WAYSIDE TOP OF RAIL FRICTION CONTROL: AN EMBEDDED TRACK SOLUTION IN A HIGH DENSITY TRAM NETWORK

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SUMMARY

This paper reviews details associated with the first embedded track wayside Top-of-Rail (TOR) equipment installation completed in Australia. This project, managed by tram operator Keolis Downer, has significantly reduced a severe wheel squeal noise problem on St. Kilda Road, Melbourne, Victoria. Given TOR friction modifier (FM) use for noise abatement was new to Yarra Trams, a comprehensive trial evaluating impacts to vehicle braking/traction and effectiveness as a noise solution was conducted with success, confirming the proposed embedded track wayside solution was safe and viable for ongoing Melbourne tram network use. Noise monitoring results have confirmed the applied TOR technology to be efficacious, with a significant reduction in wheel squeal events following installation of the wayside equipment, combined with mostly positive feedback from residents in the Domain precinct. Further work evaluating possible additional TOR friction control technology benefits mitigating rail wear and corrugation growth are planned for investigation.

1. INTRODUCTION

The Yarra Trams franchise is the world's largest operational tram network with 250km of double track that is currently operated by Keolis Downer. Trams are known to be an iconic feature of Melbourne and are the primary mode of public transport for inner suburban residents. 75% of the tram network shares operating space with other modes of road vehicle traffic.

St. Kilda Road is the busiest tram corridor in the world, with headways being almost every minute during peak hours. To ease congestion and improve access to this area, a new metro train station will be built underground in the high-density living precinct of this Domain.

Following completion of a temporary tram track realignment as part of the project staging works, some trams were observed to exhibit prominent wheel squeal when traversing the new track construction, resulting in numerous complaints from local adjacent residents.

Several methods were tested at the problem location for noise attenuation, with the use of a water-based TOR FM proven by far to be the most effective solution.

This paper outlines the benefits of TOR friction control technology for noise abatement, and the implementation of an embedded track TOR system automatically dispensing the FM product during tram operation. Furthermore, noise reduction results are presented in detail as well as lessons learnt for future installations.

2. BACKGROUND

The temporary realignment of the central reserve tram track, road and bicycle lanes along St. Kilda Road between Toorak Road West and Dorcas Street, occurred in April 2018 (Figure 1). These are staging works required to establish the construction site and commence building the future station underneath the road.

Further changes to the alignment will occur again in October 2019 as part of the ongoing construction works and then reinstated to the legacy alignment after 2021. Trams and other traffic were diverted around the work site, whilst still maintaining access along this major transportation corridor.

The scope of tram works during first stage construction included installation of over 800 metres of track including turnouts, crossover and diamond crossing infrastructure (Figure 2).

Installation of tram poles, overhead fitting and wires was also completed, along with a new temporary tram stop constructed at St. Kilda

Road and Park Street due to required closure of the existing Domain Interchange tram stop.

Figure 1. Domain Precinct Temporary Tram Works

The revised track alignment contains several curves with radii ranging from a sharp 22 metres at Park Street intersection to a shallower 90 metres on the mainline along St. Kilda Road (Figure 2). These curves were introduced to accommodate site constraints controlled by the underground station box excavation and allowed for a 25km/hr design speed, adopted for the segregated and reserve running double track. This speed is a reduction from the prior 60km/hr limit for this area.

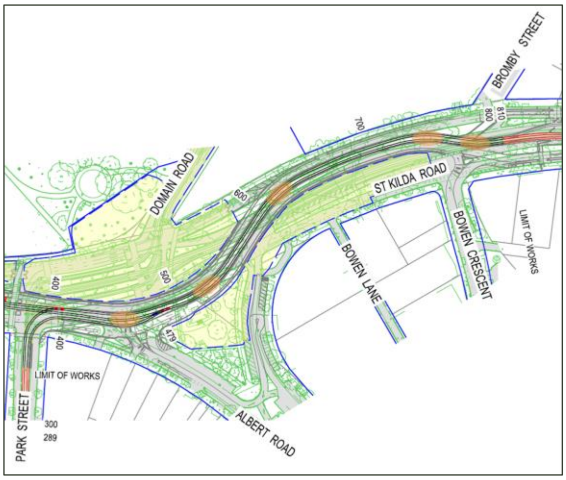

Figure 2. Domain Precinct Tram Track Realignment

The track structure uses Ri57A grooved rail fastened using Pandrol E-clips on dual block concrete sleepers laid at standard gauge (1435mm). This is embedded in a special 50MPa tramway concrete slab foundation with compacted crushed rock and bitumen surface (Figure 3). Head hardened rail was nominated for the tight radius curves at the Park Street intersection with standard carbon rail nominated for all other sections.

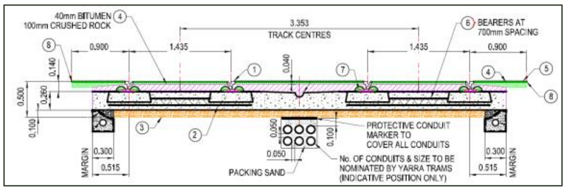

Figure 3. Bitumen Surface / Crushed Rock Track Structure

A mixed range of tram types operate via this alignment (Figure 4). This includes the high floor Comeng fleets (A, B and Z Class) and low floor Siemens fleets (D Class). A total of eight tram routes directly operate along St. Kilda Road including Routes 3/3a, 5, 6, 16, 64, 67 and 72, with Route 58 detouring at Park Street on the third track section.

Figure 4. Top: B Class Tram (High Floor),
Bottom: D Class Tram (Low Floor)

Following tram service resumption along the new track realignment in late April 2018, feedback was received from adjacent residents regarding the unusual introduction of prominent tram noise, specifically the presence of atypical high pitch wheel squeal events.

These events were predominately occurring within the longer and sharper 80 to 90 metre radius curves along St. Kilda Road for both the Inbound (Citybound) and Outbound (Southbound) tracks. Sections of track where wheel squeal occurred are highlighted in orange (Figure 2). The noise events were found to be not linked to a specific tram type or number.

Several possible remediation measures were initially proposed and trialled to address the noted noise issue with limited or no success. These included:

i. Water spray cart to temporarily wet and lubricate the tracks.

ii. Crack sealant application on either side of the rail to introduce flexibility into the embedded track structure.

iii. Rail grinding to restore the rail head to the target design profile (Figure 5).

Figure 5. Rail Grinder Truck on St. Kilda Road

3. TOR FRICTION CONTROL OVERVIEW

3.1 Wheel Squeal Overview

There are several literatures on the mechanism of wheel squeal [1-11]. In essence, wheel squeal primarily arises from high lateral creepage experienced by vehicle wheels when navigating sharp radius curves. Due to the rigid design of a railway bogie, the wheels cannot alight themselves perfectly along the curve direction and tend to slide laterally on the tight curves. The lateral friction force generated at the wheel-rail interface can lead to an unstable wheel response in the form of stick-slip oscillations (or more accurately, roll-slip oscillations) causing noise (squeal) radiation.

The resultant rapid frequency of oscillation subsequently generates extreme noise emissions within a typical frequency range of 1000-5000Hz. This instability in wheel-rail contact behaviour will also precipitate short pitch corrugation growth [12]. These problems are common in shaper radius curves, especially locations where gauge face (GF) and /or TOR friction control products are not applied.

3.2 TOR Friction Control as a Solution

TOR friction control technology has been successfully deployed by numerous transit systems globally to mitigate wheel squeal and other track-based problem noise conditions (Table 1). Additional typical noise conditions successfully reduced are:

i. Rolling noise from wheel-rail surface roughness: 30-2500Hz.

ii. Wheel flanging noise: 5000-10000Hz.

TOR friction control products with positive friction characteristics, such as the LB Foster KELTRACK® Trackside Transit (KTT) product used for this project, have been proven to reduce stick-slip oscillations by allowing low rail wheels to roll more freely. This elimination of negative friction behaviour at the wheel-rail interface produces notable reductions in high-frequency wheel squeal noise and corrugation growth [13]. Based on these considerations, TOR friction control using a FM product with positive friction characteristics was subsequently viewed as a viable option for further investigation by Yarra Trams to mitigate noise levels at the St. Kilda Road location during tram passage.

Location	Track Type	Curve Radius (m)	Noise Reduction after TOR Applied (dBA)
A	Ballasted	436mR	7.2 dBA (Leq)
B	Ballasted	150mR	20.3 dBA (Leq)
C	Concrete Slab	1000mR	7.0 dBA (Leq)
D	Ballasted	270mR	7-9 dBA (Leq)
E	Embedded	25mR	18.0 dBA (Leq)
F	Ballasted	113mR	12.1 dBA (Leq)
G	Concrete Slab	38mR	15.0 dBA (Leq)
H	Ballasted	30mR	10.0 dBA (Leq)
I	Ballasted	180mR	8-22 dBA (LLFMAX)
J	Embedded	19mR	11.9 dBA (Leq)
K	Concrete Slab	125mR	10.4 dBA (Leq)
L	Ballasted	195mR	11.3 - 18.0 dBA (Leq)

Table 1. TOR Friction Control Noise Mitigation Trial Results

3.3 Ancillary TOR Friction Control Benefits

The introduction of KTT to the low rail TOR surface wheel contact band additionally controls friction at an intermediate co-efficient of friction level (CoF) at the wheel-rail interface, thereby ensuring no adverse impacts to vehicle braking or traction.

Friction modifier usage also generates positive steering effects in the form of reduced wheel angle-of-attack (AoA) contact dynamics against curve high rails, thereby reducing lateral track loading under passing trains. This reduction in dynamic lateral (i.e. gauge widening) force additionally reduces extreme wheel contact stress against the high rail gauge face and low rail TOR surface in curves, which can precipitate additional forms of rolling contact fatigue if left unresolved (e.g. head checking, shelling, spalling, etc.).

In addition to noise abatement, Yarra Trams therefore anticipates the introduction of TOR friction control to the St. Kilda Road area will produce ancillary benefits in the form of reduced rail wear and rolling contact fatigue (RCF) growth for targeted curves. Evaluation of these parameters will be performed moving forward as means to more quantitatively determining the ‘complete package’ benefits of TOR friction control incorporation.

4. Initial TOR FM Manual Application Trials

In consideration of the global body of technical trial data supporting TOR friction control as an effective solution for wheel squeal mitigation, Yarra Trams consequently decided to investigate this technology following the noted lack of success achieved using other remediation measures.

Noting that TOR friction control using a water-based FM product (i.e. KTT) had never previously been trialled or commercially used in the State of Victoria, a comprehensive type approval process was completed by Yarra Trams to confirm suitability of the technology for use. This approach reflected a lower cost evaluation exercise versus the perceived risk of proceeding directly to more costly and complex wayside equipment solutions.

4.1 Tram Braking and Traction Testing

Firstly, the impact of FM product application on tram braking and traction required assessment. Clearly understanding FM impacts to stopping distances specific to Yarra Trams operating conditions was imperative to confirm no new risks would be introduced as a result of TOR application, as well as maintaining zero harm to safety of tram operations.

Two different tram types (B and D class) were selected for braking trials performed at New Preston Depot under the following conditions:

i. Dry conditions with no FM product.

ii. Dry conditions with FM product applied.

iii. With water sprayed on top of the applied FM product to mimic heavy rainfall conditions.

Several test runs were conducted on the straight depot test road at different tram speeds (Figure 6).

Figure 6. New Preston Depot Test Site for Braking Trials

The FM product was initially applied in 15mm diameter drops along the running surface of both rails at three metre intervals for a distance of 50 metres (Figure 7). This is to ensure all wheels of the tram were covered by the FM product throughout the braking zone. Using a fine paint roller, the product was then uniformly spread across the width of the TOR wheel contact area in the tram running direction. These tests confirmed no significant increase in stopping distance or adverse effects to tram tractive effort following FM application. This information was used to support the type approval submission.

Figure 7. FM Manual Application Method

4.2 Noise Abatement Testing

A preliminary wheel squeal reduction effectiveness test was then completed during non-operating hours (01:00-05:00) following the tram braking and traction trial. A single D class tram observed to exhibit wheel squeal during prior baseline noise monitoring was used for this test. An inbound reverse curve track section located between Park Street and Bromby Street (90 metre left-hand curve and 80 metre right-hand curve) was selected as the trial location.

The KTT water-based FM product was manually applied using the same paint roller application methodology incorporated for the braking and traction trial. Application began approximately 10 metres before the start of the first curve and continued until the end of the second curve. The same three test conditions as the braking and traction trial were evaluated (Dry conditions, FM product only and FM product with water). No FM product was applied to the adjacent outbound track to accommodate supplemental comparative evaluation of non-TOR versus TOR test conditions.

Introduction of the FM product produced an immediate effect, with the treated curves demonstrating no wheel squeal events during the FM product only phase. The FM product with water test also produced similar favourable results, confirming suitable resiliency of the applied FM product under heavy water-washing (i.e. rainfall) conditions (See Section 6 - Noise Reduction Results). The manual trial additionally confirmed only a small amount of FM product is required to achieve effective noise abatement.

The opportunities and risks associated with ongoing use of TOR friction control technology for noise abatement were comprehensively reviewed after the success of the manual FM application trial. Use of an automated application system was subsequently agreed to be the preferred approach moving forward versus continuing with a more labour intensive, higher risk manual application process. Two automated options were initially considered: (i) Onboard and (ii) Wayside systems. Onboard system use was subsequently deemed not feasible due to the noted tram fleet variability requiring alternate TOR system designs for incorporation. Also, since the current noise problem was localised to a specific track section, it made sense to incorporate a wayside (i.e. trackside) equipment solution providing similar localized TOR friction control coverage.

5. EMBEDDED TRACK TOR SOLUTION

5.1 TOR Equipment Selection Considerations

Any site planned for treatment with TOR FM always contains unique operating, environmental, and safety conditions that require comprehensive evaluation to ensure the proposed solution achieves optimized performance effectiveness consistently producing expected results. When identifying an appropriate TOR FM distribution system solution for the targeted St. Kilda Road section, the following key elements required consideration:

i. The reverse curve section targeted for both the Inbound and Outbound tracks required use of a wayside distribution system versus more complex and expensive vehicle-mounted TOR application solutions typically used to achieve broader network coverage extent.

ii. The high road vehicle, bicycle, and pedestrian traffic densities present in the St. Kilda Road area mandated the need for a non-obtrusive, effectively sized trackside system that would safely and aesthetically blend into the neighbouring environment.

iii. The existing embedded design of the track structure in this area (bitumen and crushed rock-concrete slab track structure) required use of TOR FM distribution hardware that could similarly be embedded to maintain track structure design integrity.

iv. The proposed system must be low maintenance to minimize the number of site visits required to service the equipment in the noted high traffic density operating corridor.

v. The equipment design must contain consistent and precise application rate controllability to ensure zero impacts to tram braking and tractive effort.

5.2 TOR Equipment Overview

In consideration of the items discussed in Section 4.1, the wayside TOR distribution system selected for use was a LB Foster PROTECTOR® IV (PIV) DC solar-electric TOR unit (Figure 8). The primary system operating features for this equipment type are:

- 95 litres FM product tank capacity.
- Separate compartment containing electrical and pump/motor components.
- 4ea. TOR distribution bars - 2ea. per rail side (installed on field side).
- Solar-DC powered (80W solar panel c/w 12amp voltage regulator).
- Field side-mounted Tram sensor - Triggers one FM discharge (**X** seconds) per Tram.
- Parallel shaft, permanent magnet gear motor - 12V DC, 14A @ full load.
- Dual chamber gear pump - One main feed line per rail side.
- Remote Performance Monitoring hardware for offsite system status health checks.

Figure 8. LB Foster PROTECTOR® IV TOR Applicator

The selected equipment type was supplied with specialized enclosures in consideration of the targeted embedded track operating environment. These enclosures provide protective shrouding encapsulating the TOR distribution bars (4 enclosures), Tram sensor (1 enclosure) and between-rails components (1 enclosure) directing FM product to both rails. The design of the enclosures is such that their interior dimensions provide sufficient working area to access applicator components when performing equipment inspection and maintenance tasks.

The enclosures are supplied with robust plate steel covers (20mm thick) complying to Australia Standard AS 3996-2006 - 'Access covers and grates' - Load Classification 'D' to ensure optimized safety for area vehicle, bicycle, and pedestrian traffic. The finalized custom design of the Yarra Trams embedded track wayside TOR equipment solution was completed by LB Foster (Figure 9).

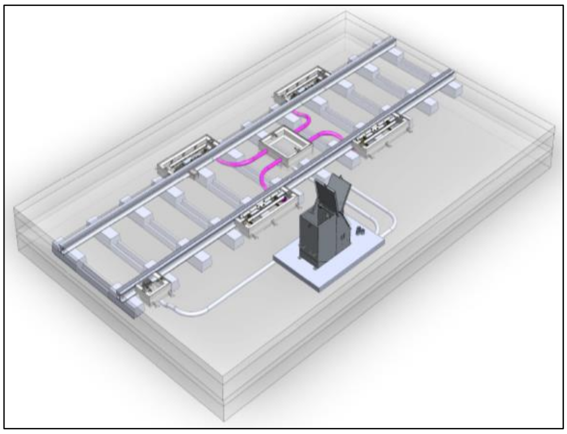

Figure 9. Finalized Wayside TOR Equipment Design

The finished Inbound track TOR applicator site shown in Figure 10 demonstrates the seamless integration of this equipment solution into the surrounding tram operating environment, and the non-obtrusive symmetry with area vehicle and pedestrian traffic.

Figure 10. St. Kilda Road Inbound Track TOR Site

The incorporated LB Foster embedded track design was an applied variation of an existing wayside gauge face (GF) design previously incorporated for other transit railway customers globally. Like the Yarra Trams project, some amount of customized design work is typically required for each location selected for a wayside GF or TOR embedded track solution in order to accommodate the following unique considerations for each customer site:

i. **Track structure design** (i.e. track foundation, sleeper type and spacing, rail and fastener types, etc.) influencing:
   - Allowable excavation depths
   - Routing of protective conduit for FM product distribution hoses and Tram (or Wheel) sensor cable
   - Location of TOR distribution bars and Tram (or Wheel) sensor
   - Main applicator tank location containing system electronics and product reservoir

ii. **Vehicle wheel circumference** - TOR distribution bars must be spaced in consideration of the distance required to complete one full wheel rotation for targeted vehicle types. Subject to track structure design considerations, the TOR bars are then spaced to maximize the extent of FM product conditioning applied to the "naked" wheel tread surface of passing vehicles.

iii. **Applicator bar type** (i.e. are new enclosure designs required for different bar types?).

iv. **Regional, State and National construction standards** - Governing material specifications for the wayside application equipment and protective enclosures planned for installation.

v. **Other conflicting area infrastructure or operating concerns** (i.e. type and extent of vehicle / bicycle / pedestrian traffic, Existing water mains, electric / fibre-optic cables, etc. within the planned construction corridor).

For the Yarra Trams project, approximately 120 hours of new design and Finite Element Analysis (FEA) work was required in consideration of:

i. The TOR distribution bar recommended for use had never previously been deployed for an embedded track project, thereby requiring design of new enclosures suitable for this bar type.

ii. Enclosure design compliance required to Australia Standard AS 3996-2006 - 'Access covers and grates' - Load Classification 'D' specifications.

iii. The need to precisely identify TOR bar and enclosure locations accommodating the Yarra Trams track structure design in order to ensure optimized FM product conditioning of passing Tram wheels.

5.3 TOR Equipment Installation Details

Wayside TOR equipment installation work for the St. Kilda Road Inbound and Outbound track locations was performed in three main phases:

Phase 1: Pre-installation site mock-up review

Phase 2: Inbound track installation and equipment commissioning works

Phase 3: Outbound track installation and equipment commissioning works

Specific details for each of the three noted phases are as follows:

Phase 1: Pre-Installation Mock-up Review

Phase 1 work involved review of a mock wayside TOR equipment site at the Civil Works Contractor's yard three days prior to the planned commencement of actual construction and installation work (Figure 11). A skeletonized array of rail and dual block concrete sleepers was constructed as a duplication of the targeted Yarra Trams track structure to:

i. Confirm the as-designed locations for wayside TOR equipment enclosures and track-mounted hardware were suitable for use.

ii. Identify and correct any design issues noted for the TOR bar, Tram sensor and between-rails enclosures.

iii. Increase understanding of the track structure and wayside TOR equipment planned for installation amongst both the Civil Works and TOR Applicator vendor work crews to ensure optimized efficiency, effectiveness, and safety of work effort during actual track access.

iv. Complete partial assembly of the wayside TOR units to further improve efficiency of effort during track access work windows.

The Phase 1 mock-up work was invaluable as a knowledge-sharing exercise, allowing the Civil Works and TOR Applicator Vendor work crews to achieve a greater understanding of the planned installation work, the precise roles and responsibilities of each party, and areas of work task over-lap requiring a heightened diligence to site safety and situational awareness. This work further identified minor improvements required in the between-rails enclosure design to improve entry alignment of the main product supply hoses feeding FM product to the TOR distribution bars (i.e. minimized bending of hoses to ensure optimized FM product flow and consistency of volumetric output).

Figure 11. Pre-installation TOR equipment Mock-up Site

Phase 2: Inbound Track Installation and Commissioning

Phase 2 work involving installation and commissioning of the Inbound track TOR site was completed over a four-day period, primarily during the non-operating hours of the early morning maintenance work window interval scheduled daily by Yarra Trams. Work activities during this period were as follows:

Phase 2 - Day 1 (Figure 12)

- Cutting and removal of bitumen and crushed rock layer above the rails and sleepers in locations planned for TOR applicator bar, between-rails distribution hardware, and associated enclosure installations.
- Removal of concrete slab below the sleeper surface to accommodate routing of plastic conduit protecting the supply (long) and distribution (short) hoses transferring FM product from the main TOR unit tank to the TOR distribution bars.
- Cutting and removal of concrete, crushed rock and bitumen layers took longer than expected due to greater than anticipated track structure hardness challenges.

Figure 12. Day 1 of Inbound Track TOR unit installation

Phase 2 - Day 2 (Figure 13)

- Cutting and removal of remaining bitumen and crushed rock layer above the rails and sleepers covering planned installation locations for the Tram sensor and main TOR unit tank.
- Preliminary fitting of TOR bars to both rails to guide subsequent installation of the TOR bar enclosures. (**Note:** All TOR bars were later removed to accommodate pending concrete work restoring the track structure).
- The between-rails enclosure and protective conduit lines for the supply and distribution hoses are installed.

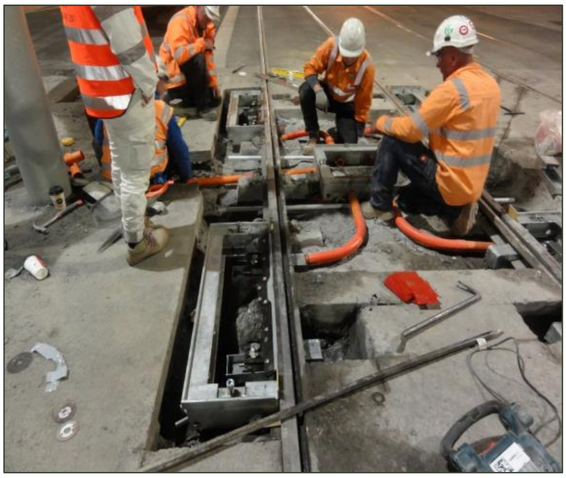

Figure 13. Day 2 of Inbound Track TOR unit installation

Phase 2 - Day 3 (Figure 14)

- Remaining sections of protective hose conduit are installed.
- Tram sensor enclosure and protective conduit for sensor cable are installed.
- A network of smaller diameter hose conduit is installed to provide water drainage for each enclosure, as directed to existing area of drainage infrastructure.
- Concrete works is completed for the entire installation area footprint, restoring the track structure to full depth concrete slab. This work included construction of a concrete pad for the main TOR unit tank.
- All TOR distribution bars, the Tram sensor, and between-rails hardware (i.e. hose manifolds) are re-installed following completion of the concrete works. All supply and distribution hoses and the Tram sensor cable are routed through applicable protective conduit paths and connected at entry and exit points (**Note:** The supply (long) feed hoses were not connected at the main tank end due to the TOR unit remaining to be placed onsite).

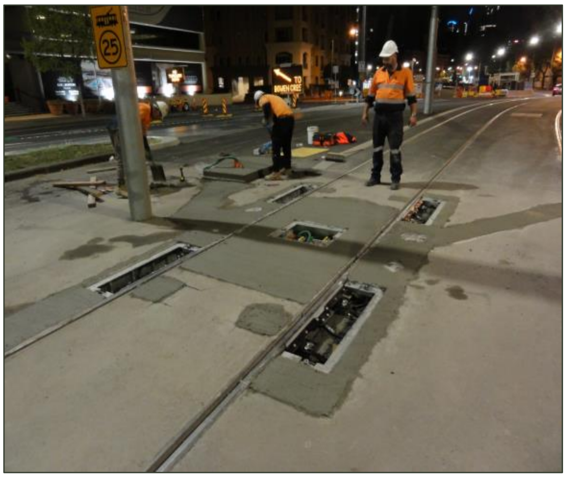

Figure 14. Day 3 of Inbound Track TOR unit installation

Phase 2 - Day 4 (Figure 15)

- Main TOR unit tank delivered to site and placed on the concrete pad.
- Tram sensor cable and main supply (long) FM product hoses are connected to the TOR tank. The finalized supply hose length for this site is 7 meters.
- The TOR unit is energized via connection to the in-tank battery and solar panel charging system. The solar panel for this site was fastened to the TOR unit tank lid at this location.
- TOR unit priming is completed to initiate FM output to each of the four distribution bars. An initial application rate setting producing a single discharge of FM product preceding each Tram pass is programmed into the TOR unit digital control box.
- Operating integrity of the TOR unit Remote Performance Monitoring (RPM) system is validated to conclude wayside TOR equipment installation and commissioning works for the Yarra Trams Inbound track location.

Figure 15. Day 4 of Inbound Track TOR unit installation

Phase 3: Outbound Track Installation and Commissioning

Phase 3 work involving the Outbound Track was essentially a repeat of Phase 2 work activities previously performed for the Inbound Track. Installation and commissioning works were completed over a similar four-day period. Some minor design changes were incorporated to accommodate differences in site conditions at the Outbound Track location as follows:

i. The TOR unit tank required placement at a location a longer distance away from the Southbound Track section containing the TOR distribution bars. Final supply hose length connecting the TOR bars to the TOR tank is approximately 18 metres.

This longer distance was required to accommodate alignment differences in the adjacent streets that did not provide an acceptable, safe Tram clearance envelope for closer proximity tank placement adjacent to the track as per LB foster custom design.

ii. Outbound Track supply hoses and the Tram sensor cable were routed from the track to the TOR unit via existing underground conduit infrastructure already in place to avoid significant additional site excavation work across three lanes on St. Kilda Road. The finalized Tram sensor cable length is around 20 metres.

iii. The solar panel used to charge the TOR unit was placed higher up on a nearby pole as a theft prevention measure in consideration of increased pedestrian traffic through this area.

The finished Outbound track TOR applicator site is shown in Figure 16. The TOR unit is not located within the track corridor and on the west side of this TOR site across the inbound track.

Figure 16. St. Kilda Road Outbound Track TOR Site

6. NOISE MONITORING RESULTS

6.1 Noise Data Collection Details and Methodology

Prior to introducing TOR friction control mitigation measures, wheel squeal was observed from each of the different Tram types (A, B, D, and Z classes) traversing the targeted St. Kilda Road Inbound and Outbound track sections between Toorak Road West and Park Street. Wayside noise measurements were collected at the same locations along St. Kilda Road (Figure 17) before and after each of the various noise mitigation methods evaluated, including but not limited to KTT dispensed by the embedded track TOR application system.

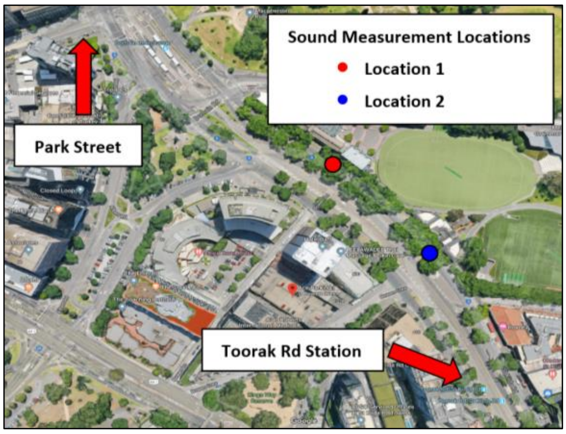

Figure 17. Sound Measurement locations for the Wayside Noise Monitoring

Note: Satellite image is outdated and does not reflect the Inbound and Outbound as-built track alignment in place during testing.

For each noise measurement data collection cycle, the following information was recorded:

- Tram type - A/Z, B or D class
- Direction of travel – Citybound (Inbound) or Southbound (Outbound)
- Weather conditions

Noise measurements were recorded in increments of 1 second to capture both Tram approach and pass-by. For this project, the following acoustic parameters were used when analyzing noise data:

1. $\mathbf{L_{AFmax}}$: The maximum A-weighted sound pressure level, measured on “fast” time-weighting

2. **$L_{Zeq,\,1s}$**: The un-weighted equivalent continuous sound pressure level at which the L_{AFmax} occurred

The following are additional considerations associated with noise data collected for this trial:

- Road traffic and other area noise sources (i.e. construction) were considered reasonably constant during monitoring periods. Only tram passes audible over these extraneous noise sources were used for analysis.
- Concurrent tram pass-bys on both tracks were also not included since the recorded sound could not be assigned to a specific tram.
- Tram types 'A' and 'Z' were assessed as single tram type ('A/Z') due to differences between the two tram types not being clear at the time of monitoring.
- Tram speed was not measured.
- Precise desired noise reduction performance criteria to determine measure of success were not assigned within the analysis work scope.

Although noise data was collected in 1 second increments for each tram pass, only the instances when wheel squeal was at its "loudest" are reviewed in this paper. "Loudest" is defined as the maximum L_{AFmax} value recorded during each individual tram pass.

6.2 Noise Reduction Results

Pre-mitigation ('dry') maximum noise levels (L_{AFmax}) recorded for all trams regardless of direction ranged from 70-84 dBA, as shown in Table 2 below.

PRE-MITIGATION ('DRY') TEST PHASE		
TRAM TYPE	**CITYBOUND**	**SOUTHBOUND**
A/Z Class	71 - 80 dBA	71 - 84 dBA
B Class	70 - 80 dBA	69 - 80 dBA
D Class	71 - 84 dBA	74 - 75 dBA*
* Only two pass-bys occurred during this period		

Table 2. LAF_{max} range (dBA) - Pre-mitigation ('dry') test phase - All tram types

As previously discussed, KTT was subsequently manually applied for initial 'proof of concept' evaluation to confirm if a permanent, more complex wayside FM application solution should be incorporated.

During the KTT manual application phase, a second KTT test with water test condition was also evaluated. This was done to simulate heavy rainfall conditions and evaluate impacts to FM rail conditioning and performance effectiveness (i.e. would it wash off?). For both these phases, a dedicated tram (D Class No. 3536) was used for all noise measurements. This tram type was selected based on it having generated wheel squeal during pre-mitigation noise monitoring.

Figure 18 shows the maximum A-weighted noise level for a 1 second period for each train pass under each test condition. Noise reduction is achieved instantaneously upon introducing KTT using manual application, with noise levels remaining low even after introducing water onto the KTT-treated rails.

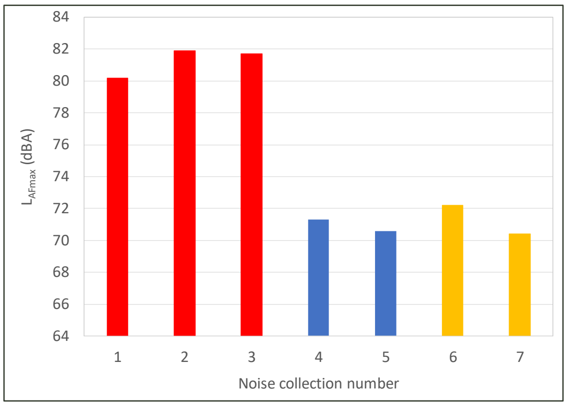

Figure 18. Maximum A-weighted noise levels for a 1 second period - D Class test tram

Red - Pre-mitigation (3 passes)
Blue - Post-manual KTT application (2 passes)
Yellow - Post-manual KTT application and water (2 passes)

Figure 19 shows the 1/3 octave frequency noise spectra for the same three test conditions. Two peaks can clearly be seen at 2000 and 3100Hz for the pre-mitigation noise data sets, which fall within the frequency range typically associated with wheel squeal events (1000-5000Hz). Following manual application of KTT, recorded values within the same frequencies were significantly reduced to <55dB.

Figure 19 also indicates suitable resiliency of the applied FM product under heavy water-washing (i.e. rainfall) conditions. This corroborates the expected as-designed enhanced rail conditioning retentivity performance of the thin film layer KTT product once applied.

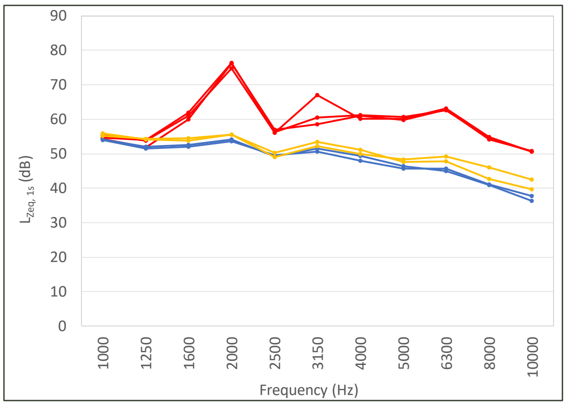

Figure 19. 1/3 octave frequency spectra
D Class test tram

Red - Pre-mitigation
Blue - Post-manual KTT application
Yellow - Post-manual KTT application and water

Noise measurements were also collected after the wayside TOR unit was installed and activated. Overall, FM product application using the embedded track TOR system significantly reduced noise levels for all tram types in both directions to a level between 65 - 78 dBA, albeit with one data outlier at 80 dBA (Table 3).

POST-FM APPLICATION TEST PHASE		
TRAM TYPE	CITYBOUND	SOUTHBOUND
A/Z Class	65 - 74 dBA	65 - 78 dBA
B Class	65 - 72 dBA	71 - 76 dBA
D Class	68 - 74 dBA	68 - 73 dBA

Table 3. LAF_{max} range (dBA) – All tram types
Post-FM application (Wayside TOR unit test phase)

Focusing on D Class trams again, Figure 20 and Figure 21 confirm a similar elimination of extreme noise events (i.e. those ≥ 65dB) for both Citybound and Southbound passes respectively, following wayside KTT application.

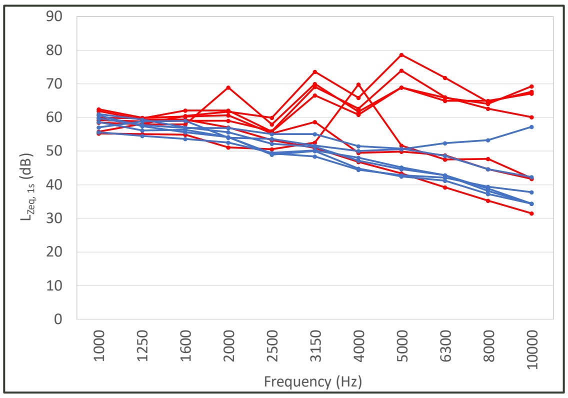

Figure 20. The 1/3 octave frequency spectra for the Citybound D Class trams

Red - Pre-mitigation
Blue - Post-wayside KTT application

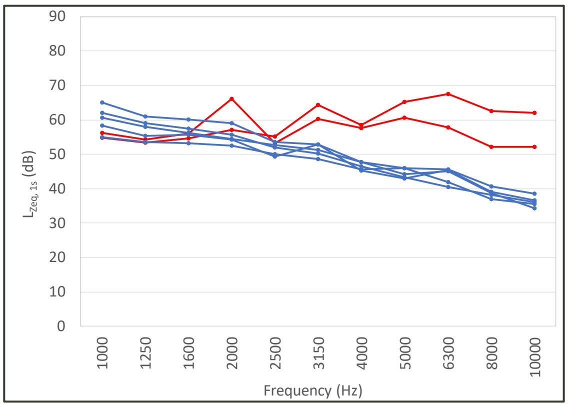

Figure 21. The 1/3 octave frequency spectra for the Southbound D Class trams

Red - Pre-mitigation
Blue - Post-wayside KTT application

Table 4 summarizes the noise reduction results for the frequencies at 3150 and 5000Hz associated with tram squeals recorded during pre-mitigation noise monitoring for the same Citybound and Southbound D Class trams. Typically, a drop of 10dB is roughly considered to reflect a 50% reduction in subjectively perceived noise loudness (i.e. volume).

	CITYBOUND		SOUTHBOUND	
	3150 Hz	5000 Hz	3150 Hz	5000 Hz
Pre-mitigation (Average Lz_{eq})	63 dB	62 dB	62 dB	63 dB
Post-FM via TOR unit (Average Lz_{eq})	51 dB	46 dB	51 dB	44 dB
Noise level difference	**-12 dB**	**-16 dB**	**-11 dB**	**-19 dB**

Table 4. $Lz_{eq,1s}$ of D Class trams during Pre-mitigation (no TOR) vs Wayside TOR test phases

7. LESSONS LEARNED

With this project being the first wayside embedded track TOR equipment installation performed in Australia, it was not surprising that several items were identified as possible opportunities for improvement should similar projects of this type be performed moving forward by Yarra Trams. The following is a summary of some of the key items identified:

i. Communications

- Regular planning and pre-construction conference calls are imperative given the varied locations of project team members (Canada, USA, Perth and Melbourne)
- Create a file share repository of key project information accessible to relevant project personnel (e.g. Meeting minutes, design drawings, contract documents).

ii. Embedded Track Equipment Design

- International Standard of Units (i.e. Metric) to be used for all design drawings.
- Completion of a pre-installation mock-up of proposed embedded track components (i.e. Track structure and TOR applicator track-based components c/w enclosures) must be mandatory to correct any design or fitment issues.
- Drill hose entry holes for the between-rails enclosure after pre-installation mock-up work has been completed to ensure finalized hole locations are suitable for use.
- Create a separate protective enclosure design for the Tram sensor bracket J-bolt assembly (i.e. Enclosure design for the TOR bar clamp J-bolt is not suitable for use with the Tram sensor).
- Create a standard drawing specific to the conduit, hose and TOR applicator tank array placed on a concrete slab foundation.

iii. Development of Scope & Planning

- Initiate earlier development and distribution of proposed work scope to project stake holders.
- Investigate opportunities for the Civil Works contractor to source and supply the TOR bar, Tram sensor, and between-rails enclosure items, and other wayside TOR application equipment where applicable if deemed more cost effective to do so.

iv. Construction

- Establish work site excavation depths prior to construction.
- Investigate options to increase the duration of on-track access hours available to the Civil Works contractor and TOR applicator equipment vendor.
- Improve the method of interim steel plating installed to protect excavated areas following conclusion of daily work activities in order to minimize on-track work time associated with performing this task.

v. Commissioning

- Include allowances in the project work scope accommodating on-track access by the TOR applicator equipment vendor to perform post-installation system operating integrity checks and optimization tasks.
- Improve post-installation hand-over procedure to Yarra Trams Operations and Infrastructure personnel.

vi. Maintenance

- Improved Inspection and Maintenance reference materials required for wayside TOR equipment (Hard copy and electronic versions to be provided).
- Incorporate post-project implementation work scope items covering the receipt, storage, and handling of the wayside TOR systems to improve off-hours access to the equipment for completion of inspection and installation prep work tasks.
- Improved definition of customer roles and responsibilities following project completion (e.g. ongoing TOR equipment Inspection and Maintenance work activities).

8. CONCLUSIONS

The first embedded track wayside TOR equipment installation completed in Australia has significantly reduced wheel squeal noise issues for Yarra Trams operator Keolis Downer on a high-density tram network in Melbourne.

Given TOR friction control technology is new to Yarra Trams, comprehensive trial activities were successfully completed to confirm a localized embedded track wayside TOR equipment solution could be safely and effectively introduced for use on the network.

Noise reduction results for frequencies associated with tram squeals during pre-mitigation (i.e. non-TOR) FM noise monitoring (3150 and 5000Hz) have been reduced by 11-18.5dB, representing an approximate 50% reduction in subjectively perceived noise loudness existing prior to TOR incorporation. In addition, feedback received from area residents has been mostly positive. Further work evaluating possible additional TOR friction control benefits for the targeted St. Kilda Road area related to corrugation and rail wear abatement is planned.

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