An assessment of the effectiveness of noise reduction systems on Dublin's light rail system (Luas)

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Summary
Luas is Dublin's modern light rail system. Similar to the majority of urban electrical tramways, the system is relatively quiet when compared to diesel locomotives with similar power output. However, electrical rail systems do produce airborne noise. The principle noise source is the interaction of the wheels with the rails; termed "rolling noise". However, rail track type also influences noise emissions. A comprehensive review of acoustic compliance monitoring undertaken along the Luas network identified that rolling noise emissions were highest on straight sections of traditional slab track with speeds in excess of 50 km/ph. Measured levels were approximately 2-3dB higher than ballasted rail with similar speeds. Following a detailed consideration of available reduction systems the Railway Procurement Agency (now Transport Infrastructure Ireland), installed two track based noise reduction systems. Un-tuned rail dampers and bespoke absorbing rubber infill panels were installed on separate 100m stretches of the network. Pre- and post-installation attended monitoring was undertaken to determine external noise reductions achieved by each system. To take account of the varying nature of the noise levels from railways a number of indices were measured including $L_{Aeq,Tp}$, L_{AE} and L_{AFMax} to determine noise reductions achieved. One third octave band analysis was also undertaken. Tram pass-bys for the section of track installed with rail dampers decreased by up to 3.5dBA (L_{AE}). For the section of track installed with the bespoke absorbing rubber infill panels tram pass-by levels decreased by up to 4dBA (L_{AE}). Reductions were obtained at frequencies between 63Hz and 20kHz. The noise reduction systems trialled are suitable for use in tandem or in conjunction with other rail abatement measures including bogie shrouds and rail grinding. The findings of this research is being used when considering acoustic mitigation measures for future lines.

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1. Introduction

Railway transport is purported to be the most environmentally friendly transport mode as it consumes less energy and produces less carbon dioxide than any other transport mode [1]. However, the EU's Green Paper Future Noise Policy of November 1996 by the European Commission states that the "public's main criticism of rail transport is the excessive noise level" [2].

The railway sector acknowledges noise as a problem and has a long history of noise control. Two of the key reasons for noise control are (i) the environmentally friendly image of rail transport can be compromised if actual – or assumed – levels of noise emissions are too high, and (ii) rail vehicles are clearly identifiable as sources of the noise emission. Unlike general road traffic; rail operators are easily singled out as those responsible [3].

Luas is Dublin's light rail system and an iconic symbol of Dublin as a vibrant world class city. Operations commenced in 2004 with the opening of the Luas Green and Red Lines. In December 2017 Luas Cross City, a 5.6km extension of the Green Line, commenced passenger services providing a link between the two lines and extending the network to Cabra in north Dublin. The system is serviced by Nr.40 Citadis 401 trams which operate on the Red Line and Nr.26 Citadis 402 and Nr.2 Citadis 502 trams operating on the Green Line. Both the Citadis 401 and 402 trams are four bogied vehicles with three motor bogies and one trailer bogie. The Citadis 502 trams are five bogied vehicles with four motor bogies and one trailer bogie.

Continuing compliance with Railway Order (Planning) noise conditions is a priority for Transport Infrastructure Ireland (TII), the government body responsible for the planning, construction and operation of light rail in Dublin. Acoustic monitoring is periodically undertaken by both the Luas Operator and TII to demonstrate compliance.

In 2011 the Railway Procurement Agency (RPA) (now TII) undertook a research project to trial two noise reduction systems on the Luas light rail system.

2. Objectives

The objectives of the research project were to (i) review data from operational noise surveys undertaken following opening of the alignment in 2004 to identify areas of higher noise levels on the existing system (ii) critically review light rail noise reduction methods (iii) select two noise reduction systems for trial installation and (iv) critically review the implemented noise reduction methods and determine, through the analysis of project specific noise data measured pre-and post-installation of noise reduction methods, any changes in noise levels.

3. Methodology

3.1 Review of data from operational surveys

Since services commenced on the Luas network, annual noise monitoring surveys have been conducted by the Operator upon opening of the system. In 2009 RPA produced an operational noise monitoring procedure to be implemented by the Operator [4]. This procedure was closely aligned with ISO 3095:2005 [5]. In accordance with the procedure, specific broadband and one third octave analysis were to be measured at monitoring locations along with other details including, for example, tram speed and tram number.

Upon review of acoustic data from 2009 to 2011 it was identified that rolling noise on straight areas of traditional slab track with higher speeds i.e. greater than 50 km/hr, produced the greatest pass-by sound pressure levels. Whilst most existing railway tracks are still of a traditional ballasted type, many more recently constructed light rail systems tend towards the use of non-ballasted track. Slab track, as shown in Photograph 1, is formed by fixing rails directly to a reinforced concrete slab. This track type has a number of significant advantages over ballasted track including high availability, low maintenance and low structure height. In addition, life cycle studies have demonstrated that slab track is very competitive from a cost point of view [6].

Photograph 1. Traditional slab track

However, in general, slab track is louder and causes more vibration than traditional ballasted track. While this is in some part attributable to slab track's decreased sound adsorption qualities i.e. more reflective nature, a more significant factor is that slab track typically uses softer rail fasteners to provide vertical compliance similar to ballasted track; these can lead to more noise as it permits the rail to vibrate over a greater length [7]. For Luas, sound exposure levels (L_{AE}) and maximum sound pressure levels (L_{AFMax}) were approximately 2-3dB higher at monitoring locations adjacent to slab track than trams passing at 70 km/ph on ballasted track with rail in a similar condition.

3.2 A review of noise reduction methods on light rail systems

Upon determining that traditional slab track with greater speeds resulted in higher sound pressure levels feasible noise reduction approaches were investigated.

There are a number of noise mitigation options open to railways. The principal options include the following (i) Traffic planning i.e. speed restrictions (ii) Rail maintenance through rail grinding (iii) Noise barriers and (iv) Technical ‘at-source’ options, e.g. continuously welded rail, wheel and rail dampers [8]. The principal options are considered in Sections 3.2.1-3.2.4 below.

3.2.1 Traffic planning

Train speed reduction is not an effective means of reducing noise emissions. Significant reductions in noise emissions can only be achieved by large reductions in train speeds which is not compatible with a commercially competitive railway [9]. The local benefit of reducing noise levels by reducing the operational speeds of vehicles must be weighed against the potential delays and disturbance of rail passengers i.e. the need of few versus the need of many [10].

3.2.2 Rail maintenance through grinding

Rail roughness can have a substantial influence on rolling noise. According to Hardy and Jones [11] once a rail has reached an unacceptable level of roughness the remedy is to grind its surface. A range of grinding trains and techniques are available, all of which remove a certain amount of material by means of sets of rotating or oscillating grinding stones [12].

The author has previously reported that reductions of up to 12dB ($L_{Aeq,Tp}$) can be achieved on heavily corrugated traditional slab track on the Luas network [13]. However, in 2011 RPA were separately investigating the acoustic benefits of rail grinding and thus, rail grinding as a noise reduction method was not considered further in this project.

3.2.3 Noise barriers

Noise barriers are the most commonly employed noise abatement measure. They are applied on a wide scale on both existing and new railway lines [14]. Noise barriers are a tested means of noise control and reductions achieved are a function of barrier height, insulation and absorption along with distance to source and receiver [15]. Reductions of up to 10dB can be achieved depending on quality of installation and maintenance. Noise barriers do have disadvantages and as concluded by the STAIRRS project, noise barriers, in particular high barriers, have low-cost effectiveness [16]. Barriers can also have a negative visual impact. Therefore, noise barriers were not considered further in this project.

3.2.4 Technical 'At-Source' options

Continuously Welded Rail (CWR) are rails that are welded together thus ensuring that there are no rail joints to produce impact noise. Noise from jointed rail may be as much as 5dB higher than from CWR [17]. CWR requires less maintenance than jointed rail, so that the benefits of low noise are easily obtained. However all rails on the Luas system are CWR and thus this option was discounted.

Other technical at source options include wheel dampers and bogie shrouds. The Silent Freight project showed that wheel dampers can produce a reduction of between 7-9dBA [16]. However previous research undertaken by the author, unreported to date, has demonstrated that for Dublin's light rail system track noise (L_{Track}) is the dominant contribution to total rolling noise (L_{Total}) with wheel noise (L_{Wheel}) playing a more insignificant role. Furthermore, a review of acoustic data for attenuation provided by bogie shrouds installed on the Bordeaux Citadis trams identified negligible reductions of approximately 1dB. Therefore, wheel and bogie related treatments were discounted.

Thompson et al. [18] report that a promising means to reduce the component of railway rolling noise radiated by the track is to increase the damping of the rail. Rail dampers are pre-shaped elements of elastic material to be fixed to both rail sides. They dampen the vibrations of the rails when a train passes over them, thus reducing the noise. To be effective, rail dampers must add considerable mass to the rails [7]. Thompson et al. [18] reported a reduction of up to 6dB following installation of tuned rail dampers on a section of test ballasted track. Rail dampers can be part of an effective local action plan option where track contribution dominates rolling noise. However, rail dampers may not provide the same noise reduction for all trains and are not as effective on smooth rails as corrugated rails [18].

3.3 Selection of noise reduction systems

Following review of acoustic data and consideration of Technical 'at source' options along with the track type under investigation, it was decided that one noise reduction method should aim to reduce slab reflections whilst the second noise reduction system should aim to reduce rail vibrations.

The system chosen to reduce slab reflections was bespoke absorbing rubber infill panels/mats. A large Irish rubber recycling company (Crumb Rubber Ireland Ltd.), which produces rubber mats for different purposes e.g. playing surfaces, was requested to develop and propose a prototype of a rubber mat which could prove efficient from a noise reduction point of view. Cost and visual appearance were a significant factor in selecting the absorbing rubber mats over other systems.

The system chosen to reduce rail vibrations were Tata Corus rail dampers. This system is similar to that investigated by Thompson et al. [18], however dampers installed on Luas were not tuned. The reported success of the rail dampers on systems throughout Europe was a determining factor in selecting this system over other similar systems.

3.4 Installation of noise reduction systems

In June 2011 both the bespoke absorbing rubber mats and rail dampers were installed by Contractors along a fast section of slab track (70km/h) between two stops on the Luas Green Line.

Absorbing rubber mats were installed under the rails covering the full slab width over a 100m length on both the inbound and outbound track. The rail dampers were installed over a 100m length on the inbound track. There was a gap of 100m between the two systems on the inbound track to ensure noise measurements undertaken on each system were not affected by the other system. Photographs 2-3 show the installed systems on the traditional slab track.

Photograph 2. Absorbing rubber mats.

Photograph 3: Rail dampers.

3.5 Measurement campaign

To determine the reduction or otherwise in noise emissions, attended tram specific noise monitoring was undertaken at four Noise Monitoring Locations (NMLs); NML-A and NML-B were located adjacent to the absorbing rubber mats; whilst NML-C and NML-D were located adjacent to the rail dampers. Monitoring was undertaken adjacent to the two systems prior to installation (baseline) and post-installation. Control locations were also established where no rail dampers or rubber mats had been installed. Three baseline events were undertaken over a six week period prior to installation. Three post-installation surveys were undertaken over a six week period following installation.

All measurements were attended and undertaken in general accordance with ISO 3095:2005 [5] and the RPA monitoring procedure [4]. The acoustic parameters measured during each monitoring event were (i) $L_{Aeq,Tp}$ (ii) L_{AE} (iii) L_{AFMax} and (iv) linear one third octave frequencies (20Hz – 20kHz). Three tram passes were monitored at each location during each of the three baseline and post-installation measurement events. In addition, the following supportive information was noted during each tram by pass (i) tram direction (ii) tram number (iii) estimated tram speed (iv) exposure time and (v) any screeching or braking of the tram. During the majority of surveys, a number of events were dismissed due to obvious contamination e.g. two trams approaching at the same time. Noise measurements were made using Class 1 data logging integrating sound level metes fitted with 1:1 and 1:3 Octave Band Filters. A stop watch was used to record the speed of all trams and an anemometer was utilized to measure wind speeds.

4. Results

This section presents the measurement results recorded at the NMLs. The mean logarithmic sound pressure levels for the baseline and post-installation measurement events. Section 4.1 presents the results of the monitoring events for the NMLs adjacent to the absorbing rubber mats. Section 4.2 presents the results of the monitoring events for the NMLs adjacent to the rails dampers.

4.1 Absorbing rubber mats

4.1.1 Trams travelling Outbound

Table I presents the results of baseline and post installation sound pressure levels measured at NML-A for trams travelling outbound. At NML A-Outbound, the logarithmic average L_{AE} and $L_{Aeq,Tp}$ levels reduced by 2.4dBA and 3.3dBA respectively with L_{AFMax} levels reducing by 2.1dBA.

Table II presents the results of baseline and post installation sound pressure levels measured at NML-B for trams travelling outbound. More significant reductions were observed at NML B-Outbound. The logarithmic average for L_{AE} levels recorded reduced by 4.0dBA post installation. Logarithmic averages for $L_{Aeq, Tp}$ and L_{AFMax} levels recorded reduced by 4.3dBA and 4.8dBA respectively post installation.

Table I. NML-A Outbound.

Noise index	*Baseline*	*Post Installation*	*Log. Aver. Difference*
L_{AE}	75.5	73.1	-2.4
$L_{Aeq,Tp}$	62.9	59.6	-3.3
L_{AFMax}	70.0	67.9	-2.1

Table II. NML-B Outbound.

Noise index	*Baseline*	*Post Installation*	*Log. Aver. Difference*
L_{AE}	74.5	70.5	-4.0
$L_{Aeq,Tp}$	62.5	58.2	-4.3
L_{AFMax}	70.1	65.3	-4.8

Figure 1 illustrates the average one third octave band analysis for the three baseline events and the three post absorbing mat installation events at NML-B Outbound. The acoustic attenuation provided by the absorbing mats is evident particularly in frequencies greater than 400Hz. Reductions achieved between 315Hz-20kHz range from 0.3dB-7.2dB. The reduction of 7.2dB was achieved in the 613Hz band. For NMLA-Outbound a similar trend was evident with reductions ranging from 0.2dB-5.6dB between 315Hz-20kHz. The reduction of 5.6dB was achieved in the 1kHz band. Results in graphic form for NML-A Outbound are not reported in this paper.

4.1.2 Trams travelling Inbound

Table III presents the results of baseline and post installation sound pressure levels measured at NML-A for trams travelling inbound. The logarithmic average L_{AE} and $L_{Aeq,Tp}$ levels reduced by 3.8dBA and 4.8dBA respectively with L_{AFMax} levels reducing by 3.9dBA.

Table IV presents the results of baseline and post installation sound pressure levels measured at NML-B for trams travelling outbound. Reductions at NML-B for trams travelling inbound were lower than for trams travelling outbound. The logarithmic average for L_{AE} levels recorded decreased by 2.2dBA post installation. Log arithmetic averages for $L_{Aeq,\,T}$ and L_{AFMax} levels recorded also decreased by 1.9dBA and 1.9dBA respectively post installation.

A detailed analysis of the one third octave band analysis for both NML-A Inbound and NML-B Inbound (not presented in this paper) identified reductions primarily between 315Hz-20kHz. A reduction of 5.2dB was achieved at 2kHz for NML-A Inbound. A reduction of 3.2dB was achieved at 2.5kHz for NML-B Inbound.

Table III. NML-A Inbound.

Noise index	*Baseline*	*Post Installation*	*Log. Aver. Difference*
L_{AE}	74.9	71.1	-3.8
$L_{Aeq,Tp}$	63.1	58.3	-4.8
L_{AFMax}	69.6	65.7	-3.9

Table IV. NML-B Inbound.

Noise index	*Baseline*	*Post Installation*	*Log. Aver. Difference*
L_{AE}	73.6	71.4	-2.2
$L_{Aeq,Tp}$	62.3	60.4	-1.9
L_{AFMax}	68.8	66.9	-1.9

NML-Control 1 was located at the edge of the installed rubber mats on both the inbound and outbound tracks and acted as a control location. Reductions achieved at this location for trams travelling in each direction were less than 1dBA following installation.

4.2 Rail dampers

Table V presents the results of baseline and post installation sound pressure levels measured at NML-C for trams travelling inbound. At NML-C, the logarithmic average L_{AE} and $L_{Aeq,Tp}$ levels reduced by 2.6dBA and 2.4dBA respectively with L_{AFMax} levels reducing by 2.6dBA.

Table VI presents the results of baseline and post installation sound pressure levels measured at NML-D for trams travelling inbound. The logarithmic average for L_{AE} levels recorded reduced by 3.5dBA post installation. Logarithmic averages for $L_{Aeq,\,Tp}$ and L_{AFMax} levels recorded reduced by 3.9dBA and 3.6dBA respectively post installation. From Table V and Table VI it may be observed that for trams travelling inbound, the rail dampers reduced noise levels associated with tram pass-bys. The highest reductions for rail dampers were identified at NML-D.

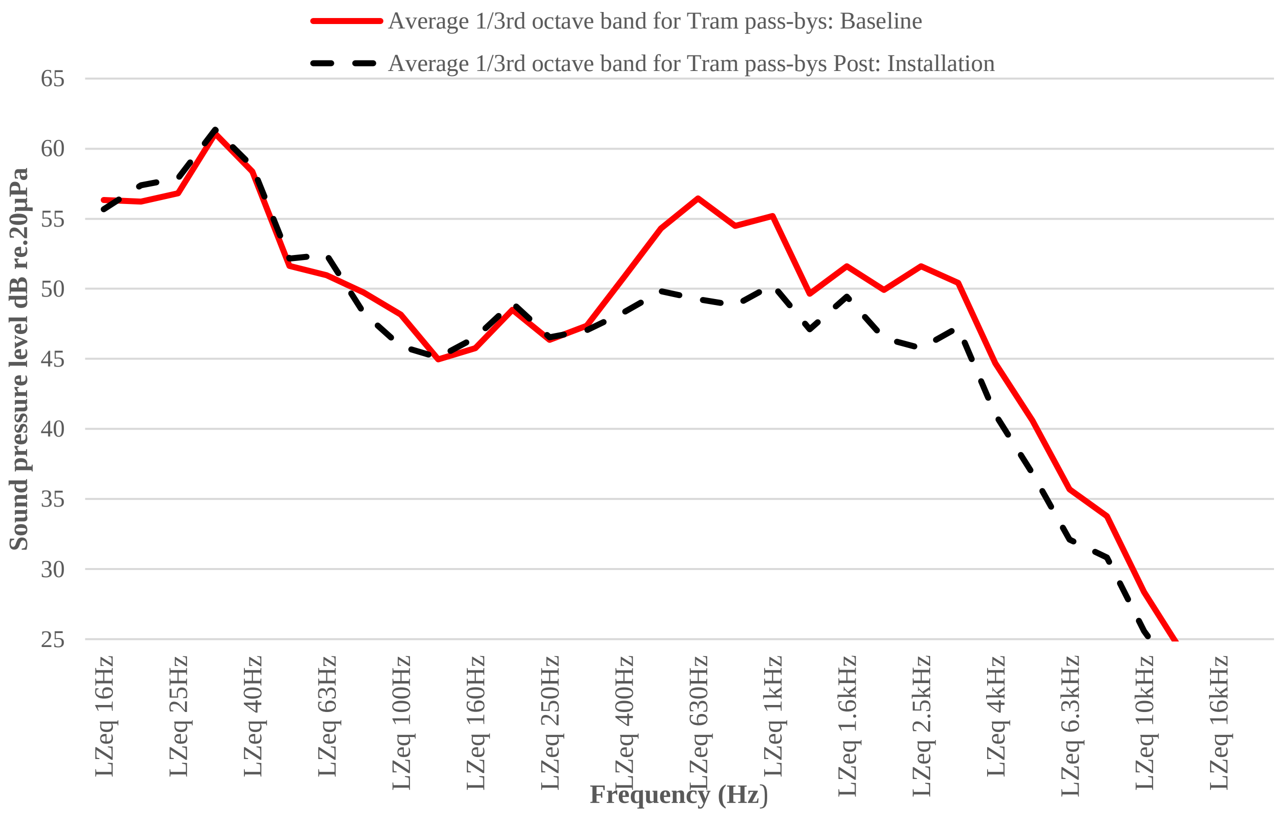

Figure 1. Baseline and post mat installation averaged 1/3rd octave band analysis at NML-B Outbound

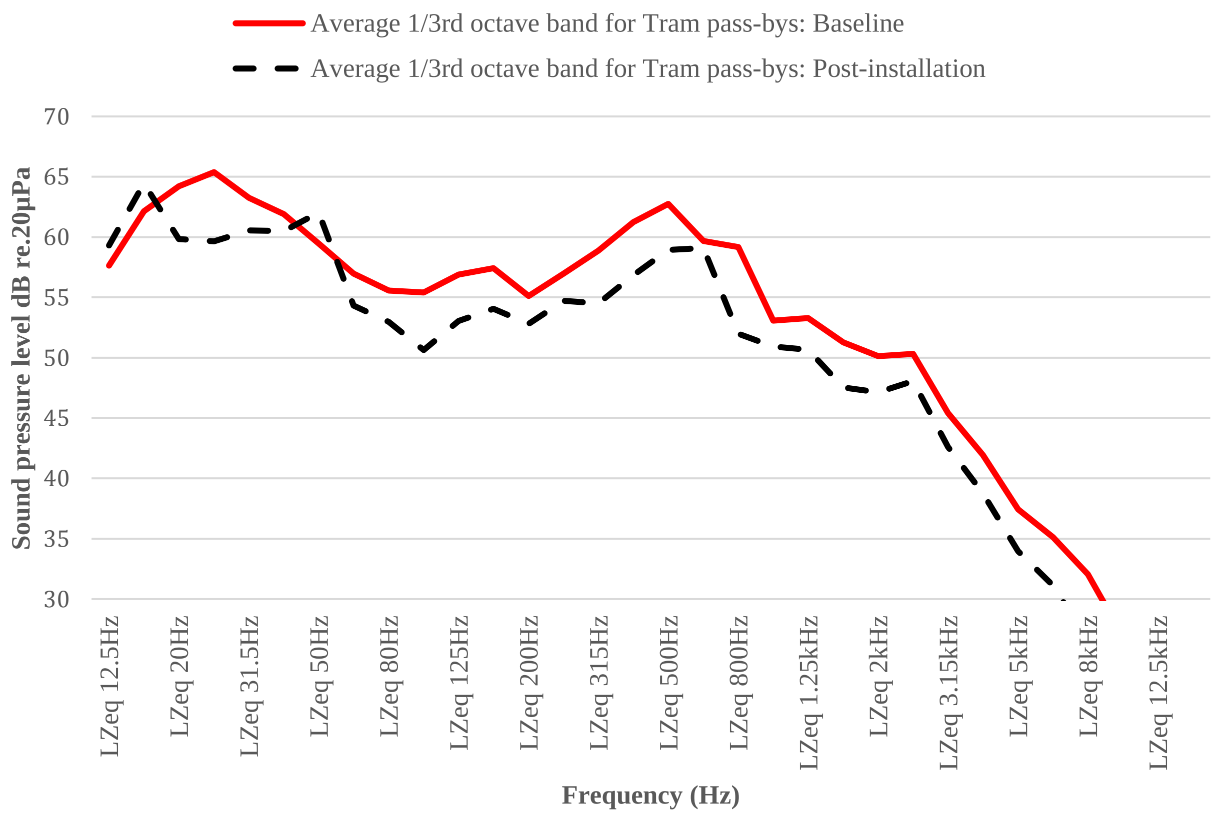

Figure 2. Baseline and post mat installation averaged 1/3rd octave band analysis at NML-D Inbound

Table V. NML-C Inbound.

Noise index	*Base*	*Post*	*Log. Aver. Difference*
L_{AE}	78.8	76.2	-2.6
$L_{Aeq,Tp}$	66.5	64.1	-2.4
L_{AFMax}	74.5	71.9	-2.6

Table VI. NML-D Inbound.

Noise index	*Base*	*Post*	*Log. Aver. Difference*
L_{AE}	77.3	73.7	-3.5
$L_{Aeq,Tp}$	66.8	62.9	-3.9
L_{AFMax}	72.4	68.8	-3.6

Figure 4 illustrates the average one third octave band analysis for the three baseline events and the three post rail damper installation events at NML-D Inbound. The acoustic attenuation provided by the rail dampers is evident particularly in frequencies greater than 63Hz. Reductions achieved between 63Hz-20kHz range from 0.6dB-7.2dB. The reduction of 7.2dB was achieved in the 800Hz band. For NML-C Inbound reductions ranging from 0.2dB-7.6dB between 250Hz-3.15kHz. The reduction of 7.6dB was achieved in the 800Hz band. Results in graphic form for NML-C Inbound are not reported in this paper.

Rail dampers were not installed on the outbound track and thus it would have been expected prior to commencement of the surveys that noise levels recorded for outbound tram movements at NML-C, and NML-D would remain relatively constant. Measured levels at these locations for trams travelling outbound were within 1dBA when comparing pre- and post-installation results.

5. Discussion

Both the absorbing rubber mats and rail dampers installed on a section of the Luas network resulted in reductions in tram pass by noise emissions. Slightly greater reductions were achieved by the absorbing mats than the rail dampers. The absorbing mats resulted in reductions of up to 4.8dB ($L_{Aeq,Tp}$) at adjacent NMLs. The rail dampers resulted in reductions of up to 3.9dB ($L_{Aeq,Tp}$) at adjacent NMLs.

The literature identifies that the significant factor in slab track being louder than ballasted track is the use of softer rail fasteners to provide vertical compliance similar to ballasted track [7]. A less significant element to the 'noisier' slab track is the decreased sound adsorption qualities i.e. more reflective nature of the track type. However, for the trial conducted on sections of the Luas network, both factors i.e. softer rail fasteners and reflective nature had an equal effect.

The reductions achieved following installation of the rail dampers were below reductions achieved on other rail networks using dampers. In particular, the reductions achieved by the rail dampers are below levels achieved by Thompson et al. [18] who had reported a reduction of up to 6dB following installation of tuned rail dampers on a section of test track. However, it should be reiterated that rail dampers installed on Luas were not tuned.

When considering changes in noise levels experienced by the public, a change of 10dBA represents an approximate doubling in loudness. Similarly, a decrease in noise represents an approximate a halving in loudness. A difference of 3dBA between the levels of two sounds separated by a time interval is generally considered to be the minimum perceptible difference. The results from the two systems above may therefore be considered to be perceptible to the human ear.

The frequency content associated with tram pass bys in the sections with the systems installed has changed. This is demonstrated by a review of the one third octave band data presented in Figure 1 and Figure 2. In addition, a change in character of the noise emissions was subjectively noted during the measurement surveys.

6. Recommendations for future research

Further research into the area of track noise mitigation and the systems trialled, as detailed in this paper, is planned by TII. Set out below are recommendations for future research:

1) The rail dampers tested for this study were not tuned. By tuning the rail dampers to 'Luas' specific frequencies encountered, greater reductions may be achieved;
2) Greater reductions may have been achieved if the two systems were used in tandem. Alternatively, the use of either system in combination with rail grinding or low trackside noise barriers, for example, could be undertaken to identify if there is an ideal coupling of the technologies; and
3) This paper has investigated reductions achieved on slab track only following the

installation of the two systems. Ballasted track should be investigated using these systems.

7. Conclusions

Light rail systems are a sustainable and climate friendly means of transport, reducing the number of cars on the road, thus reducing carbon dioxide emissions. Rail transport can, however, result in environmental pollution with noise, perhaps, the most commonly cited pollutant.

The research detailed within this paper will aid TII in ensuring ongoing compliance with noise limits. Furthermore the findings of this research will be used to inform mitigation measures to be selected for future Luas lines.

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