Are the Trains Getting Quieter?

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ABSTRACT

The Australian rail industry has made remarkable progress over the last fifteen years to better understand rail noise and devise mitigation strategies. There have been significant developments in curve noise, locomotive noise, and general rolling noise, both in understanding their root causes in Australia and in how to reduce these types of noise. But the industry has been slow to implement these developments and risks losing its reputation as an environmentally friendly mode of transport.

This paper explores the successes, failures, and untapped opportunities in regards to implementing noise mitigation. We emphasise understanding the broader rail system and the drivers of rolling stock and network operators, and how acousticians can leverage this broader context. We then examine rail noise mitigation through the lens of opportunity cost. With reference to recent examples, and the current rail infrastructure boom, we pose a challenge to regulators, planners, operators and proponents to be open to different ways of implementing mitigation.

1 INTRODUCTION

In his 2007 keynote address at the ISCV14 conference, Prof. David Thompson posed the question “are the trains getting any quieter?” (Thompson, 2007). Prof. Thompson discussed the tremendous developments that had occurred in relation to rolling noise over the preceding years, but also briefly highlighted the challenges in moving from a) research and development of a technical solution, to b) actual implementation. This paper picks up on that latter theme and discusses a series of case studies to highlight the challenges of bringing about reductions in noise in a railway environment.

2 THE “SWISS-CHEESE” MODEL OF CHANGE IN THE RAIL INDUSTRY

The “Swiss-cheese model” of accident causation (Reason, 1990) is well known to anyone involved in safety risk assessment. The principle, illustrated in Figure 1 in relation to COVID-19, is that a typical approach to mitigating risk is to implement layers of controls. Each layer, however, has weaknesses, and if these weaknesses align then the control system can fail and the accident can still occur. The idea is to ensure that not only are the layers of control appropriate and implemented correctly, but that subsequent layers provide protection from the weaknesses in other layers.

Achieving change in the rail industry is also like navigating a swiss cheese model, except in this case the aim is to achieve an outcome (noise reduction) rather than avoid one (an accident). The layers represent the various stakeholders involved and their particular requirements, drivers, and objections to change. The particular layers will change from case-to-case, but when trying to implement noise reduction initiatives, these could include:

- Technical – the need for a “feasible and reasonable” acoustic and engineering solution to the noise problem
- Economics / market incentives – the business case and funding to support the acoustic solution
- Safety – the safe operation of the railway and how the proposed acoustic solution impacts on this
- Maintenance – the implications for the maintenance of the railway inherent in the acoustic solution
- Operations - the implications for the operation of the railway inherent in the acoustic solution
- Regulatory – the interaction with railway regulation of the proposed acoustic solution
- Government policy – how the acoustic solution aligns with the priorities of the government of the day
- Political climate – the appetite for change in the community and the willingness of the government to spend political capital to implement the acoustic solution

In this case, the holes in the swiss-cheese layers are not weaknesses. Rather, they represent the narrow path that an acoustic solution must thread in order to be successful. Put another way, if any of the layers is only slightly misaligned, then the solution can be blocked.

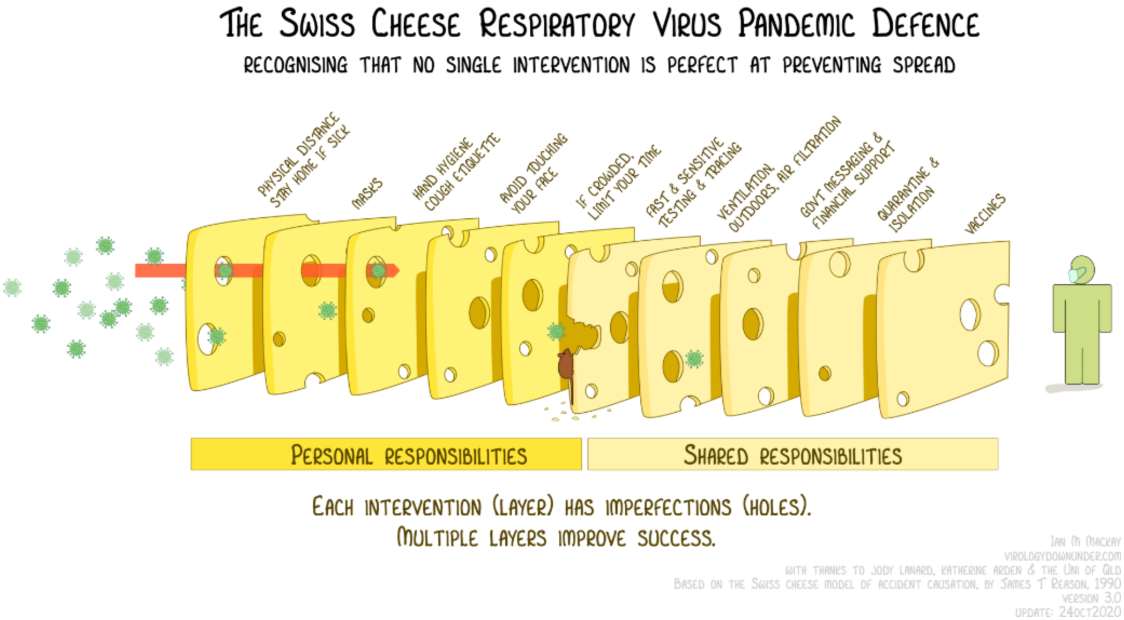

Figure 1 The swiss cheese model as applied to COVID-19 (Wikipedia, 2021)

Should any acoustician be so courageous as to attempt to implement change in the rail industry, their job therefore is to manage the various layers to ensure that the holes in the “swiss-cheese of opportunity” are aligned. This is a tremendous challenge, and typically involves stepping outside of acoustics and engaging directly with other disciplines to shepherd the proposed change through each layer of the Swiss cheese. Some changes can take years to implement, requiring perseverance and compromise. Rarely is any change in rail achieved quickly and with unanimous support.

Below we have attempted to illustrate this process through a number of case studies that we have been directly involved with over the past twenty years. Some of these have been successful. Others have not. They collectively illustrate some of the challenges in “making the trains quieter”.

3 CASE STUDIES

3.1 Rolling Noise

The most ubiquitous noise from railways is rolling noise. Rolling noise is emitted by the wheels and rails, which are excited by vibrations at the wheel/rail interface (Thompson, 2009). The vibrations are due to microscopic irregularities, called “roughness”, on the surfaces of the wheels and rails.

Rolling noise can be controlled in a number of ways. For example, the vibration in the wheels and rails can be dissipated before it can be emitted as noise. For wheels, this can be achieved through various designs of wheel dampers (see e.g. (GHH-Bonatrans, 2018)) that convert the vibration energy to heat. For rails, the effective length of rail that is vibrating can be reduced by increasing the track decay rate, either by channeling vibration into the ground or by dissipating it as heat through rail dampers (see e.g. (Schrey and Veit, 2021)). Many of the noise mitigation initiatives pursued in Europe have already been in place in NSW for some time. Australian freight rolling stock typically use composite brake blocks that minimize the roughness on the surface of wheels. Passenger rolling stock employs wheel-mounted brake disks that exhibit some of the damping characteristics of wheel dampers, and local track forms have very stiff rail pads that efficiently transfer vibration energy into the ground thereby producing a relatively high track decay rate. One area where we lag other railways, however, is in controlling rail roughness.

Rail roughness manifests as unevenness along the top of the rail head. Important wavelengths for rolling noise are between 10mm and 500mm, which manifest as noise between 50Hz and 2kHz for trains travelling at 80km/h. Roughness amplitudes are typically less than 0.01mm and are usually expressed in dB re 1 micron.

Rail roughness is controlled by rail grinding using purpose-built machines. These machines are equipped with a number of grinding motors, each of which is topped with an abrasive grinding stone that rotates perpendicular to the surface of the rail. The motors (and hence stones) are orientated so that they collectively grind a faceted shape into the surface of the rail head, referred to as the “rail profile”.

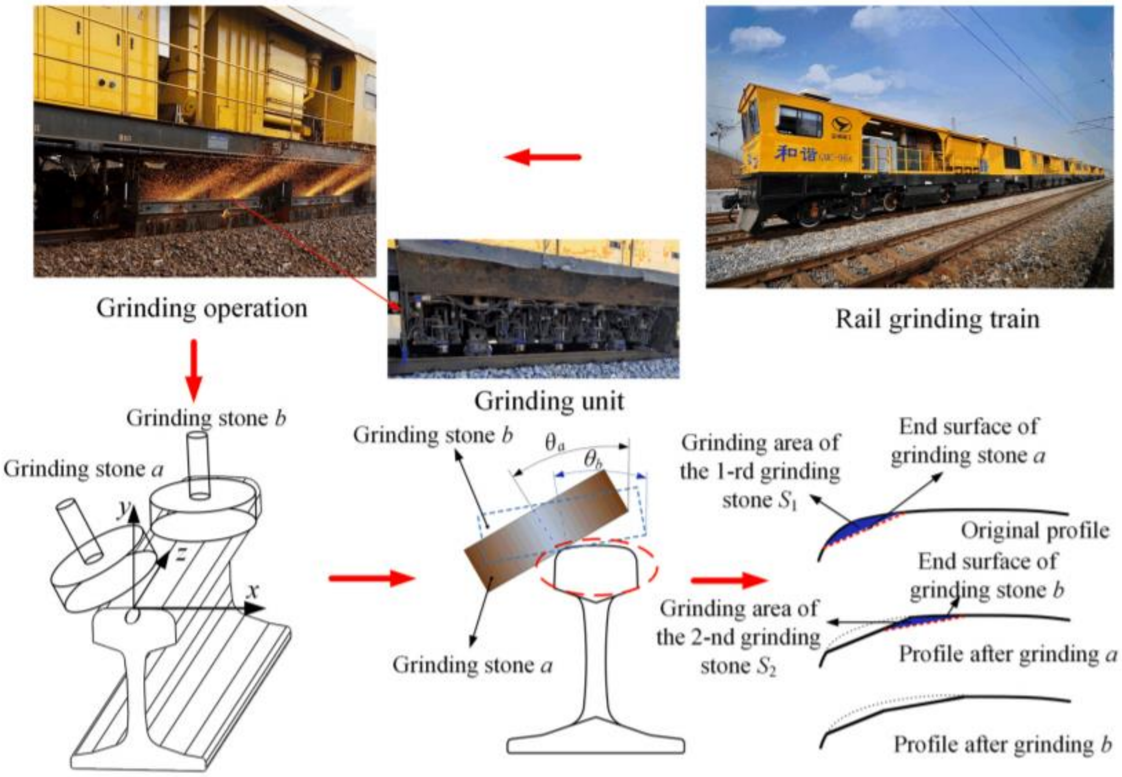

Figure 2 Overview of rail grinding (from (Xie, et al., 2020))

Rail grinding serves several purposes, the main one being removing micro-cracks (such as rolling contact fatigue) and other defects before these can grow and jeopardise the safe operation of the railway. The frequency of grinding is related to the amount of traffic a section of track carries. Busy sections, and those that carry heavier freight trains, may require grinding every six months. Quieter sections may only require grinding every few years.

Typically, rail grinding is performed in a track possession, where the track is closed to all vehicles other than the rail grinding machine. To reduce interruptions to revenue services, this usually occurs in the narrow window between 1am and 3am when there are no passenger trains operating.

As there is only one grinding machine contracted to service the 1600km of track on the Sydney network, this sets up a conflict of priorities. The grinder has little downtime and must complete its scheduled grind each night so that the surface cracks are removed. But the possession window is very short, so the grinder must complete its operations quickly before the lines are reopened to revenue trains. There is a minimum amount of metal that must be removed from the head of the rails to control the micro-cracks. This requires the grinder to repeatedly run back and forth over each section of track which limits the length of track that can be ground each shift.

Producing a smooth and quiet rail with this grinding technology takes time. It is possible to achieve good acoustic outcomes with the current grinding technology operating in Sydney (Vegh, et al., 2014), but this requires additional high-speed grinding passes and special track protection measures to be put in place, which consumes valuable time from the short possession window. As a result, this approach was employed only on one specific section of track. It is not feasible to adopt such an approach more broadly across the network.

Regrettably, a typical grinding operation can actually make noise worse. The operation of the grinding stones can impart a sinusoidal unevenness into the surface of the rail head, with a wavelength related to the speed of the grinder and the rotational speed of the grinding motors. In Sydney, this usually manifests as so-called “grinding induced corrugation” (GIC) with a wavelength of around 50mm and an amplitude of 10-20dB re 1 micron. There are alternative grinding technologies that can eliminate this GIC effect, such as “shuffle-block” grinders and “offset” grinders (Loram, 2021), but these are not currently used in Sydney.

There is an opportunity to influence grinding outcomes on the horizon. The current grinding contract on the Sydney rail network will expire in 2021, after running for eight years (NSW Government, 2018). However, the standards that govern grinding do not currently contain requirements to deliver a good acoustic outcome (Transport for NSW, 2019). An update to the grinding standard would help deliver substantial noise benefits across the network, but this won't come from track engineers or rail grinding specialists. They may own the standard, but their motivation is to maintain the rail assets, not to reduce noise. Only those whose primary remit is to deliver noise benefits have the motivation to lead this initiative. This opportunity therefore, is one for us acousticians.

So, to reduce rolling noise in NSW, the rails must be made smoother. To achieve smooth rails with the existing technology requires more time than is available without interfering with revenue services. To achieve smooth rails within the available time would require technology that is not available under the current maintenance contract. In other words, the technical solution is clear, but the cost of implementation is prohibitive.

Another rolling noise mitigation initiative that has failed to gain traction in NSW is low-profile noise barriers. Unlike conventional noise barriers, low-profile barriers sit close to the tracks and only need to be around 1m high to effectively shield rolling noise. The efficacy of low-profile barriers has been discussed for some time (see e.g. (ETTT Alliance, 2015)). They have many advantages compared to conventional barriers; they are considerably cheaper in terms of both capital and maintenance costs, do not require vegetation removal, are less prone to vandalism and graffiti, and do not disturb sight lines and vistas across the rail corridor. Installation of low-profile barriers, however, has often been met with two main objections – maintenance and safety.

Figure 3 Low profile barriers sit on the ballast close to the track (from (Zvolenský, et al., 2017))

Most rail in NSW uses a ballast track form. Low-profile barriers would need to sit either directly on, or immediately adjacent to, the ballast. Every few years, the ballast needs to be cleaned to remove the accumulated fines and restore drainage. Low-profile barriers may interfere with ballast cleaning and some other maintenance operations. The barriers may need to be removed before such work can occur, adding time and cost to the maintenance activities.

Due to their proximity to the rails, low-profile barriers impede emergency egress from the tracks. The need for such egress can occur in the event of a train breaking down and requiring evacuation. It can also occur when a train unexpectedly arrives while maintenance workers are on the tracks.

The "safety card" is often played to block a change from occurring. Nobody wants to be responsible for a reduction in safety or for endangering the health of others. In the case of low-profile barriers though, it is easy to point to numerous examples on the Sydney network where egress from the tracks is equally, or even more, impeded. Rail tunnels throughout the City Underground, Airport Line and on Sydney Metro are a case in point. Viaducts, such as those on the Eastern Suburbs Railway and on the Main North at Epping, are another.

Similarly, maintenance is equally impacted by unconventional trackforms such as tunnels and viaducts. Access to the tracks in these, and many other parts of the network, is restricted and can only be obtained under high levels of protection (RailSafe, 2021).

It may be possible therefore for low-profile barriers to be implemented if a section of track was reclassified for safety and maintenance purposes to be equivalent to a viaduct or tunnel. This would require additional time and investment for maintenance, and updated operational procedures, but only so far as these are already applied to other locations on the network.

Rolling noise is ubiquitous, and hence reducing rolling noise can deliver substantial benefits, but it is rarely the most impactful rail noise. Sydney sits in a geographic "bowl" with steep ridges on three sides. For residents who live on these steep gradients through the Blue Mountains, Hornsby Shire and Illawarra, it is locomotive noise that often has the greatest impact.

3.2 Locomotive Noise

Mainline locomotives operating in NSW, and across Australia's standard gauge network, use diesel-electric traction systems. Locomotives are essentially an electric power station, like those that might power a remote community or mine, where the electricity is used to turn wheels rather than to power homes. Most mainline locomotives have power outputs of 3-4MW.

The main noise source on a locomotive is the engine exhaust. The engines are typically turbo-charged, 12-16 cylinder diesel units, of either two-stroke or four-stroke design, and operate at up to around 1000rpm. The engine noise is broadband, with strong low-frequency tones associated with engine-firing at frequencies less than 50Hz, and high-frequency tones (several kHz) from the turbochargers.

Locomotives also include several fans that provide significant secondary noise sources. These include the dynamic brake fans, radiator fans and traction motor blower fans. Other noise sources include large air compressors used to run the brake system on freight trains, and the electrical system, particularly traction inverters.

The main challenge in controlling locomotive noise continues to be mitigating the engine exhaust noise. The low-frequency nature of this noise, combined with the multiple engine speeds and hence varying frequency tones, mean that mufflers typically need to be large and multi-chambered. Constraints on muffler performance include the tight space envelop through which the locomotive must operate which limits how large the muffler can be, and the relatively low tolerance for back pressure and quest for increased fuel efficiency, which limits the complexity of the muffler design.

3.2.1 Noise from New Locomotives

In NSW, new locomotives must meet the noise limits imposed through Environment Protection Licenses (EPLs) set by the NSW Environment Protection Authority (EPA). These include noise limits that must be met before a new locomotive is approved for operation, and ongoing requirements that ensure noise emissions are controlled throughout the locomotive's life. The current EPL regime applies these noise requirements to rolling stock operators, following an earlier EPL regime that applied to infrastructure operators such as RailCorp and ARTC.

The genesis of the current locomotive noise limits was the introduction of the 81 Class locomotives in 1982. These noise limits were established as best practice for the time, but have remained essentially the same ever since. Over this time, aircraft noise levels have reduced by around 10dBA (Sydney Airport, 2013).

The success or otherwise of the EPL regime and its predecessors in controlling locomotive noise depends on your perspective. On one hand, locomotives have not been getting louder over the past 25 years. In general terms, locomotive noise emissions have met, or slightly exceeded in some instances, the limits imposed by the EPA. On the other hand, there has been no decrease in noise emissions over time. A locomotive manufactured today will be no quieter than a locomotive introduced in the late 1990s. When challenged on this, manufacturers have replied "my clients are not asking for quieter locomotives".

Herein lies a problem with relying solely on regulation to control noise – regulation only sets a lower limit on performance; it does not drive improvement beyond compliance. There is no incentive for an operator to pay extra for a locomotive that is quieter than the mandated limits. This will not open up new opportunities for them or increase their profitability or competitiveness.

There are other approaches to regulation which can drive improvement over time. The United States nonroad diesel engine emissions standards (United States Environment Protection Agency, 2020) included progressively more restrictive limits over time, but these were accompanied by substantial government grants to fund the transition (United States Environment Protection Agency, 2021). Perhaps a similar scheme may be required in Australia to nudge railways from a "business as usual" approach and promote innovation.

Locomotives can spend around half their time at idle. This is unproductive time for a rail operator and leads to higher fuel costs, increased emissions and noise impacts on local communities. Locomotives are required to stop in yards, at signals and in passing loops, and at ports and loading/unloading terminals. Examples on the local network include passing loops at Gosford specifically built to allow passenger trains to overtake freight trains, the relief line at Cowan where freight trains wait out the morning and afternoon freight curfews on the Metropolitan network, and at Thirroul where freight trains await slots at Port Kembla.

Locomotives can be idling near residences for extended periods - even hours at a time. While noise emissions from idling locomotives are generally 10-15dBA lower than at full power, they still present a substantial and annoying noise source, particularly with the ability of low frequency noise to penetrate residential facades and cause secondary effects like rattling windows and shelves.

The ideal way to mitigate idling noise impacts is to eliminate the need for the freight train to stop. This is impossible in a congested network like Sydney's, where headways between freight and passenger paths may be only a few minutes, and freight train services can stretch from Adelaide to Brisbane. There is an engineering solution however – Automatic Engine Start Stop (AESS) systems. As the name suggests, AESS switches off the prime mover during extended periods of idling, with auxiliary systems instead run off batteries or a much smaller (and quieter) auxiliary drive system. However, implementation of AESS, even on new locomotives, remains a challenge.

The main issue with AESS is reliability – the system must be able to restart the locomotive prime mover everytime and immediately as required. Any delay can mean the train misses its path through the network and this can cause downstream delays to both freight and passenger services. No operator wants to be responsible for shutting down the afternoon commute for hundreds of thousands of people because their engine won't start.

There is also a safety component to this risk. The pneumatic brake system on freight trains is run from the compressors on the locomotive. No air system is perfectly sealed, and so these systems leak air pressure over time and the compressor is required to periodically recharge the brake lines. If the AESS fails and the compressor is not able to maintain the air pressure to the brakes, then the freight train can run away. This is highly unlikely, but not without precedent and catastrophic result.

Moreover, in the authors' experience, at least one class of modern locomotives had their AESS systems deactivated. Due to the specifics of the locomotive design, the auxiliary system lacked sufficient power to run the air conditioning in the driver cab, hence the cabs became hot and uncomfortable when idling for any length of time in summer. Drivers were understandably unimpressed with this outcome, and hence the AESS systems were switched off.

3.2.2 Noise from Older Locomotives

The EPA's EPLs only limit noise from new locomotives. Noise requirements were not back-dated, hence locomotives introduced prior to 1982 operate without noise restrictions and have no ongoing compliance requirements. The NSW EPA Locomotive Class Register (NSW Department of Planning, Industry and Environment, n.d.), shows that fewer than 40% of the approved locomotive classes were subject to a type approval process and hence demonstrated compliance with the noise limits discussed in Section 3.2.1.

The locomotives fleet is old. To put this into perspective, the average age of articulated trucks in NSW is 11.9 years (Australian Bureau of Statistics, 2021) and 25% are less than 5 years old (Transport for NSW, 2021). Statistics for locomotives are not as readily available, but the latest available figures from 2007 (Australasian Railway Association, 2007; Environ, 2013) suggest the average age of a diesel electric locomotive in Australia is now more than 30 years. The mainline fleet in NSW is likely to be older still as the 2007 figures included the relatively youthful fleets operating in the Pilbara iron ore and Hunter Valley coal networks. In other words, there are a lot of locomotives operating on the NSW network which are not subject to any noise restrictions or regulations and have technology that is half a century old.

These older locomotive generally fall into two categories – those with traction systems from Electro Motive Diesel (EMD) and those with traction systems from General Electric (GE). Recent upgrade projects have shown that noise emissions from both types of older locomotive can be controlled in line with current best practice.

The 2800 Class was introduced to service in Queensland in 1995. Aurizon sought to introduce the locomotive into service in NSW in 2012, triggering the requirement to comply with the noise emission requirements in ARTC's EPL. While it had a substantial muffler, its low frequency noise emissions were well above these limits, hence a new muffler was developed (Croft, et al., 2014). The new muffler was 60% larger in volume and included quarter wave tubes tuned to attenuate the low-frequency tones from engine firing. The muffler reduced the low-frequency noise emissions by (nominally) 10-15dB and the locomotive thus satisfied the requirements of the NSW EPA. The upgraded 2800 Class, rebadged to 3200 Class, shows that older GE locomotives can be upgraded to have noise emissions similar to modern locomotives.

The older EMD locomotives, however, present a greater challenge. Adding a muffler to an exhaust stream can generate back-pressure, which reduces the efficiency of the engine. Whereas GE prime-movers are four-stroke, EMD prime-movers are two-stroke and hence are less tolerant of back-pressure. Additionally, many older EMD locomotives were never designed to have mufflers at all, which not only further reduces their tolerance to back-pressure, but also means that there is no space provision within the locomotive to accommodate a muffler. Nevertheless, a recent project to upgrade C Class locomotives demonstrated how these and other challenges can be overcome.

A collaboration of UTS Tech Lab, Hushpak Engineering and Acoustic Studio designed a muffler for the C Class that reduced problematic low-frequency noise emissions by up to 15dB.

The C Class was not subject to noise limits under an EPL as it was introduced 25 years prior to these requirements coming into force. The catalyst for the upgrade was a desire to run these locomotives to a particular mine-site that operated under noise requirements imposed by the Department of Planning, Industry and Environment. This led to the bizarre circumstance that the C Class could run unimpeded along its 250km journey from the loading point to the gate of the mine, and impose unregulated noise emissions on thousands of receivers through the Blue Mountains, Sydney and the Central Coast, and yet not enter the mine to complete the final 2km of its journey due to noise restrictions. Or to put this another way, where the C Class slipped through the net of the regulation on the mainline, the backstop of the mine site's noise requirements were a regulatory catalyst for change that delivered benefits for thousands of people across the state.

In summary, technical solutions have been proven for both GE and EMD classes of older locomotives. There is therefore no engineering impediment to noise from older locomotives being substantially mitigated across NSW and the interstate standard-gauge network. To date, however, from the approximately 200 older locomotives that are likely to still be in service in 2030, only nine locomotives have been updated: three 3200 Class and six C Class. So, impressive solutions have been developed to mitigate this challenging problem, but implementation is only 5% complete.

What set the 3200 Class and C Class apart from their older counterparts was a combination of a viable technical solution, a motivated asset owner, a market opportunity, and regulation requiring change in order for the market opportunity to be realised. This particular set of circumstances occurs only rarely.

3.2.3 The Economics of Older Locomotives

Reducing noise emissions from locomotives is an example of a market failure. The locomotive owners who bear the cost of the mitigation reap no benefits from the investment. The cost of noise is an externality that is borne by the community and economy at large and has no impact on an individual rail operator's business. Conversely, the community who suffers the impacts of the noise emissions has no ability to bring about change. They have no control over the noise emissions of the locomotives and no mechanism by which they can reduce them.

The cost of replacing or upgrading older locomotives is prohibitive. A new locomotive costs around $6m. An older locomotive operating on low-margin grain and container services might generate around $50k-$100k p.a. in profit. Even if 100% of this profit was allocated to the purchase of a new locomotive, it would take 50+ years to pay for it. Installing a new muffler in an older locomotive costs around $40k. This constitutes (nominally) 40% of the annual return to the operator, and without any improvement in productivity. On this basis, there is no financial justification for operators to either replace or upgrade their older locomotives. Rather, operators will keep the older locomotives running for as long as possible.

We estimate the cost of upgrading the fleet of older locomotives with modern muffler to be around $4-5m. The economics of freight rail mean that this investment will not come from industry.

Traditionally, it has been the role of Government to intervene to address market failures. Without regulation, neither the 3200 nor C Class locomotives would have been upgraded. As explained above, however, older locomotives are exempt from the main regulatory instrument, the EPA's EPL regime. Attempts were made by the NSW EPA to include older locomotives in its revamped Regulation of Railway Activities scheme (NSW Environment Protection Authority, 2020) but these were heavily contested by the industry (Pearce, 2020), attracted substantial political pressure, and were ultimately quashed.

So, older locomotives will continue to operate for many years to come. There is neither regulation nor financial incentive to replace or upgrade them. A different path is needed if the remaining 95% of older locomotives are to be addressed.

Happily, not every attempt to address rail noise is so mired. The following two case studies show that positive change is possible, albeit slow to occur.

3.3 Wheel Squeal

Wheel squeal, the high pitched and extremely loud noise emitted by some trains when negotiating tight curves, was once seen as an intractable problem. In recent years, wheel squeal has accounted for more than half of all rail noise complaints received by Transport for NSW (TfNSW), and until recently it was considered to be something that people living near the railway would just have to live with.

The last decade has seen tremendous progress in controlling wheel squeal, especially from freight trains. Today, there are proven and inexpensive solutions, a regulatory framework to steer their implementation, and a timeframe over which we can expect wheel squeal to be largely addressed, at least on the freight lines.

How this was achieved provides a salient example of acousticians working across disciplines and not being afraid to step outside of our narrow field to drive change. It is also a story of government stepping in where industry had failed to solve an issue and even to act in their own best interest.

Wheel squeal became a widespread concern with the rollout of concrete sleepers in the 1990s. The reason wheel squeal is more prevalent on concrete as opposed to timber sleepers is still not understood (Jiang, et al., 2015), but the maintenance and operational advantages of concrete sleepers mean that the railways will not revert back to timber sleepers. A detailed investigation in 1996 (Kerr, et al., 1998) identified Angle-of-Attack (AoA), the angle at which wheels address the rail in a curve, as a key feature associated with wheel squeal but was not a reliable predictor of squeal occurrence. Friction at the wheel/rail interface was also an important consideration in one class of squeal events.

Arising from this and other related work in Sydney, and in collaboration with the EPA, RailCorp installed an AoA recording system on a sharp curve at Beecroft in 2007. There was considerable resistance to this, even from those who supported the technology, because this represented the first installation of an AoA detector on a curve. Up until this point, AoA systems had been used for condition monitoring of (usually) freight bogies on tangent track. The Beecroft installation represented the first use of an AoA system for curve noise diagnostics. The success that has followed over the subsequent 14 years has rested on this innovation.

With the advent of the Beecroft AoA system, and the subsequent addition of a microphone installed close to the track, there was suddenly an enormous dataset of steering and noise results, all matched to the individual vehicle ID tag. This enabled the cause of the squeal to be pinpointed (Jiang, et al., 2015; Jiang, 2018). Far from being an intractable problem, wheel squeal was revealed to be a distinct event associated with poor steering from particular classes of wagons forming less than 10% of the fleet. Furthermore, all these wagons had a common element – they all had basic three-piece bogies.

In parallel with this work, South Australia was grappling with a similar wheel squeal issue in the Adelaide Hills. Suspecting wagon maintenance as the issue, the South Australian EPA introduced license conditions to require operators to remove wagons from service that repeatedly emitted wheel squeal noise and subject them to inspection (South Australian Environment Protection Authority, 2018). While many of the same wagons were identified at both Beecroft and the Adelaide Hills, the wagon inspections have not reduced the incidence of wheel squeal (Evans, 2009). Invariably, no faults or defects are found when the wagons are inspected. This is because, as Jiang's work revealed, the issue is not maintenance but rather a problem with the fundamental design of three-piece bogies.

Building on this work, in 2016 Transport for NSW built a bogie test rig, shown in Figure 4. With this instrument, and in partnership with rail freight operators, TfNSW measured the key bogie steering performance characteristics (warp stiffness and rotational resistance) of a range of bogie designs, and in both worn and refurbished condition. These results confirmed the field observations that three-piece bogies have insufficient warp stiffness to ensure proper steering performance. This makes them much more likely to present high AoAs in tight curves, and hence to emit wheel squeal noise. Transport for NSW also used the test rig to trial a number of bogie modifications and identify inexpensive options for trials in the field.

TfNSW then funded and carried out, in partnership with rail operators, high speed tests of the shortlisted bogie modifications and obtained approval for the modified bogies to enter service. Using the Beecroft instrument, as well as other monitoring stations, TfNSW analysed the performance of the modified wagons over hundreds of revenue service trips and proved the efficacy of the inexpensive solutions to the industry.

So, having classified the problem, identified the root cause, developed solutions, gained network approvals for the solutions, and proven them in revenue service, and after many years and considerable investment, surely this was "job done" and the solution could be handed over to industry for implementation… Unfortunately, not. Implementing change is difficult, and overcoming legacy practices and understandings is challenging, especially in rail. Regulation was needed to ensure these solutions were actually put into practice.

As a first step, the rail noise team at TfNSW developed a new requirement under the Minimum Operating Standards for Rolling Stock (Asset Standards Authority, 2017). The gravity of this is worth emphasizing. This was a requirement inserted into the principal safety and performance standard for freight rolling stock, which is owned by the Lead Engineer Rolling Stock, relating to the structural and dynamic performance of freight wagons (not to noise), but driven by acousticians. This was only possible because of the considerable trust built up over a number of years between the rolling stock engineers and the rail noise team, and the evidence accumulated through the Beecroft system and test rig to support the change. The development of these requirements also included engagement with rail operators to get their buy-in and endorsement up front. This involved travel to Brisbane, Melbourne, Adelaide and Newcastle to meet with various operators, and to negotiate the requirements for the new standard. Again, this was made easier through the relationships built up over a number of years, and by taking key personnel from these operators along on the journey. The case was bolstered by independent economic advice commissioned by TfNSW to show that the proposed bogie modifications were actually revenue positive after only a few years. A key consideration for the operators was that wagons not be removed from service to be upgraded. Rather, that the upgrades be aligned with the existing overhaul schedule of the bogies. This had the effect of setting a timeline over which the fleet would be upgraded; most bogies are overhauled every 5-6 years. The new standard was introduced in 2017 and freight operators have been reporting on progress each year since. According to the original plan, around half of all three-piece bogies should have been upgraded by now. Implementation, however, has not quite kept pace with this initial projection.

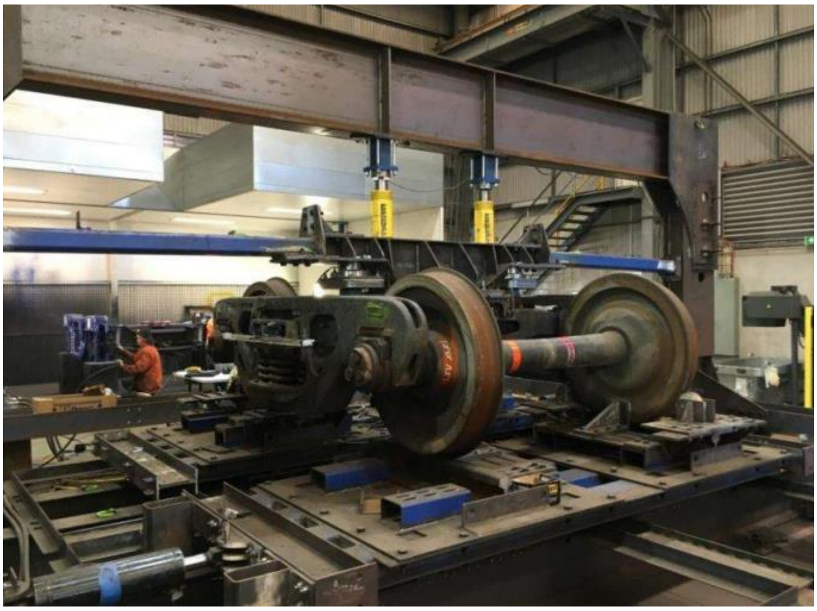

Figure 4 TfNSW bogie test rig (Jiang, 2018)

The standard was an important step in that it established a regulatory precedent, but TfNSW is not strictly a regulator of rail activities and so lacks teeth to enforce implementation. The NSW EPA however, as a true regulator with the requisite authority, has adopted the requirements of the new standard in their Rolling Stock Operator Licensing regime (NSW Environment Protection Authority, 2020). The EPA has set a date of 2025 for all wagons to be compliant, and rolling stock operators are required to report each year on their progress. So far progress has been slow – the public records indicate that around 100 wagons (<5% of the total requiring modification) have been upgraded. Nevertheless, this is an important first step and there are still four years until 2025!

A brief aside regarding the Australian Acoustical Society Code of Ethics (Australian Acoustical Society, 2020). Section 3 of the Code of Ethics requires member to “work only in their areas of competence or under the guidance of another member who is competent in that area”. Clearly, as acousticians we cannot be experts in rolling stock engineering or other specialist areas of rail. The key to driving the change described above, however, was to a) obtain sufficient understanding of interfacing disciplines in order to understand the drivers and concerns of engineers in those areas, and b) to then work with colleagues in those disciplines to shepherd the initiative through the required development and approvals.

This example demonstrates the considerable time and effort required to successfully implement change. The efforts to address wheel squeal started 25 years ago. Each small advance rested on the success of the previous work, without which the entire endeavour could have become stalled at any point. It was only through patience, determination, considerable skill and investment that this initiative was able to succeed. And, it was all driven by acousticians mostly working in government.

Acousticians have also made their mark below-rail, driving innovation in friction management that is reducing noise, but also improving the efficiency of the whole railway.

3.4 Rail Lubrication

In 2011, the head of Civil Maintenance at RailCorp asked a simple question. The EPA required RailCorp to install 30 top-of-rail-friction-modifier-applicators (TORFMAs) across the network in an effort to mitigate curve noise. This was a large investment, both in capital and operating costs. RailCorp already had TORFMA units at Waverton-Wollstonecraft, and they were causing headaches in terms of wheel slips and general maintenance. So, before he would install another TORFMA unit, he asked simply “do they work?” What followed was the most comprehensive rail friction management study the railway had ever conducted.

The outcomes from that study (Curley, et al., 2015) were that both gauge face lubrication (GFL) and top-of-rail-friction-modification (TORFM) had a role to play in mitigating curve noise. In terms of managing the rail assets, however, GFL was a long-established practice whose primary purpose was to reduce wear of wheels and rails. TORFM on the other hand was relatively new to RailCorp and was seen as purely for noise control, i.e. an afterthought mandated by the environmental regulator but not part of the railway’s “core business”. The next steps therefore concentrated on GFL.

Traditionally, this would be the point where an acoustician would declare “job done”. The people responsible had been advised that they should implement effective GFL across the network. The responsibility to do so could be handed across to the civil maintenance teams in accordance with their role and function. The problem with this approach was that there were already nearly 600 rail lubricators on the network… so why weren’t they controlling curve noise?

TfNSW adopted a different approach. Rather than handing over responsibility, the rail noise team took the running. They investigated rail lubrication practices on the network and quickly found why curve noise persisted - rail lubrication was delivered through mechanical grease pots which were not effective.

Figure 5 Old-style grease pot (left) compared with a modern electronic lubricator (right). Photos © Jeff O’Grady, Airlube Pty Ltd.

Grease pots have some fundamental drawbacks:

- Grease pots are ineffective. The applicator blades have eight ports through which the grease is dispensed. The pipe length between each port and the main hose coming from the reservoir was different, which meant there was much more resistance to feeding some ports than others. As a consequence, the flow rate to some ports was much lower, leading to the grease drying out in some ports and thus they became blocked. This cycle repeated in quick succession until only one (nor none) of the ports was dispensing grease. This meant that not much grease was actually making it onto the wheels and rails and hence the friction was not being controlled.
- Grease pots are unreliable. The grease is activated by the passing wheels depressing a plunger – a small metal piston that is driven down under the weight of the wheels. The plunger is vulnerable to damage under the impact of train wheels, requiring plunger assemblies to be regularly replaced.
- Grease pots are difficult to maintain. To fill the reservoir, workers had to climb up onto the ballast shoulder, wind back the internal spring and manually pump grease from a drum. This is hard and slow work, and is all inside the “danger zone” which means that it could only be done in the absence of rail traffic, i.e. in a possession or other form of track protection that is time-consuming to implement and can only occur at certain times.
- Maintaining lubricators is dirty and hard work. Rail grease is amazingly sticky. It is designed to latch on to polished steel wheels passing at over 100km/h. This means it gets into everything – hands, clothes, tools – and it is almost impossible to remain clean when working with it.

Finally, while rail lubrication is a safety-critical task, it is a long way down the hierarchy of things that are required to keep the railway running day-to-day. The civil maintenance crews were given only a limited amount of time to perform their duties and so prioritized those tasks that were necessary to ensure the railway could continue to operate tomorrow, and only picked up on the tasks that had impacts over the longer term when they had time. Lubricator maintenance was understandably given lower priority, and hence was not always performed.

So, what was needed was an effective, safe and low-maintenance rail lubrication system. And if the rail noise team wanted effective GFL then they were going to have to find it and drive its implementation.

Fortunately, the technical solution was clear. Electronic rail lubrication systems had been proven on networks across the world, and even in other jurisdictions in Australia. Once commissioned, they required almost no maintenance beyond keeping grease in their substantial reservoirs, and this could be achieved in minutes from outside the danger zone.

This was still not sufficient however, and perhaps no other industry better represents the old expression made famous by Sir Humphrey Appleby in Yes, Minister, "Something must be done, but nothing should be done for the first time". And in rail, this expression applies even at the level of each individual network. These modern electronic lubricators required type approval before they could be adopted locally, and so the acousticians became rail lubricator proponents.

Over the next few years, the rail noise team partnered with international rail lubrication experts to set up several rail lubrication trial sites on the Main North lines between Sydney and Newcastle. They partnered with suppliers of four different GFL systems to install the GFL units, maintain them, and measured their effectiveness using techniques and metrics they developed in-house. They established a rail lubrication type approval process and a trial site at Awaba where new rail lubrication systems could be tested. In partnership with the international experts, they wrote a new engineering standard for rail lubrication – the first engineering standard published by the new Asset Standards Authority. With GHD as the Authorised Engineering Organisation, the rail noise team successfully shepherded two lubrication technologies through to type approval, which involved not only the long-term field trials, but also writing complete maintenance schedules, life-cycle cost projections, safety documentation, and failure modes analyses. They even helped deliver training to Sydney Trains civil maintenance personnel as part of a handover process in which the lubricators were vested for ongoing maintenance at the conclusion of the trials.

Finally, the rail noise team developed a business case for Sydney Trains to apply for funding to roll out the electronic lubrication system across the network. Happily, this was successful, and Sydney Trains subsequently took carriage of the procurement and delivery of this rollout. Currently, the rollout is nearing completion and the network now joins networks in Queensland and the Hunter Valley in being serviced by low-maintenance and effective rail lubrication systems.

3.5 Wrap-up of Case Studies

The above case studies have shown that achieving good noise outcomes in rail is possible, but it is tremendously difficult and takes exhausting amounts of time and effort. Too often, the layers in the Swiss-cheese model are misaligned at some stage through the process and the innovation is stalled. In many cases, an injection of funding would nudge the problematic layers back into alignment, allowing the noise project to progress. But where would this funding come from? The fact is however, that rail noise already attracts substantial funding. The challenge is how this funding, and the opportunities that deliver the best noise outcomes, can be brought together.

4 FUNDING RAIL NOISE MITIGATION

Rail noise mitigation is principally funded by government. This includes ongoing initiatives like the Freight Noise Attenuation Program (Transport for NSW, 2021) for the TfNSW managed freight lines, but more broadly it is mandated through requirements under Planning Approvals for new projects (for which government proponents represent the majority in noise-sensitive areas).

Project-based noise mitigation has two main drawbacks, however – it is limited in geographic extent, and it is constrained in what it can do by the authority of the Proponent. The recent Epping to Thornleigh Third Track (ETTT) project provides an illustrative example (ETTT Alliance, 2015).

The Proponent is only responsible for the operational noise impacts at receivers adjacent to the project. For the ETTT, this includes receivers from just north of Epping Station to around Wells St at Thornleigh, i.e. where the additional track begins and ends. Residents outside this six-kilometre section of new track, who are subject to the same increase in rail traffic and hence rail noise, are not considered for mitigation by the project.

The ETTT was designed to increase the freight capacity on the Main North line. The Proponent of the ETTT, TfNSW, does not, however, own or operate any freight trains. Neither do the civil contractors engaged to construct the project, nor does their capability and expertise extend to rolling stock. Not surprisingly therefore, the project's Operational Noise and Vibration Review considered at-source noise control of rolling stock to be beyond the project's remit, and instead recommended conventional noise mitigation – noise barriers and at-property treatments. Just like the projects before it that were faced with the same conundrum. The project ultimately spent between $5m and $10m on noise mitigation. A considerable investment but directed at the least economically efficient mitigation measures.

The major stakeholders absent from the discussion around noise mitigation are the network operator and the rolling stock operators. The network operator will be tasked with maintaining whatever infrastructure the project constructs, including noise barriers. The rolling stock operators would benefit from upgrading their rolling stock, which would also reduce noise levels at-source, and in the case of wagon steering improvements, reduce rail maintenance, air emissions and fuel use as well. There must be a better way.

One concept for connecting network and rolling stock operators with the substantial noise mitigation funds that are available through projects would be a Noise Credit scheme. This could operate in a similar manner to carbon credit schemes, i.e. a marketplace that allows proponents to purchase at-source noise controls to mitigate the noise impacts from their projects. Rolling stock owners could offset the cost of upgrading their wagons and locomotives through the sale of credits. Rolling stock manufacturers could differentiate their products by offering lower noise vehicles that would allow operators in turn to sell credits. Network operators could similarly fund noise mitigation such as friction modification and acoustic rail grinding through the sale of credits.

Clearly, such a scheme would need rules, accreditation and oversight. This would include how credits are valued, possibly based on the total dB reduction across the network compared against a benchmark year, and how benefits are realised and maintained over time. The plurality of carbon exchange schemes across the world, including in Australia, proves that this bureaucratic hurdle is readily surmountable.

A further benefit of such a scheme is that it would allow investment now, to deliver benefits to the community now, for projects that are currently in the pipeline. Proponents such as TfNSW or ARTC could purchase noise credits to offset the mitigation costs on future projects. With mitigations such as improved wagon steering or repowered locomotives yielding benefit-cost-ratios well in excess of one, the noise credit could even be a revenue positive investment.

However, the greatest opportunity for such a scheme lies in extending mitigation across the whole network and not just within project boundaries. Consider an example project involving adding a new track to 5km of an existing rail corridor. The track carries freight and passenger trains through a residential area, and the project will substantially increase the number of trains. The main noise sources are rolling noise from passenger trains and wagons, wheel squeal from freight wagons, and locomotive noise. Conventional noise mitigation required under the Conditions of Approval would deliver 4m high noise barriers on both sides, equating to capital costs of around $10m at a nominal cost of $1m/km (assuming no difficult terrain or other complications). Maintenance of noise barriers ranges widely in cost from around $30k to over $100k per km, depending on the local terrain, the amount of graffiti or damage that needs to be repaired, the height of the barrier, etc. (Stanley, 2021). Taking the lower bound of this range, the annual maintenance costs would amount to $300k, equating to nearly $5.5m over the life of the asset (5% discount rate).

If instead of conventional mitigation, this money was instead directed to at-source noise control, the following could be achieved:

- Upgrade of all older locomotives with exhaust silencers - $5m.
- Upgrade of 2500 freight wagons to fix their steering and thereby largely eliminate wheel squeal across the network - $5m. Note: a significant proportion of rail wear is caused by poorly steering freight wagons. Improved steering would substantially reduce rail wear, thereby delivering an ongoing maintenance windfall to the network.
- Acoustic rail grinding to control rail roughness - $300k p.a. assuming grinding once per quarter at nominally $75k per cycle.

If at-source noise control was applied through a noise credit scheme, then these benefits would be delivered not only for residents next to the 5km of new track, but for people living next to the rail lines over the entirety of the 1600km network (and beyond in the case of intra-state and inter-state freight trains). Instead of several hundred residences benefiting from the mitigation, there could be tens of thousands.

Finally, and in contrast to regulation, a market for noise credits sets no lower bound on noise reduction. Rolling stock operators would be incentivised to reduce the noise of their fleets as far as economically viable under the scheme. With an appropriate price for noise credits, this could deliver substantial noise reductions over time, and we may finally be able to say "Yes! The trains are getting quieter."

5 CONCLUSIONS

The case studies presented above show where rail noise initiatives have succeeded and where they have failed. The key lessons from these experiences include:

- The opportunity for change in rail comes seldomly. In order to capitalise on an opportunity, all the pieces must already be in place and ready to go. It is too late to wait for an opportunity to arise to start development of the solution.
- Regulation is an important driver of change and improvement. It is often decried as "red tape" and "stifling innovation" but well-designed regulation can be the catalyst for progress. Regulation also has its limitations, however, including that it will only ever set a minimum standard, i.e. a lower-bar on performance. To drive continuous improvement, regulation must either be progressively tightened over time, or accompanied by market incentives to perform beyond mere compliance.
- Acoustics is a narrow field of engineering, but it intersects with many other disciplines. It follows therefore that achieving an acoustic outcome will often require the support of other disciplines. Acousticians must engage with other stakeholders and demonstrate how they will benefit from the proposed initiative, which means getting to understand their drivers and success factors.
- Having a technical solution is only the first step. Implementation requires support from the industry and regulators, a positive business case, a motivated operator/asset owner, a market opportunity, and a lot of time and investment. If any of these elements are missing, then the project is unlikely to succeed.
- If you want something to happen, you have to drive it yourself, all the way through to completion. This includes stepping into areas well beyond acoustics.
- The NSW Government is investing considerable funds into rail noise mitigation. If a mechanism could be established whereby some of this money could be directed to at-source noise control, then the benefits of noise reduction could be spread across the network and not limited to the specific project locations.

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