for trams should be based on the requirements of VDV 154, ie a value of L_{eq} measured over T>=15 secs at 7.5m from the track centre line and 1.2m above the rail head, of 55 dB(A) without air conditioning running and 60 dB(A) with air conditioning running at full load.

5.5 PA System and Door Closure Alarm Noise – Design And Specification

Public address systems at fixed points such as stops and stations should be designed to provide maximum audibility with minimal environmental impact. An appropriate standard against which their impact may be assessed is BS 4142, “Method for rating industrial noise affecting mixed residential and industrial areas”. This predicts likelihood of complaint by comparing an introduced noise source with the pre-existing background level.

Public address systems and door closure alarms on board trams can be considered as fixed components for the period during which the tram is stationary and can therefore be assessed similarly to fixed PA systems.

5.6 Track Maintenance Activity – Powers

The times and locations of planned routine track maintenance are often known well in advance and therefore it is important to consult with the Local Authority and the affected residents at an early stage to minimise disturbance and negative reaction. The setting of limit levels is not appropriate here as it is often left to the Local Authority to decide on, or to negotiate, levels and/or procedures in granting a consent to such works under Section 61 of the Control of Pollution Act 1974. The nature of activity needs to be reviewed at an early stage of its planning so that low-noise options may be considered, but inevitably much track maintenance work, both routine and in emergency, will generate high noise levels, often at night.

There may be routine non-operational overnight activities around the system whose noise impact may also need to be considered in planning system operation. This could include pressure washing at tram stops and graffiti cleaning.

5.7 Depot Maintenance Activity – Design And Powers

BS 4142 is a completely appropriate standard for considering the potential impact of maintenance depots on local communities, and should be used in combination with modelling of the various noise events that might arise (based, where possible, on measurements of similar events elsewhere) during the design and planning stage.

6 Acceptable noise levels from sub-systems

6.1 Running noise – Ballasted track

Pass-by will be dominated by this source and therefore the levels specified in 5.2 are relevant for acceptance testing. During operation of tram systems, wheel and rail condition can deteriorate between periodic turning and grinding respectively. A resultant in-service increase in running noise of up to 5 dB(A) before intervention is considered acceptable by UK Tram.

6.2 Running noise – Street running

UK Tram recommend that vehicle running noise be specified only for ballasted track, as the acoustic characteristics of street running track are not as consistent and amenable to reliable modelling as the ballasted version.

6.3 Electrical Control Equipment

In order for the on-board electrical control equipment not to contribute to environmental noise when trams run at 60 km/h and above, it should emit no more that 69 dB(A) measured 7.5m from the track centre line, with no audible pure tones (although this latter requirement may not be easy to achieve via best practicable means).

6.4 Fans – Traction Equipment And Ventilation/Air Conditioning

The maximum level of noise due to each fan for traction equipment should be set at $69 - 10\log_{10}(n)$ dB(A) measured 7.5m from the track centre where n is the number of traction equipment fans per tram unit, and for air conditioning systems this should be set at $60 - 10\log_{10}(n)$ dB(A).

6.5 Compressors

Where compressors are present, their level should not exceed 55 dB(A) measured 7.5 m from the track centre line.

6.6 Substation and trackside cabinets

The specified noise levels for substations and trackside cabinets need to take into account the likely ambient levels within which they will operate, and here BS 4142 may be used to assess impact. However, it is reasonable to state that their level should not be worse than that expected from on-board electrical control equipment, ie 69 dB(A) at 7.5m, and also that pure tones should not be present.

7 Acceptable vibration levels from the system

7.1 Levels close to the track

Although some applications at the Powers stage have specified vibration levels close to the track, these do not have a great deal of relevance to received vibration levels at properties, as propagation through the surrounding ground is not easy to predict without understanding the nature of that ground at all locations. Therefore UK Tram do not recommend vibration source levels from trams.

7.2 Vibration At Properties Adjacent To The Track

7.2.1 Building damage

BS 7385 provides frequency-based levels at the foundations of properties at which building damage might arise, and it is suggested that this standard be used as one element of the system specification for vibration.

7.2.2 Disturbance to occupants

BS 6472 is a well-established methodology for determining the likelihood of disturbance from vibration, and its application is advised as the second element of system specification for vibration.

8 Achievable characteristics of principal on-track maintenance operations

Although there will be some minor maintenance activity where alternative tools and techniques may be found to reduce disturbance, some major activity will inevitably cause high levels of noise. The obvious example of this is rail grinding where levels of around 80 dB(A) are possible up to 25m from the process. On-track maintenance machinery for conventional ballasted track, such as ballast regulators and tampers, can produce even higher levels, typically 85 dB(A) at 25m. It is therefore important that the noise impact of such plant be understood and included within the planning of maintenance activity and associated discussions with Local Authorities and affected residents.

Support to UK Tram Activity 4
"Operational Noise and Vibration"

Phase 2b, Report 1

Best practice guidance
Noise & vibration generation, standards and monitoring

November 2007

Title	Support to UK Tram Activity 4 “Operational Noise and Vibration” Phase 2b, Report 1 - Best practice guidance – Noise & vibration generation, standards and monitoring
Customer	UK Tram via Faber Maunsell and Centro
Customer reference	FMJ-5W-1048
Confidentiality, copyright and reproduction	
File reference	CD 47211
Report number	DeltaRail-ES-2007-121
Issue number	Draft 4

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9 Introduction

This report is one of three Best Practice Guidance documents produced by the Activity 4 Group of UK Tram to assist the promoters, designers and operators of tram systems, and their suppliers, to minimise the environmental noise and vibration impact of their systems in a cost-effective manner. It draws on the output of Phase 1 of the Activity 4 work, the findings of which have been used to develop the background document “Phase 2a Systems and Components – Guidance on acceptable levels of noise & vibration”

Guidance is given here on the methods of generation of environmental noise and vibration emissions by tramway systems, the appropriateness of existing standards for use in the evaluation of tramway noise and vibration, and the timing and initiation of system monitoring.

10 Definitions of noise and vibration terms

A-weighting:
An adjustment to sound pressure levels to take account of the fact that human hearing is not equally sensitive to all frequencies

Decibel scale (dB):
A linear numbering scale used to define a logarithmic amplitude scale, thereby compressing a wide range of amplitude values to a small set of numbers

Ground-borne noise:
Low frequency sound (rumble) within buildings that results from vibration-excitation of the inner surfaces of buildings as trams pass

Ground-borne vibration:
Vibration caused by the passage of a tram, felt as a sensation of movement

L_{eq}:
The level of a notional steady sound which, at a given position and over a defined period of time, has the same acoustic energy as the actual fluctuating sound

L_{Aeq}:
The L_{eq} of an A-weighted sound level

$L_{Amax, slow}$:
The maximum A-weighted sound level measured during a defined time period with a meter set to “Slow” response

L_{Afmax}:
The maximum sound level with the meter set to “Fast” response

Vibration Dose Value (VDV):
The time-integrated 4th power of vibration acceleration, normally in units of $m/s^{1.75}$. A means of calculating the vibration “dose” received by a person over a defined time period

Peak Particle Velocity (ppv):
The maximum instantaneous velocity of a particle at a point during a given time interval, normally measured in units of mm/s

11 Noise generation mechanisms

11.1 Rolling noise

The rolling noise from trams results from vibration excitation of wheels and rails by the combined roughness at their interface, ie at the contact patch, as the wheel rotates. The roughness wavelengths of relevance to rolling noise on trams are in the approximate range 10mm to 500mm, with amplitudes typically between 0.1 micron and 100 micron. This vibration, which propagates to other connected structures such as bogie frames, street surfaces, sleepers etc, results in the radiation of sound to the environment. The character and level of this radiated sound is predominantly a function of the wheel and track shape, size and construction, the vehicle speed and the number of wheels per tram.

Fundamentally, the quietest wheel designs will be of small diameter, substantial and symmetrical in longitudinal cross-section, with smooth running surfaces which can be achieved by not using cast-iron tread brakes, and also by the avoidance of wheel flats. Quiet rails are less straightforward to specify, as it is not easy to control the radiation of acoustic energy from either the rail itself or from connected structures such as embedding material, street surfaces and sleepers.

The PCC resilient wheel designed in the 1930s, as still used on tram systems in the Netherlands and Belgium, has been reported as being subjectively quiet in rolling. The view from railway noise research experience is that resilient wheels in general do not show any trend towards being substantially noisier or quieter than solid wheels. This is because the mechanism of vibration excitation of the wheel and track and the associated response and sound radiation of these components is very complex.

Discontinuities in the track such as rail joints, switches and crossings, can be considered as extreme, transient, examples of rail roughness leading to impulsive noise as the tram passes.

11.2 Curving noise (eg squeal)

A second interaction effect is that of “Curving Noise” caused when vehicles are unable to negotiate curves of small radius by pure rolling, because of incompatibilities between vehicle dynamics and track geometry. It can take the form of one or more high level, high frequency pure tones (curve squeal) but can also have a lower frequency characteristic, sometimes known as “graunching”. This is a result of excitation of the wheel and the track via creep at the contact patch and/or flange contact with the rail, with the ensuing vibration leading to the described sound radiation.

Although curving noise is more likely to occur with rigid wheelsets, squeal and graunching has nevertheless been reported on vehicles with independent wheels – possibly due to the fact that there are varying degrees of independence (eg links via geared shafts vs motored pairs). There is always a compromise between the requirement for high speed stability from vehicle suspensions and the ability to conform to tight track geometry.

11.3 Electro-mechanical equipment

Wheel rail noise tends to be the dominant running noise element from conventional railway vehicles over a wide speed range, and will therefore be similarly dominant for trams operating on conventional ballasted track at higher speeds. However, at lower speeds, both for street running and on ballasted track, a range of equipment and components associated with delivering traction can be the dominant noise sources. Two traction equipment sources that can have a particular impact are gears and fans. Gears can produce high levels of tonal noise, depending on the degree of continuous contact provided by the meshing geometry, so that straight-cut, simple spur gears etc are more prone to producing tonal noise than helical or hypoid arrangements. Vibration coupling between gear elements such as bearing housings and other structures can then lead to efficient radiation of sound to the environment.

Fans for the cooling of traction equipment such as transformers and traction motors can produce high levels of broadband sound (containing many frequencies), or tonal sound, the latter often being a function of the “siren” effect as fan blades pass a fixed component. The character and level of the sound is dependent on the number of fan blades, the flow arrangement (eg axial or centrifugal), the fan speed, the pressure drop across the fan and turbulence created at the fan and also within inlet and exhaust ducting and other air paths.

Compressors for air systems or air conditioning units can be the cause of wayside noise. If a compressor is rigidly mounted to a vehicle structure this provides a greater radiating surface for the acoustic energy created.

Similarly, other vibrating components mounted to the body or bogie can excite these structures leading to additional sound radiation.

When friction brakes are used, they can generate additional noise by squealing as they are applied, but they can also short across suspension elements resulting in additional vibration, and hence noise radiation, from vehicle components.

11.4 Electrical control equipment

A specific item of traction noise that can be the cause of a potentially very annoying element of tram noise is the electrical control equipment. Inverters, thyristors and choppers can all be the cause of tonal noise ranging in frequency from 100 Hz (a “hum”) to several kHz (a “whistle”), either of constant or variable frequency, the latter either being speed-dependent or performing a series of ramps of increasing or decreasing frequency as the vehicle accelerates or decelerates respectively.

All these phenomena result from magnetostrictive vibration excitation of the electrical control equipment, and hence sound radiation, with frequency characteristics that are a function of the electro-mechanical forces being generated, eg the residual AC ripple on a nominally DC supply.

The electrical components themselves will often radiate this noise directly, but it is also possible for coupled components, including body structures and substantial cables, to transmit vibration and hence radiate sound.

11.5 Air conditioning or ventilation equipment

The same factors that influence electro-mechanical equipment fan and air movement noise, as discussed in 3.3, apply in the case of air conditioning and pressure ventilation systems. External openings for the air inlet or exhaust elements of such systems can emit fan noise and air turbulence noise, as can vehicle structures that are vibration-coupled to fan mounts, housings and ducts.

12 Ground-borne noise and vibration generation mechanisms

12.1 The fundamental generation mechanisms

Vibration from trams is manifested in local buildings either as a sensation of movement, or as a low frequency rumble when the vibrating inner surfaces of the building radiate sound. The important factors influencing these phenomena are the combined roughness at the wheel/track interface and the mass/spring systems that are formed by vehicle and track components, interacting with the dynamic characteristic of the ground in which the track is located. The wavelengths of relevance to ground-borne noise and vibration from trams range between approximately 50mm and 20m, with amplitudes typically in the range of 1 micron to 1mm.

12.2 Vehicle-Related Factors

The unsprung mass of the vehicles is a major factor in determining the potential severity of ground-borne noise and vibration from trams. Wheel out-of-roundness and eccentricity are also important as these contribute to the combined "roughness" at the interface with the track. Wheel flats can contribute to vibration generation and can also lead to wheels wearing out-of-round. Suspension characteristics can also have a bearing on vibration generation, but not to the same extent as these other factors.

12.3 Track-Related Factors

Track vertical alignment ("roughness") is a key factor in generating vibration as trams pass. Any vertical displacement of the passing wheelset will generate fluctuating forces that lead to vibration generation and propagation through the track components and the ground. The degree of resilience in the track structure will influence the transmission of vibration but, as with any mass/spring system, there is the potential to amplify the vibration at around the resonance frequencies as well as to attenuate at higher frequencies. Resilient elements that may need consideration are embedding material or precoating material for street running rails, rail pads, sleeper soffit pads, resilient baseplates, floating slab.

Discontinuities in the track are also potential causes of impulsive vibration, and therefore such features as switches, crossings, joints and dips can all have an influence.

12.4 System-Related Factors

As well as the combination of wheel and track roughness, a coincidence of track dimensions and vehicle dynamic characteristics at particular speeds (eg wheel base and vertical alignment) can lead to resonances in vibration behaviour which are not only a potential cause of high levels of vibration generation but which also can lead to derailment.

13 The appropriateness of existing standards

13.1 System Noise

Defra Planning Policy Guidance 24 "Planning and Noise", applicable in England (and its equivalent documents PAN 56 and TAN 11 in Scotland and Wales respectively) draws on World Health Organisation recommendations and the levels used within the Noise Insulation Regulations for Railways 1996 to set ranges of noise level at locations where planning permission for new dwellings is sought, at which:

A Noise need not be considered as a determining factor in granting planning permission…

B Noise should be taken into account when determining planning applications…

C Planning permission should not normally be granted…
D Planning permission should normally be refused…

For railways the levels are the energy average, A-weighted, free field (away from reflecting surfaces) values (L_{Aeq}):

Time period	**A**	**B**	**C**	**D**
07.00 – 23.00	<55	55-66	66-74	>74
23.00 – 07.00	<45	45-59	59-66	>66

An A-weighted maximum level of 82 dB, measured with a slow response ($L_{Amax, slow, 2300 – 0700 hrs}$), occurring "several times per hour" (interpreted here as twice or more) is considered to lead to at least a Category C environment.

The Noise Insulation Regulations for Railways 1996 are designed specifically for new or additional railways and other guided transport systems, and require insulation to be provided at residential properties exposed to specified trigger levels of noise. The fundamental trigger levels are a day time (06.00 – 24.00) A-weighted level 1m from the façade of 68 dB and a night time (00.00 – 06.00) level of 63 dB.

The Category A values, based on World Health Organisation guidelines to avoid serious annoyance during the day and sleep disturbance at night, have been used on several UK schemes to define desirable limits of exposure for dwellings in the vicinity of new tram schemes. These are, however, onerous criteria, and may be more appropriate as triggers for the consideration of pragmatic control measures rather than as absolute targets. The 82 dB(A) L_{Amax} value twice or more per hour is, however, suitable as a limit not to be exceeded.

The trigger levels under the Noise Insulation Regulations for Railways 1996 are, however, appropriate to be used as absolute limits, especially as, under England and Wales law, new schemes must be assessed against these triggers. Scotland and N Ireland will tend to follow a similar approach. Under the Regulations it is always an option to provide insulation at properties where the triggers are met, but it is preferable to control noise emission at, or close to, the source if possible and thus avoid the need to insulate properties, as this has a greater benefit in terms of the affected area and population.

13.2 Vehicle Noise

The levels suggested in VDV Paper 154 (2002), and adopted by UITP, for pass-by noise are appropriate for the specification and acceptance testing for trams that are running on ballasted track. Here the roughness of the test track and the local acoustic environment is required to follow the spectrum specified in pr EN ISO 3095 (2001) "Railway Applications – Acoustics – Measurement of noise emitted by railbound vehicles", which is repeated in the 2005 formal issue of this standard. Where it is not possible to set up an ISO-compliant section of track for testing, however, it is recommended that it is acceptable to test on a section of track where the rail head is, from visual inspection, of good quality and without any obvious rail head roughness or pitting, and no joints or other discontinuities for 50m either side of the measurement location, in which case it is suggested that the pass-by levels may be raised by **3 dB(A).**

The pass by noise shall be measured 7.5m from the track centre line, 1.2m above the rail head, in terms of L_{Afmax} (the maximum level with the meter set to “Fast” response”) at 60 km/h, if that speed is achievable, or at the maximum speed of the tram if that is lower. For a speed V other than 60 km/h the value should be adjusted by the factor 30 $\log_{10}$ (V/60) to provide the value at 60 km/h.

On ISO 3095-compliant track the pass-by level at 60 km/h shall not exceed **79 dB(A)**. If the test section of track has not been set up to be ISO-compliant, but has been approved via visual inspection, then the pass-by level shall not exceed **82 dB(A)**.

It should be noted that, although ISO 3095 is normally applied in a manner that is more appropriate for heavy rail (ie with distant microphones and on conventional ballasted track) it is written with sufficient flexibility to allow tram-specific environments to be covered.

13.3 System Ground-Borne Noise And Vibration

British Standards BS 6472:1992 “Evaluation of human exposure to vibration in buildings” and BS 7385 “Evaluation and measurement for vibration in buildings..Part 2: 1993 Guide to damage levels from groundborne vibration” have previously been used in the UK to set vibration limits at receivers when specifying the impact of new tram systems, and their continued use is recommended.

For ground-borne noise (rumble), the use of a limit of 40 dB(A) measured on a meter with “Slow” response for any individual tram pass-by event is based on American Public Transit Association Guidelines from 1981, and has subsequently been applied successfully to a number of UK rail schemes (eg the Channel Tunnel Rail Link tunnels, Jubilee Line Extension, Crossrail, Croydon Trams). Its continued application is therefore recommended.

13.4 Vehicle Ground-Borne Vibration

Although some applications at the Powers stage have specified vibration levels close to the track, these do not have a great deal of relevance to received vibration levels at properties, as propagation through the surrounding ground is not easy to predict without understanding the nature of that ground at all locations. As a result of this uncertainty, UK Tram does not recommend the adoption of such a measure.

14 Achieved noise and vibration characteristics on existing UK systems

There is not a large database of typically achieved data from UK Tram systems, and the data that exists is often weighted towards situations where problems have occurred.

The Noise Mapping of tram systems as mandated by the Environmental Noise Directive requires that appropriate source terms for all of the tram/track combinations in UK operation be determined. The decisions made on this, combined with the results of mapping, will indicate the current noise climate created by trams on a 5-yearly basis.

15 Timing and initiation of system monitoring

It is very important to “baseline” the noise and vibration environment before a new tram system commences operation and, ideally, before any construction work commences, so that a clear indication of the prevailing conditions is obtained. It is often very difficult to establish exactly what changes have truly occurred in the absence of such an exercise. It may be that such baselining is required anyway at the stage of seeking powers.

Once the system has opened it is equally important to establish the true noise and vibration impact to (a) validate any models and assumptions made and (b) to identify potential unexpected problem locations. However, it is not advised to consider measurements made immediately after the opening of a system as being definitive because there will inevitably be initial unforeseen problems that can quickly be rectified and also because the system will need a period of time to “run in”. An example of this is rail head roughness, which can require a certain amount of trafficking, post installation and/or post grinding, before it reaches a comparatively steady-state condition.

It is therefore proposed that a monitoring approach as follows be adopted:

- Measure noise and vibration at locations around the proposed route of the system before infrastructure works commence.
- Measure around the system, as a minimum at the same locations as the pre-construction set, 6 months after the opening of the system, and then after a further 6 months, with subsequent monitoring on an annual basis.

Support to UK Tram Activity 4
"Operational Noise and Vibration"

Phase 2b Report 2

Best practice guidance
Design and specification for minimum noise & vibration impact
Mitigation and avoidance of emerging problems during operation

November 2007

Title	Support to UK Tram Activity 4 “Operational Noise and Vibration” Phase 2b, Report 2 - Best practice guidance - Design and specification for minimum noise & vibration impact. Mitigation and avoidance of emerging problems during operation
Customer	UK Tram via Faber Maunsell and Centro
Customer reference	FMJ-5W-1048
Confidentiality, copyright and reproduction	
File reference	CD 47211
Report number	DeltaRail-ES-2007-123
Issue number	Draft 4.1

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16 Introduction

This report is one of two Best Practice Guidance documents produced by the Activity 4 Group of UK Tram to assist the promoters, designers and operators of tram systems, and their suppliers, to minimise the environmental noise and vibration impact of their systems in a cost-effective manner. It draws on the output of Phase 1 of the Activity 4 work, the findings of which have been used to develop the background document "Phase 2a Systems and Components – Guidance on acceptable levels of noise & vibration"

Advice is given here on factors that need to be taken into account from the earliest specification stage of a scheme through to the design and construction phases, as well as on mitigation approaches to problems that might arise during operation and on the influence of maintenance and renewals strategy on noise & vibration.

17 Definitions of noise and vibration terms

A-weighting:
An adjustment to sound pressure levels to take account of the fact that human hearing is not equally sensitive to all frequencies

Decibel scale (dB):
A linear numbering scale used to define a logarithmic amplitude scale, thereby compressing a wide range of amplitude values to a small set of numbers

Free field:
A location sufficiently far from acoustically reflective surfaces, except the ground plane, for reflected sound not to have a significant effect on the resultant sound field

Ground-borne noise:
Low frequency sound (rumble) within buildings that results from vibration-excitation of the inner surfaces of buildings as trams pass

Ground-borne vibration:
Vibration caused by the passage of a tram, felt as a sensation of movement

L_{eq}:
The level of a notional steady sound which, at a given position and over a defined period of time, has the same acoustic energy as the actual fluctuating sound

L_{Aeq}:
The L_{eq} of an A-weighted sound level

L_{Amax}:
The maximum A-weighted sound level

$L_{Amax, slow}$:
The maximum A-weighted sound level measured during a defined time period with a meter set to “Slow” response

L_{Afmax}:
The maximum A-weighted sound level with the meter set to “Fast” response

Vibration Dose Value (VDV):
The time-integrated 4^{th} power of vibration acceleration, normally in units of $m/s^{1.75}$. A means of calculating the vibration “dose” received by a person over a defined time period

Peak Particle Velocity (ppv):
The maximum instantaneous velocity of a particle at a point during a given time interval, normally measured in units of mm/s.

An achievable specification for the cost-effective minimisation of noise and vibration impact

UK Tram recommends the following specification for new tram systems:

17.1 Noise

- The tram system as a whole, comprising vehicles running in normal service on associated infrastructure, including the effects of any lineside structures constructed as part of the scheme, shall be designed to ensure that the levels shown in Table 3.1 are predicted never to be exceeded on any day of the week, when the maximum planned traffic flows apply:

Averaging period	Level, dB
06.00 – 24.00	68
00.00 – 06.00	63

Table 3.1 Maximum acceptable L_{Aeq}, 1m from any façade of residential properties adjacent to the track, due to tram operations alone

- Furthermore, the design aims for the tram system as a whole, predicted for the situation where the maximum planned traffic flows apply, shall be as shown in Tables 3.2 and 3.3.

Averaging period	**Level, dB**
07.00 – 23.00	55
23.00 – 07.00	45

Table 3.2 Maximum desirable free field L_{Aeq} in the vicinity of residential properties, due to tram operations alone

Period	**Level, dB**
23.00 – 07.00	82 more than twice/hour

Table 3.3 Maximum desirable free field L_{Amax}, slow in the vicinity of residential properties, due to tram operations alone

- When the predicted noise levels for the proposed system design exceed these design aims, further mitigation shall be considered, with the aim of reducing levels to, or preferably below, these values.

- When the total predicted ambient noise levels from all sources including the new tram system when operational, in terms of L_{Aeq} during any continuous 1 hour period in the vicinity of residential properties, exceeds the ambient noise level due to all noise sources existing prior to the installation and operation of the system by 5 dB(A) or more, further mitigation shall be considered, with the objective of reducing the predicted exceedance to, or preferably below, this value.

- In operation, individual tram vehicles shall not emit a greater level of environmental noise, when negotiating any curves on the system, than when travelling on adjacent straight track of similar design, and shall not create any pure tone “squeal”.

- New trams shall be designed to, and type-tested against, the specification shown in Table 3.4, which is based on VDV 154:

Conditions	Speed km/h	Level, dB(A), 7.5m from the track centre line 1.2m above the rail head
Stationary, without air conditioning running	0	L_{Aeq} over a minimum of 15 secs 55
Stationary, air conditioning on full load	0	L_{Aeq} over a minimum of 15 secs 60
Ballasted track with ISO 3095 (2005) measurement conditions and with ISO 3095 (2005) track roughness	40 60 80	L_{Afmax} * 74 79 83
Where not possible to set up for testing on track with ISO-compliant roughness: Ballasted track, with rail head, from visual inspection, of good quality and without any visible rail head roughness, corrugation or pitting, and no joints or other discontinuities, for 50m either side of the measurement location. Otherwise ISO 3095 (2005) measurement conditions.	40 60 80	L_{Afmax} * 77 82 86

*Acceptance test to be carried out at the highest of the indicated speeds that is possible within the operational and safety constraints of the trams and available track at the test site

Table 3.4 Design and type-test noise specification for new trams

17.2 Ground-borne noise

- The pass-by of any individual tram shall not generate ground-borne noise (rumble), within neighbouring occupied properties, greater than 40 dB(A) measured on a meter with “Slow” response.

17.3 Ground-borne vibration

- To minimise disturbance to occupants of buildings, the tram system as a whole, comprising vehicles running in normal service on associated infrastructure, shall be designed to ensure that the levels shown in Table 3.5 are predicted never to be exceeded on any day of the week, when the maximum planned traffic flows apply:

Period	**VDV m/s$^{1.75}$**
07.00 – 23.00	0.40
23.00 – 07.00	0.13

Table 3.5 Maximum acceptable Vibration Dose Values (VDV) as defined in BS 6472** on any floor within occupied buildings adjacent to the track, due to tram operations alone

**Using the definition of VDV within the version of BS 6472 "Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz)" that is current at the time of the prediction

- To ensure that buildings are not subject to vibration levels that could have any detrimental effect on their fabric, the system shall be designed to ensure that the levels shown in Table 3.6 are predicted never to be exceeded during the pass-by of trams.

Building type	**ppv, mm/s** (maximum of the three orthogonal components)
Reinforced or framed buildings	50
Un-reinforced or light framed buildings	15

Table 3.6 Maximum acceptable Peak Particle Velocity (ppv) at the foundations (low on an external wall) of any building adjacent to the track, due to tram pass-by, following the approach of BS 7385

17.4 Monitoring during operation

- Noise and vibration shall be measured at a representative set of locations around the proposed route of the system before infrastructure works commence.
- Noise and vibration shall be measured, as a minimum at the same locations as the pre-construction set, 6 months after the opening of the system, and then after a further 6 months, with subsequent monitoring on an annual basis.
- If contractually agreed noise and vibration values are found to be exceeded during the initial monitoring 6 months from opening, action shall be taken to restore the values to those within the contract.
- During subsequent monitoring, a 5 dB allowance in airborne and ground-borne noise levels is permissible before action is required to be taken to restore the values to those within the contract.
- During subsequent monitoring, any increase in vibration levels beyond those indicated in Tables 3.5 and 3.6 requires action to be taken to restore the values to those within the contract.

18 Design considerations to meet specification requirements

18.1 Noise

Rolling noise

The essential approach to avoiding high levels of rolling noise is to ensure that both the wheel and the rail are as smooth as possible. For the vehicles this means that cast-iron tread brakes must be avoided, which will normally be the case with contemporary stock. Efficient wheel slide and slip protection is extremely important to keep the wheels smooth and flat-free. At the design stage there is less that can be done to ensure smooth rails, other than to ensure that they are either supplied in a smooth condition, or ground immediately upon installation to a high precision.

The periodic wear phenomenon of rail head corrugation is a recurring problem on many light and heavy railway systems. With a pitch from around 20mm to 80mm, corrugation can increase rolling noise by up to 20 dB(A), a subjective quadrupling of loudness. Some resilient track forms have been found to reduce the rate of formation of roughness and corrugation while others have had the opposite effect. The European research project “Corrugation” sheds some light on this by suggesting that a highly damped embedded rail or a very soft rail fixation can reduce the formation of corrugations, as can very rigid, or very soft, lateral rail fixation. This avoids resonances of the wheel/track system that coincide with excitation frequencies as trams pass. However, the knowledge to date does not allow firm advice on the control of corrugation growth to be provided here.

Track discontinuities and harsh transitions should be avoided where possible at joints, switches and crossings, to minimise impulsive sound emission. Points, crossings and rail joints should not be positioned in the vicinity of identified sensitive receivers wherever possible. Flange running at on-street crossings can also reduce impulsive noise, although there are speed limitations associated with this arrangement, and the wheel profile may need to be designed to take this mode of operation into account.

It is possible to reduce rolling noise at source marginally, but not always reliably, by some methods. Resilient wheels, wheels fitted with constrained layer dampers and wheels fitted with tuned absorbers have all been investigated in recent years with a view to reducing rolling noise. Although in some instances the results have been promising, there is not, as yet, a wheel design with such features that is recommended as a reliable method for reducing rolling noise significantly. However, all such designs are known to have reduced curving noise, especially squeal, by a worthwhile amount and therefore it is always worth considering wheels with such features for this benefit alone.

It will always be beneficial for rolling noise if the wheel is of low diameter (as is normally the case for trams) and largely symmetrical in cross section when viewed in a longitudinal direction. This is only the case where the roughness of the rolling surface remains unchanged. It is known that wheels of smaller diameter tend to become more easily damaged (eg shelling or spalling) in operation, with potential adverse consequences on rolling noise, potentially negating the acoustic benefits unless such damage is protected against.

At the design stage it is advantageous for the suspension designer to control the transmission of vibration at audible frequencies (typically 20 Hz – 10 kHz) from the wheels, via suspension elements, to vehicle components that are efficient radiators of sound. This will help in reducing radiated sound both when running on continuous rail and at discontinuities.

As with the various wheel treatments available, there are many claims for the acoustic advantages of a range of trackforms used for street running or on elevated structures, which can, for example, be buried deeply or superficially within the road, embedded within a resilient material or installed in a precoated form. It is often the case with such treatments that there is no obvious mechanism for acoustic energy to be dissipated effectively and therefore it can possibly therefore still radiate significantly from coupled surfaces, such as that of the embedding material or the road. There is insufficient evidence to advise that a particular track arrangement should be chosen purely because of claimed noise performance.

On conventional ballasted track, it has been found from extensive research that tuned absorbers on the rails can reduce overall rolling noise by 5 dB, and this approach is therefore worth considering within the design of ballasted sections of track where additional rolling noise control is required for sensitive receivers.

18.2 Curving noise

Although curving noise radiation can be reduced by various wheel treatments it is preferable to avoid its causes in the first place. By design, curves of low radius or reverse curves should be avoided where possible.   Where this is not possible due to the requirement to allow trams to run within a physically restricted urban environment, some adjustment to gauge may be of benefit, depending on vehicle suspension characteristics. The vehicle designer may be able to reduce the yaw stiffness of the suspension in order to maximise compliance to the curve, but this will often compromise stability at higher speeds. Independent wheels, steering bogies, and intelligent independently driven wheels, can all help in reducing squeal, but this is not always the case. Curves of low radius should not be positioned, where avoidable, close to noise-sensitive receivers.

Lubrication of the track with conventional lubricants, or with “friction modifiers” designed to ensure a consistent friction characteristic, can be designed in to the infrastructure. This is not a desirable initial approach for street running, because of the tendency of such materials to accumulate debris and also because of safety implications for road users and pedestrians. Friction modifiers have proved successful for some applications, and less so for others, and therefore they may be more suited to retro-fitting at particular problem locations where a trial will be possible in advance of installation, rather than being integral within system design.

Water sprays, or a stream of water dispensed within the groove of street-running rail, may also be considered at the design stage, but this can have implications for asset life.

Vehicle-mounted stick applicators of lubricant to the flange root or of friction modifier to the wheel tread, or oil dispensers, are also an option that may be designed in, and are the preferred option for practical reasons, but these have not, as yet, been shown to be particularly effective for curving noise mitigation. If on-board oil dispensers are able to be controlled so that an appropriate quantity is applied to both faces of the flange at required locations, then their inclusion in vehicle design for the entire fleet is recommended as best practice. This avoids a known problem with stick lubricators where debris can be picked up in a street environment. It is known, however, that space constraints on low floor cars can make it difficult to implement such a solution.

18.3 On-board equipment

If compressors are fitted to vehicles these should be the screw type where possible.

Electrical engineers may be able to design systems to avoid the various magnetostrictive effects that lead to hum and the tonal character of on-board and trackside electrical equipment.

Gears can usually be designed or selected to minimise the generation of noise at the meshing frequency, by reducing backlash and ensuring as constant a contact and transmission of force as possible.

Fan and air movement systems for air conditioning or ventilation for passengers, and for the cooling of traction equipment, can have a large variation in emitted noise depending on the care of design. It is always better to use a larger, slower, fan where possible, and also to ensure that the fan is operating with a pressure drop that is at an efficient point in its characteristic, and that there are no close fixed components close to the blades. Ducts without sharp bends or internal discontinuities also help to reduce the noise from the system.

Door closure alarms should be at a noise level that ensures audibility to all those who need to hear them, but not more widely to the environment. The same consideration also applies to public address system loudspeakers on board vehicles and also at stations and stops. In both instances the use of a large number of alarms, or loudspeakers, with a low acoustic output is recommended rather than fewer devices of higher noise level. This has the added advantage of improving audibility for all passengers. On-board loudspeakers should be installed away from tram doors so that sound energy escaping to the environment is minimised.

18.4 Control of sound propagation

Once running (rolling + on-board equipment) noise has been controlled as much as possible at source, methods may be designed-in to reduce the amount of sound energy that propagates to the environment. One such approach is to place skirts around bogies to act as close barriers. These can provide some reduction, but often not as much as would be expected, as the lower part of the wheel, and the track and coupled structures, are all radiators of sound that are not shielded. As skirts are preferred as a matter of course for aesthetic and safety reasons, any marginal acoustic benefit is a bonus. The acoustic advantage of skirts can be maximised by making them as continuous and close to the ground as possible. Close proximity to wheels is also beneficial, and therefore bogie-mounting will help in this respect. An acoustically absorbent lining on their inner surface will add to their efficiency, as will sufficient structural strength, fastenings and clearances to prevent them from rattling in service. Arrangements can be made, as in the Bombardier K4000 family, for body-mounted bogie skirts to be pushed out by the bogie as it swings on very tight curves, thus avoiding the need to compromise their proximity to the bogie under normal operation.

Low barriers close to the track can also be beneficial, especially when combined with skirts on vehicles, but are not always practical, especially in a street-running situation. Tall barriers are reliable in their acoustic performance if designed correctly (fundamentally of sufficient mass/unit area, preferably with a sound absorbent lining facing the tram, and without any gaps either at the base or between panels). They are, however, costly and visually intrusive, they attract graffiti, and can have safety implications.

18.5 Ground-borne noise and vibration

The vehicle designer can make the biggest contribution to reduced environmental vibration by minimising the unsprung mass of the tram. Wheel slide protection should be used to avoid wheel flats which can in themselves lead to impulsive vibration and which can also result in wheels wearing out-of-round, another major cause of vibration. Regarding conventional street-running track or ballasted track, the vertical alignment of the rail head should be kept to tight tolerances to avoid ground-borne noise and vibration generation from combined wheel/rail “roughness”. This vertical alignment ranges from the shorter wavelength roughness that can generate ground-borne noise, ie around 50mm and upwards, up to the longest wavelength likely to generate ground-borne vibration from trams, ie around 20m. It should be noted that this wavelength range may not totally coincide with those of interest from a ride point of view.

As with sound, track discontinuities and harsh transitions should be avoided where possible at joints, switches and crossings, to minimise impulsive vibration generation. Points, crossings and rail joints should not be positioned in the vicinity of identified sensitive receivers wherever possible. Flange running at on-street crossings can also reduce impulsive vibration, although there are speed limitations associated with this arrangement, and the wheel profile may need to be designed to take this mode of operation into account.

For vibration-sensitive locations, a range of track options are available for controlling the transmission of vibration (and possibly associated ground borne noise) to the environment. All of these rely on adding resilience (and often mass) into the track support structure. Options available include resilient embedding material or precoating material, resilient baseplates on slab track, booted sleepers on slab track, floating slab track, sleeper soffit pads on ballasted track, ballast mats on ballasted track. These approaches have benefits that tend to have a direct relationship with rail deflection, added mass, size and cost. As deflections increase it is important not to allow rails to bend to the point where structural integrity is compromised, and also to avoid rail gauge spread beyond allowable tolerances.

19 Practical measures at the construction phase

At the construction phase of infrastructure, it is important that rail vertical alignment is maintained to the specified tolerance, and that the track is either of low roughness upon installation or is ground to a high precision before the system commences operation.

Any vibration-controlling trackforms, such as resilient baseplates, should be installed carefully, ensuring that there is free movement in the components.

19.1 Known failures on existing systems, and means to avoid their recurrence

Stick lubricators have been tried on at least two UK systems to reduce curve squeal without any obvious success.

There have been concerns at one location where ground borne noise has been generated within a local noise-sensitive building, where a crossover is located on a section of floating slab track. The cause here appears twofold – impulsive forces at the crossover and possible problems of installation or manufacture, or deterioration, of the floating slab. If at all possible, such crossovers should be avoided at sensitive locations, as even very efficient floating slab designs are not able to mitigate completely the transmitted vibration when excitation is at a high level and impulsive. Alternative low-impact crossover designs could also be considered.

Friction modifier has been assessed by one operator for the control of curve squeal, as it is known to have been beneficial previously at some locations, but this was unsuccessful because of contamination with sand from trams during braking. A subsequent installation of tuned wheel absorbers has been very successful, however, supporting UK Tram’s view that vehicle-based solutions are the preferred approach, especially for street running.

20 Mitigation approaches for emerging problems

20.1 Noise

It is not normally feasible to retro-fit systems to control running noise, hence the need to consider this at the design stage whenever possible. However, should excessive running noise be reported, or complained of, then it should be possible via specialist investigation to identify the cause and possibly improve the situation. If the problem is rolling noise, then the main factor to consider initially is the roughness of the track and wheels. Tracks may have not been installed, or put into operation, in a smooth condition, or a combination of factors may be leading to a high roughness growth rate. A precision grinding exercise will possibly therefore be able to rectify the problem. If the wheels are rough, or flatted, then the cause of this (eg WSP inefficiency, wheel slip when traction is applied, curving forces) will need investigating and the wheels will require turning or replacing. Retro-fitting of bogie skirts and/or low close trackside barriers, or tall trackside barriers, where practicable, will control sound propagation to a variable extent, with the latter treatment being the most efficient acoustically.

If the noise is due to curving, either squeal or low frequency stick-slip, it is probably too late, once the system is in operation, to modify track or vehicle cost-effectively. Therefore, additional lubrication via grease dispensers on the track, oil dispensers on vehicles, friction modifiers to provide constant friction characteristics, water sprays, vehicle-mounted stick lubricators bearing on the wheel flange root, or stick friction modifiers bearing on the wheel tread can all be considered for retro-fit. These treatments have been shown to be very successful at some locations and very unsuccessful at others. It is recommended that, where possible within economic and practical constraints, on-board oil dispensers for both faces of the wheel flange, controlled so that they operate, and dispense an appropriate amount, only at required locations, and fitted to the entire fleet, are the best retro-fit lubrication solution. The practical constraints include potential difficulties in fitting oil dispensers on low floor cars because of space limitations.

Vibration-damping of the wheel using constrained layer dampers or tuned absorbers, comprising masses mounted via resilient elements to the wheel, have proved to be reliable mitigation techniques for curve squeal in a number of reported applications. The retro-fitting of resilient wheels where previously monobloc wheels were used will probably also be of benefit, both by allowing the wheels to conform to the curve more readily and also by providing some inherent damping to the wheel.

It may be possible to retro-fit quieter fans or sound attenuators to air movement systems, but a complete redesign of such systems for acoustic purposes is not often practical.

Public address loudspeakers, both on-board trams and at stations and stops, as well as door closure alarms, can have their individual sound levels reduced retrospectively, and can have their numbers increased at the same time, in order to reduce environmental impact whilst maintaining audibility.

20.2 Vibration

If vibration problems emerge, the initial approach should be to investigate the vertical alignment of the track, or any discontinuities in the track at the location of the problem. These discontinuities could be at joints, or switches and crossings. All of these factors might be possible to address via maintenance or renewal of damaged or defective components, or replacement with lower-vibration designs, such as flange tip running, which might necessitate a new wheel profile.

It is not normally acceptable to retrofit trackforms unless the problem is extreme.

20.3 The influence of maintenance and renewals strategy on noise & vibration

A wheel maintenance strategy that maintains both the smoothness of their running surfaces and their roundness is important to minimise the noise and vibration impact of the tram system. This may require more frequent turning than pure safety considerations require, and hence lead to a shorter wheel life, and therefore the associated costs will need to be judged against the environmental, and public relations, benefit. There will also be the added benefit of maintaining wheel profiles closer to the optimum for a greater proportion of the time.

Vehicle suspensions will need to maintained so that there is no vibration shorting due to seized elements, which can lead to an increase in the effective unsprung mass and hence vibration, and also so that they can negotiate curves of small radius as efficiently as possible, to minimise curve squeal.

Rail grinding will need to be carried out at a sufficiently frequent interval to ensure that roughness and corrugation is controlled and the rail profile is maintained, especially at curves. The maintenance of profile has benefits both for noise and to avoid the rail head becoming conformal to the wheels, which can lead to a severe degradation of the vehicle’s dynamics. In mainland Europe the common approach is a regular dressing of the rail head using scrubber blocks on a retired or modified service car, coupled with periodic reprofiling with a grinding machine.

It is important for cost-effective grinding that locations of high roughness and corrugation are targeted. This may be achieved by visual inspection, microphone-based systems mounted on vehicles (eg “NoiseMon”), on-board accelerometers, or roughness measurement trolleys operating at around 1 m/s, although these are not normally amenable to operation on street-running rail. Routine monitoring with on-board systems will allow both absolute levels of roughness and the rate of growth to be recorded, facilitating preventative grinding and the efficient programming of future grinding.

Discontinuities in the rail, with associated noise and vibration implications, can be kept to a minimum by frequent inspection and rectification. This inspection can be visual or via on-board noise or vibration monitoring, ranging from drivers' reports to automated systems.

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