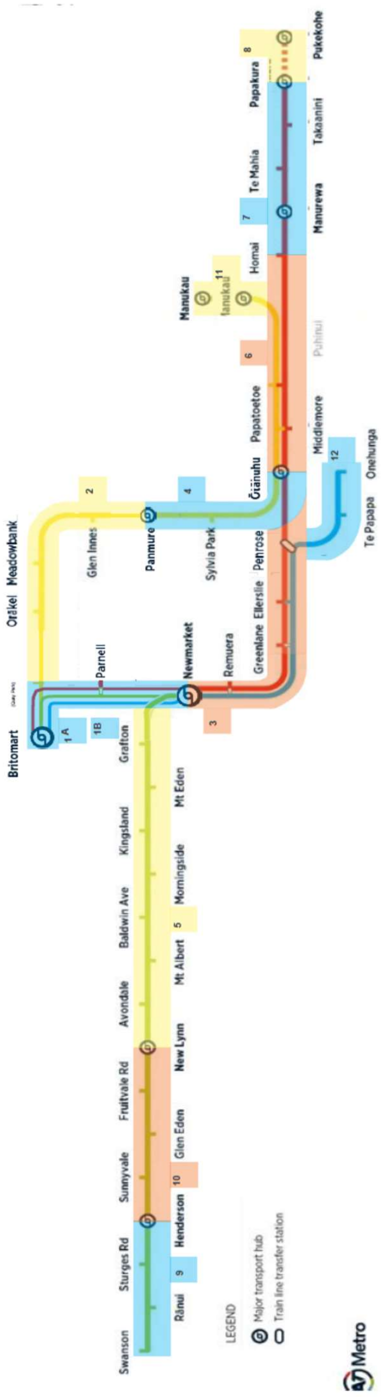
Attachment 1




AUCKLAND METRO RCF WORKING GROUP: ROOT CAUSE ASSESSMENT

Prepared for KiwiRail and Auckland Transport
17 August – 1 June 2021

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EXECUTIVE SUMMARY

This technical report has been commissioned jointly by KiwiRail (KR) and Auckland Transport (AT).

The parties

KiwiRail (KR) is the national owner and licensed rail infrastructure manager and Rail Safety Case holder for the New Zealand rail network comprising track infrastructure and civil assets, signalling and train control and overhead power supply for trains. KR is also the provider of freight train operations across the network.

KR grants access rights to Auckland Transport (AT) to the Auckland Metro Rail Network (AMRN) for Auckland passenger rail services. Passenger rail service operations are provided on behalf of AT by Transdev Auckland Ltd (TDAK) through a passenger rail services agreement with AT. TDAK hold the license and Rail Safety Case for passenger rail operations. The Auckland passenger train fleet is primarily modern (entered service from 2014 onwards) Electric Multiple Units (EMU), owned by AT, and manufactured and maintained by Construcciones y Auxiliar de Ferrocarriles (CAF), under agreement with AT. A small number of older diesel units operate on the non-electrified AMRN between Papakura and Pukekohe, owned by AT and maintained by KR, under agreement with AT.

Historic context

In August of 2020 KR found itself in a position where it needed to mitigate risk on the AMRN by applying a blanket temporary speed restriction (TSR) over the AMRN and urgently carrying out remedial works; re-railing and related sleeper replacement; the Auckland Metro Recovery (AMR) project. The works were carried out by the Auckland Region Infrastructure team. Some of these works were already planned to be carried out during 2020-24 under the Rail Network Growth Impact Management (RNGIM) project.

In parallel with the physical works a working party was established to identify the root cause of the problems that created the necessity of the TSR. The group (the RCF working group) was tasked to review previously commissioned consultants' reports on the Auckland network (primarily WSP, Autech and SNC), utilise the group's capabilities, make further internal enquiries as required and commission studies if needed. The group was required to arrive at a conclusion regarding the root cause(s) and provide recommendations for key stakeholders to consider. KR set up and has led the RCF working group and invited other stakeholders to join, contribute expertise, and to support the group.

A history of the investments made, by central government and others, towards the establishment of the current electrified metro network shows that significant investment has been made in additional track (double tracking and branch lines), new stations, new signalling, new overhead lines, and new EMU rolling stock. Existing track and civil infrastructure, including historic formation was not upgraded under any of those programmes.

In 2014, prior to the commencement of the new electrified service, AT engaged Network Rail Consultants to evaluate the overall state of the infrastructure. The evaluation effectively concluded that substantial investment (~$100m) in the AMRN track assets was needed to ensure it would be fit for purpose for the proposed EMU operation. This investment was not approved and the parties instead relied on increased inspections for safety, track speed restrictions, and accepted the infrastructure would provide lower levels of service.

In 2019 AT engaged consultants WSP, to review the AMRN infrastructure, prior to planned increases in services once the City Rail Link (CRL) was commissioned in 2024. WSP concluded "there has been a +250% increase in rail patronage between 2010 and 2019" and "the existing network infrastructure maintenance programmes, particularly those for track and civil assets, are struggling to support the level of traffic growth that has occurred on the network in recent years and are unlikely to be able to support forecast traffic growth."

In particular, the aged rail asset has experienced rapid growth of Rolling Contact Fatigue (RCF), and this has led to non-linear, accelerated growth of RCF and the related, risk-to-service, internal rail defects.

The study

The approach taken to perform the assessment, detailed commentaries, and detailed technical recommendations, are provided within the body of the report.

The study was analysed in three areas: track, vehicle, and wheel rail interface (WRI).

Findings

The key causes for the rapid growth of RCF include:

Track

a. Historic under investment in the track asset prior to 2014 up to September 2020

b. Insufficient rail grinding from 2015 to 2020

c. The existence of multiple sites where the track condition is sub-optimal in engineering factors known to accelerate the growth of RCF:

    1. Track geometry and gauge exceedances including at welds and bolted joints
    2. Aged timber sleepers unable to hold rail in place adequately
    3. Historic wheel burns/squats causing sudden dynamic loads
    4. Sub-optimal application of cant, mainly from uncorrected past practices
    5. Significant sections of the network have low track modulus (low combined stiffness of rail, sleeper, ballast, and formation), at times aggravated by poor drainage.

d. The speed of RCF propagation varies between very dry and very wet climates. It is likely that Auckland's climate has been a partial contributor to the accelerated growth.

Vehicles

a) The AM class EMUs were designed with a high primary yaw stiffness to improve passenger ride comfort. However, this increases a vehicle's propensity to cause RCF. The modelling commissioned did not fully assess the "RCF damage index" relating to this class of vehicle.

b) The AM class EMU wheel profile was modified by the manufacturer from the KR standard profile to avoid anticipated high wheel flange wear, itself related to the high vehicle stiffness. During running rights approval KiwiRail acknowledged that modelling by the supplier of the proposed alteration, showed it to be safe, but had concerns that the change would impact on the rail maintenance requirements. Modelling in this study showed the profile change increases the formation of RCF over the KR standard profile.

Wheel Rail Interface

a. Lack of comprehensive grinding since 2015

b. Lack of artificial rail inclination on track structures

c. Lack of optimised wheel and rail profiles

Recommendations

To allow the Auckland Metro system to perform at an international standard, at current service levels and those proposed after CRL, the following actions are recommended.

1	The strategy for RCF management in the AMRN be altered from **management** of internal defects to **prevention** of internal defects. This is best achieved by planned RCF grinding at sufficient frequency to remove defects at their planer (not downward) stage.
2	By December 2021, the entire AMRN is free of internal rail defects, all emerging RCF has been removed, and the intermediate profile has been established on all WRI surfaces. This is best achieved by supplementing the current rail replacement programme (RNGIM) and the national grinding programme.
3	All new rails are ground to the intermediate profile as soon after installation as possible. This is best achieved by establishing a minimum rail grinding capability in New Zealand.
4	The AMRN grinding programme be managed to a formal plan. This is best achieved by the parties preparing a 30-year plan for rail grinding in the AMRN as part of a comprehensive AMRN maintenance and renewals regime. As a minimum the plan should include elements noted in the detailed recommendations in the body of the report.
5	The key localised track contributors to accelerated RCF in the AMRN be removed. This is best achieved by KR preparing a scoping, funding and implementation plan to carryout deferred track renewal works where these are not included in other programmes. A gap analysis may be required to identify the scope of these. As a minimum the scope should include elements noted in the detailed recommendations in the body of the report.
6	The AMRN infrastructure asset be managed to a formal asset management plan (AMP). This is best achieved by the parties collaborating on the development of a multi-year asset management plan for the AMRN. As a minimum the plan should include elements noted in the detailed recommendations in the body of the report. The AMP should sit alongside AT's AMP for transport assets owned by AT, enabling exchange of knowledge and transparency of asset management and performance between KR and AT.
7	That the AM class vehicle wheel profile(s) and the AMRN rail profile be optimised. This is best achieved by the establishment of an inter-stakeholder technical WRI group. The group would be briefed to identify, and recommend, optimised wheel and rail profiles, possibly unique to the AMRN, and concurrently recommend agreed wear limits.
8	That the AM class vehicles be progressively modified to reduce their primary yaw stiffness, balanced against ride quality for customers. This is best achieved by the establishment of an

	inter-stakeholder technical group. The group would be briefed to establish the minimum allowable primary yaw stiffness (considering both dynamic stability limits and ride quality issues) and identify alternative approaches to achieving this. The brief needs to address how to minimise flange wear from wheel / rail contact on intermediate radius curves, while still allowing an RCF friendly wheel / rail profile combination.

These recommendations clearly come with a cost. Funding for maintenance of the Auckland network is not within the working group's TOR yet additional funding will be essential in providing the comprehensive future grinding plan and the track and vehicle asset upgrades which is considered essential to preventing this problem re-occurring.

CONTENTS

Executive summary 2

Acronyms 1

Key Referenced Documents 2

Acknowledgements 3

1. Report background 4

2 Why RCF is a concern 4

3 Brief technical notes on RCF formation 5

4 Historic context 6

5 TOR 8

6 Working Group 8

7 Governance 8

8 Approach to the assessment 9

9 Root cause 10

10 Key findings track 11

11 Key findings vehicles 12

12 Key findings wri 12

13 External review 12

14 Action / inactions leading to rcf 13

15 Recommendations 13

16 Minor issues 18

Appendix 1: TOR 1

Appendix 2: Development Timeline 11

Appendix 3: Technical extracts 12

Appendix 4: Summary of key reports 16

I. Summary of Autech 16

ACRONYMS

AMP	Asset Management Plan
AMR	Auckland Metro Recovery
AMRN	Auckland metro rail network
ANAA	Auckland Network Access Agreement
AT	Auckland Transport
CAF	Construcciones y Auxiliar de Ferrocarriles
CRL	City Rail Loop
EMU	Electric Multiple Unit
KR	KiwiRail
NDT	Non-destructive testing
NZTA	New Zealand Transport Agency
RCF	Rolling Contact Fatigue
RNGIM	Rail Network Growth Impact Management
TCO	Total cost of ownership
TSR	Temporary Speed Restriction
WRI	Wheel Rail Interface
WSP	WSP Global Inc (OPUS)

KEY REFERENCED DOCUMENTS

Key information relied upon for this assessment is contained in the following three reports:

1. Autech 1: DE01-00662_KiwiRail-Wheel-Rail-Study-Auckland-Transport_Report_08-03-00299-2-00_191217c-DVS.pdf

2. Autech 2: DE01-00662_KiwiRail-Wheel-Rail-Study-Auckland-Transport_Report_Rail Maintenance and Rail GrindingRev2

3. SNC 1: SN0193488 _KiwiRail Independent Review of RCF Damage Issue A(draft2) (Final).pdf"

ACKNOWLEDGEMENTS

The working group was supported by the wider KR, AT, CAF and Transdev technical capabilities as required.

1. REPORT BACKGROUND

1.1. KiwiRail (KR), as track infrastructure owner and maintainer, and Auckland Transport (AT), as specifier of passenger rail services are concerned about the rapid propagation of both early stage RCF and late-stage internal rail defects, initiated by RCF, in a significant percentage of the rails in the Auckland Metro Rail Network (AMRN). Of greatest concern is the reaction that was necessitated by this rapid growth, namely the imposition of a network wide 40km/hr speed restriction (17 August 2020) as a key risk management strategy while urgent rail replacement was undertaken.

1.2. Concerns about the increase in RCF and internal defects have been growing for some time and as a response KR and AT identified and initiated several work streams:

1.2.1. Study: Rail Consultants Autech and SNC were separately commissioned by KR to study the rapid rise in RCF and identify any root cause.

1.2.2. Manage: KR Auckland Area resources were instructed to maintain passenger safety and passenger services (to the extent possible) and by inspection and rapid deployment carry out any immediately urgent rail replacement.

1.2.3. Plan: Ensure that already proposed KR works; the RNGIM project and the national grinding project; had elements in their scope that would prevent such a situation occurring again.

1.2.4. Review, comment and recommend: A temporary technical group was created to (a) review information available, (b) create a clearer statement of root cause than provided by the Consultants in 1.2.1 above (c) comment on the likely effectiveness of 1.2.3 above, (d) recommend changes, and (e) resolve the importance of the many causes unofficially being postulated as root causes. See Appendix 1 TOR.

2 WHY RCF IS A CONCERN

2.1. RCF is of concern at a corporate and governance level in two main areas. These are:

2.1.1. Risk management and

2.1.2. Total Cost of Ownership (TCO).

2.2. Risk Management

Since the fatal Hatfield rail-crash on 17 October 2000 the risk of “managing” RCF rather than removing it has been well understood by network users and operators. RCF initially has a linear, predictable propagation, but this is followed by a nonlinear stage which is not predictable. If the RCF is “inspected and managed” rather than removed, this creates the risk of sudden failure as experienced at Hatfield.

By relying on “inspect and manage” for a longer period than appears to be prudent, the 40km/hr and urgent rail replacement works has been a necessary risk reduction strategy. Involvement in these urgent remedial works was purposefully excluded from the RCF Working Group’s TOR to avoid delays to the Auckland Metro recovery (AMR) programme.

2.3. Total Cost of Ownership

The steel rails are an expensive part of the rail infrastructure. Most rail infrastructure providers pay significant attention to life extending rails by managing the permitted wheels (axle loads, steering and profile) that operate on the network, by track design (cant and gauge), and by grinding and lubrication. Constraining budgets or constraining on-track time to the extent that these preventative works cannot be carried out leads inevitably to an increase in TCO.

A regime that provides sufficient rail grinding (and eventually rail replacement) will never reach the stage where risk management action is required to manage internal defects from RCF. However, if engineering fundamentals related to causation of RCF are not fully managed, the TCO of such an approach can be high.

3 BRIEF TECHNICAL NOTES ON RCF FORMATION

3.1. Rolling contact fatigue (RCF) is the description given to damage created in rails (and wheels) due to high contact stresses. In the rail this damage usually appears first on the surface with cracks forming in the direction of travel. If untreated, at some stage of their development, the cracks dip downwards as they propagate. Best practice removes cracks before they turn downwards. If untreated by grinding the cracks grow and over time create a risk of sudden rail failure.

3.2. RCF is a natural result of wheels passing over the rail. RCF and the consequential internal defects can be accelerated by many causes ranging from environmental to rail and wheel profiles. That RCF develops in rails in the Auckland Metro Network is normal.

3.3. The initiation of RCF is slowed by reducing the presence of all factors that cause RCF (reducing vehicle effects, harder rail, compatible wheel and rail profiles, lubrication, preventative track maintenance etc.)

3.4. The development of RCF is reset to “new condition” by grinding. The timing and quality of the grinding determines the resulting risk and TCO of the rail.

3.5. As well as removing RCF to extend rail life, routine grinding improves steering, wheel wear and even energy use.

3.6. As the formation of RCF is a normal part of the life cycle of rail in any medium density metro system such as the AMRN what the RCF working group has been asked to consider is not RCF, per se, but to identify any causes that have unreasonably accelerated RCF.

3.7. The technical background to the assessment includes the understanding that:

3.7.1. At a certain point in its development RCF growth is non-linear, so, if untreated, and with no accelerating cause, RCF growth will still accelerate. Surface RCF is not overly dangerous, so timing of grinding is important to TCO but not usually safety critical.

3.7.2. At a certain point in their development the internal defects caused by RCF also have a growth that is non-linear, so, if untreated, with no accelerating cause, will accelerate and propagate from a surface to internal defect. These internal defects do pose a risk and if allowed to form need to be removed, and closely monitored until removed.

3.7.3. Therefore, accelerated internal defects as observed in Auckland may be caused by some external agent that accelerates RCF e.g., underlying formation and drainage issues, wet climate, localised track geometry issues, high stiffness vehicles…. or it can be caused by normal load patterns, aged infrastructure, and insufficient remedial works.

4 HISTORIC CONTEXT

4.1. As shown in Appendix 2 "Auckland Rail Development Timeline", several Crown / Region funded initiatives have taken place to create and enable the Auckland Metro service. In summary they are:

DART	2004 → 2012	Additional track and formation in some areas.
Above rail	2004 → 2012	Key stations new or upgraded
AEP	2006 → 2013	New 25kv electrified network (from Papakura to Swanson)
ASP	2006 → 2013	New signalling infrastructure and ETCS Level 1 Automatic Train Protection
EMU	2007 → 2014	New build (operate from Papakura to Swanson)

4.2. This has resulted in the situation where new vehicles are operating with new overhead equipment, using new signalling, and mainly operating out of new stations but trains are travelling over mainly pre-existing aged track on historic formation.

4.2. Those with a vision for Public Transport in Auckland have long desired a fast, frequent, and efficient passenger train system for the area. The beginning of that vision was realised in April **2014** with an EMU service commencing on the Onehunga line. The benefits to passengers of a modern EMU service are their control and power systems that give the vehicles the ability to accelerate and brake rapidly, routinely operating just below the skid threshold. The longitudinal forces applied to the rail in these situations are the ideal conditions for forming RCF in the rail.

4.3. In **2014** AT commissioned a review by Network Rail Consulting on the capability of the AMRN to support the proposed EMU service. The review concluded that the network was not fit for purpose and recommended an investment of $100M. This was included in NZTA funding plans but was not approved.

4.4. Since the introduction of the EMU service KR has observed accelerated rail wear and accelerated growth of RCF and the resulting internal defects in rail. The accelerated growth of RCF and internal defects has occurred on all metro routes in Auckland:

- Routes that carry predominantly EMUs
- Routes with a mix of EMUs and freight
- On the Papakura to Pukekohe section where no EMUs operate.

This indicates that a significant underlying cause is most likely to be aged track on historic formation. That is rail/sleepers/ballast/formation that have high accumulated million gross tonne (MGT) passing with insufficient levels of maintenance, including grinding, and insufficient renewals to remedy the effects of those loads.

4.5. However, the presence of unusual wear on relatively new track in areas where EMUs alone operate, comparisons with Wellington (low occurrence of RCF) which has similar track conditions and similarly low levels of rail grinding, and comparisons on the freight routes generally (also low occurrence of RCF), also points to the likelihood of a vehicle-track interaction that is unique to Auckland EMUs.

4.6. From **2017** KR and AT engaged on concerns of WRI issues that was causing track and vehicle wheel damage, providing a poor customer ride experience in some areas, and was causing noise issues.

4.7. In March **2018** KR, in the context of approvals for the next tranche of EMUs, engaged with AT on issues around bogie rotational stiffness. The parties engaged by creating a working group to examine the issues.

4.8. The group first met 13/04/**2018** and continued until 06/09/**2019**.

4.9. From July **2019** KR budgeted $28m of funding to undertake limited rail grinding nationally with an expected finish of 2023. A partial grinding of the AMRN during 2020-21 was proposed as part of this programme.

4.10. As a general historic statement, between 2014 and the WSP report (see 4.11) there was little renewals investment and the AMRN experienced increasing failures, speed restrictions and TSRs during times of high temperatures. The ANAA funding was seen as insufficient for, and not a sufficient funding vehicle for required renewals. This concern led to the WSP review, which led to the immediate allocation of $10m of funding, from NZTA. This provided the momentum to create the RNGIM benefit / cost study and subsequent significant funding.

4.11. The WSP review was commissioned by AT/KR/TDAK and commenced in March **2019**. WSP provided an interim assurance report in May **2019** which recommended a programme of immediate actions.

4.12. WSP reported on the state of the AMRN in terms of its fitness for purpose for delivering the service and patronage task for the future, concluding that they were not fit for purpose. The comprehensive report provided a significant number of detailed recommendations.

4.13. The WSP report noted emerging RCF and the accelerated spread of rail internal defects. The report supported the “inspect and manage” approach to the existence of internal defects. This would be a difficult position to defend if continued for a lengthy period, particularly should a failure event occur.

4.14. The KR RNGIM project (funded in February 2020) proposes to provide accelerated investment in rail network renewals to correct some historic formation, drainage, and track issues. The stated goal is to bring the network up to a “modern metro standard”. The scope did not specifically address causes of RCF, nor did it address future RCF mitigation. While the goal is correct and the areas of investment sound, the RNGIM work bank is unlikely to achieve its stated goal.

4.15. Over this time, KR field staff who are responsible for day-to-day risk, had growing concerns about the extent of internal rail defects being identified and new inspection systems were introduced to detect shallow defects to help identify the possible “bow wave” of deeper defects that could eventually be a safety threat to the system.

4.16. To try to gain a better engineering understanding of the situation KR separately engaged two consultants to carry out an onsite review. AT supported the reviews where they touched upon wheel/rail matters. The focus of the reviews was on the wheel/rail interface as this is always the logical starting point of a review on RCF. The consultants reported in January **2020** but in a manner that was difficult to action, although several work-streams around rail grinding specification and strategy were implemented.

4.17. On 13 August **2020** stakeholders were advised that from Monday the 17th of August train speeds would be reduced to 40km/hr across the AMRN while urgent track upgrades were carried out.

5 TOR

A copy of the TOR used to brief and manage the RCF working group is provided in Appendix 1.

5.1. Major Variations

No significant changes were made to the TOR for the RCF working group up until the date of this report.

6 WORKING GROUP

6.1. Team members are:

Ted Calvert	Independent Coordinator with experience in managing multidisciplinary rail designs and projects).
Mark Fleet	KR, Track (civil) expertise
Mark Wilson	KR, Rail vehicle (mechanical) expertise; Data management
Andrew Hunt	KR, Rail vehicle (mechanical) expertise
Craig Inger	AT, Manager, Train Services
Damian Flynn	AT, Manager, Strategic Rail Development
Brendon Jones	CAF, Depot General Manager CAF New Zealand
Stuart Ferguson	CAF, Maintenance Manager CAF New Zealand
Gary Iddon	Transdev Auckland, GM Operations

7 GOVERNANCE

7.1. The RCF working group reports to a technical “Oversight Group”. The Oversight group consists of:

Murray Burt	Chief Engineer (AT)
John Skilton	Chief Engineer (KR)
Adam Williams	Executive General Manager - Rolling Stock Asset Services (KR)
Israel Gomez	General Manager (CAF)

The Working Group reports to the Oversight Group weekly or as required.

7.2. The Oversight Group reports to the Auckland Metro Rail Executive Steering Group which consists of:

Todd Moyle	Chief Operating Officer (KR)
Mark Lambert	Executive General Manager Integrated Networks (AT)
Rob Gibbes	Executive General Manager Construction (KR)
Christian Messelyn	Portfolio Delivery Director, Alliances (AT)
Siva Sivapakkiam	Executive General Manager, Operations (KR)
Stacey Van Der Putten	Group Manager, Metro Services (AT)
Greg Pollock	Managing Director New Zealand (Transdev)
Erin Wynne	Observer (MOT)

8 APPROACH TO THE ASSESSMENT

8.1. The reference point for the approach is that there are three legs to RCF:

- Track
- Vehicles and
- WRI (wheel/rail interface)

8.2. The point of reference for track, and WRI are the two major reports from Autech and SNC.

In terms of track, the group relied on these reports as “expert” and “comprehensive” but also referenced its own expertise (primarily Ted Calvert and Mark Fleet).

The point of reference for the vehicle and its side of the WRI has been the SNC modelling works.

In terms of vehicles, the group has relied on the SNC modelling as “expert” but not “comprehensive”. It has also referenced its own expertise (primarily Andrew Hunt, Mark Wilson, Brendon Jones, and Stuart Ferguson).

8.3. Autech, SNC and the body of literature on RCF indicate that vehicle design can have a significant impact on the growth of RCF. “RCF friendly designs” have been explored overseas from as early as 2005 but were not common until 2012 or later. The Auckland EMUs were commissioned and accepted primarily based on safety. To have a reference point for the vehicles (and further information on WRI) a modelling study was briefed with SNC-Lavalin.

8.4. The track reports noted above and the body of literature on RCF can provide long lists of causes of RCF observed and studied during the last 20 years. To reduce time and cost in this study, the philosophy of Ockham's Razor, has been used to reduce the likely key causes in Auckland. That is, the philosophy adopted is that the cause of the current situation is likely to be a collection of normal problems rather than some unusual, hither to unknown, issue. The conclusions of the reports noted above and the expertise and judgement of members in the group at commencement (Andrew Hunt, Mark Fleet, Mark Wilson, and Ted Calvert) were used to reduce the initially created list of possible causes. The full list has been documented, and to some extent listed in section 16 of the report.

8.5. As the assessment took place in the year 2020, not the year 2000 (when RCF came to the world’s attention due to the Hatfield derailment in the UK) the starting point has been that the key causes of RCF have been researched for 20 years and are well known. These are mainly listed in the Autech and SNC reports, in the pre-existing knowledge of group members or are available from literature. The Autech and SNC reports found no unusual causes of accelerated RCF on the AMRN, and this has been accepted.

8.6. The co-ordinator's role has been to leverage the team and the two key reports for the purpose of making an initial list of causes and then using the conclusions from the reports, logic, and the team resources to class them as of low or high importance in relation to RCF on the AMRN.

8.7. Agreed key causes have been assessed and form part of the recommendations in this report.

8.8. Where cause impacts have been assessed to be low, where expert members disagree or where causes are a natural part of a rail service and cannot be removed, these have been collated and presented at the end of the report. See section 16, Minor Issues below.

9 ROOT CAUSE

9.1. The cause of RCF, by the definition of RCF, must be within the wheel/rail interaction area. The root cause therefore must be in the way the wheels and the rail interact. In the AMRN it is primarily how 91lb/50kg rail interact with the wheels of AM class EMU. The root cause focus, prior to this report, has correctly been on the wheel profile and the rail profile. This is because with perfect track, and perfect vehicle "steering", the mismatch of the shape of the wheel and the shape of the rail is the key driver of repetitive high forces.

9.2. Both rail consultants (Autech and SNC) indicated that further study was merited on the wheel and rail profile, but it was **not** the root cause of the accelerated RCF.

9.3. This indicates that either the track is less than ideal in parts, the vehicle above the wheel has some less-than-ideal characteristics or both effects are at play in different situations. Both can of course be individually at work in separate locations. Or both can interact in the same location where, for example, weakly supported rail moves slightly, requiring more of the vehicle steering and if that "more" is not available, high forces come into play.

9.4. Accelerated RCF and the accelerated growth of internal defects have been observed in rail over the full AMRN. This includes new rail and new formation used only by EMUs, implying a vehicle effect. It also occurs on old rail and old formation with no EMU use, implying a track cause; however, this is less apparent outside Auckland, again implying a vehicle effect.

9.5. The conclusion of the working group is that there is no reason to disagree with the Autech report which identifies that there is no single outlier cause, but rather a widespread set of localised causes. These stem from a track asset that was not "fit for purpose" prior to the commencement of a more frequent, more demanding modern EMU operation. To have historically counteracted this would have required significant investment or would otherwise have required ongoing operational management interventions. To clarify, the "not fit for purpose" encompasses a track, a vehicle, and a practice issue.

Track: The track asset on the AMRN, as identified by Network Rail Consulting in 2014 required investment in terms of age, state of repair and underlying formation issues.

Vehicle: The vehicle, as shown by its stiffness characteristics, is best suited to track that is maintained to a high standard and has a reasonable track modulus. It has a wheel profile that was intended to reduce wheel flange and rail side wear but has been found to have a propensity to cause RCF on perfect track.

Practice: As neither sufficient track upgrades were carried out nor was the vehicle designed and operated for track of low stiffness (often poorly maintained), the only practice that would have avoided the result would have been frequent grinding and rail removal where, due to age, defects were beyond the reach of grinding.

9.6. The closest single root cause could therefore be stated as a missed opportunity during 2014-2017 to implement the recommendations of the 2014 Network Rail Consulting report. Appropriate responses would have been to:

a. Upgrade the track asset OR

b. Modify or operate the units in a way that specifically recognised the track was not upgraded OR

c. Introduce a rigorous grinding regime OR

d. Study and implement the lowest TCO approach that optimised all three issues.

To a large extent the findings of this report do not differ from the 2014 Network Rail Consulting report.

9.7. A significant number of key causes are identified below. They are listed in the three categories of track, vehicle and WRI.

10 KEY FINDINGS TRACK

Key Causes Track

Track asset related causes of accelerated RCF:

a. Historic under investment in the track asset prior to 2014 and up to August 2020.

b. Insufficient rail grinding from 2015 to August 2020

c. The existence of multiple sites where track condition is sub optimal:

  i. Track geometry and gauge exceedances including at welds and bolted joints.
  ii. Aged timber sleepers unable to hold rail in place adequately.
  iii. Historic wheel burns/squats causing sudden dynamic loads.
  iv. Sub-optimal application of cant, mainly uncorrected past practices.
  v. Significant sections of the network that have low track modulus (low combined stiffness of rail, sleeper, ballast, and formation, at times aggravated by poor drainage).

d. Possible track related environmental contributor to accelerated RCF.

The speed of RCF propagation varies between very dry and very wet climates. As noted above RCF commences as tiny defects that propagate in the direction of travel until they turn downwards and develop into “internal defects”. The speed of crack growth is significantly affected by the presence of liquids (water or grease) that are trapped in the cracks, are compressed by the wheel and the pressure extends the crack. It is likely that Auckland’s climate has been a partial contributor to the accelerated growth.

11 KEY FINDINGS VEHICLES

Key Causes Vehicles

a. High primary yaw stiffness and high x-factor

Modelling shows that these factors do NOT contribute to RCF on perfect curved track for radii less than 1000m. A reduced primary yaw stiffness should reduce RCF on poor quality track, possibly including track that has low track modulus. Modelling to demonstrate this was not included in the brief.

A reduction in primary yaw stiffness would reduce vehicle wheel flange wear.

b. Wheel profiles modified from KiwiRail standard profiles

The most common wheel profile on the national network is classified as TRA-1. Modelling shows that changing the AM unit wheel profile to TRA-1 will reduce the vehicle’s propensity to cause rail RCF. However, TRA-1 is unlikely to be the optimal profile and a change to TRA-1 will come at the expense of flange wear and rail side wear, requiring the use of existing on-board lubricators or trackside lubrication to mitigate this.

12 KEY FINDINGS WRI

Key Causes WRI:

a. Lack of comprehensive grinding since 2015
b. Lack of artificial rail inclination on track structures
c. The AM class EMU wheel profile favours wheel life (and rail side wear) over RCF minimisation. The most common wheel profile on the national network is classified as TRA-1. Modelling shows that changing the AM unit wheel profile to TRA-1 will reduce the vehicle’s propensity to cause rail RCF. However, TRA-1 is unlikely to be the optimal profile and a change to TRA-1 will come at the expense of flange wear and rail side wear, requiring the use of existing on-board lubricators or trackside lubrication to mitigate this, and/or changes to the vehicle stiffness to mitigate it.
d. Insufficient emphasis on developing and adopting a wheel / rail profile that optimises the TCO of the holistic rail system. Modelling shows that in terms of RCF generation the TRA-1 profile on the intermediate rail profile is preferred to the current AM class EMU wheel profile, but it is unlikely to be the optimum combination of profiles.

13 EXTERNAL REVIEW

As noted above, while making use of their own expertise when required, the reference point for the group has been the studies by Autech, SNC and the modelling work in by SNC-Lavalin.

13.1. Track

- Reports by Autech
- Report by SNC-Lavalin
- Report by WSP
- Phil Rogers and Paul Molyneux-Berry (SNC UK) both involved in the Network Rail RCF and whole-life rail model investigations have provided inputs as required.

13.2. Vehicle

- Vampire modelling by SNC-Lavalin

13.3. Wheel / Rail interface

- Vampire modelling by SNC-Lavalin.

14 ACTION / INACTIONS LEADING TO RCF

As noted above, a fit for purpose track and / or a fit for track vehicle operation and regular grinding provides the lowest TCO for a system. However, if funding is not available for fit for purpose track, vehicle design and operation cannot be altered, and timely surface grinding is not possible, then the funding of remedial grinding (removal of defects) is essential to avoid risk even if TCO goals are compromised. The following inactions led to the current situation:

14.1. There was underinvestment in the track asset prior to 2014.

14.2 There was insufficient consideration during vehicle design and wheel profile design about the standard of track on which the vehicles would operate. Once it was known that track remedial works were not funded there was insufficient review of both vehicle design and vehicle operating parameters (e.g., speed, acceleration, braking).

14.3. There was insufficient rail grinding between 2015 and 2020.

14.4. There was insufficient recognition of the non-linearity of the speed of growth of internal defects, leading to a regime of monitoring rather than early defect removal. Essentially the steps to combat RCF growth were too little and too slow.

15 RECOMMENDATIONS

15.1 RCF management

From a safety and TCO perspective it is unwise / unsafe to manage RCF and its consequential internal defects by monitoring and just-in-time removal.

- Recommendation 1: The strategy for RCF management in the AMRN be altered from **management** of internal defects to **prevention** of internal defects. This is best achieved by planned RCF grinding at sufficient frequency to remove defects at their planer (not downward) stage.

15.2 Grinding and rail works.

- There are many reasons to grind rail, the primary two reasons are risk mitigation and TCO. Just relying on frequent grinding, rather than also addressing underlying track issues will eliminate the risk of RCF but at a high long-term cost. Minimising TCO is about optimising the full “system” so that service goals are met at least cost by investing in vehicles to make them less damaging and investing in track, so it is more resilient.

- Recommendation 2: By December 2021, the entire AMRN is free of internal rail defects, all emerging RCF has been removed, and the intermediate profile has been established on all WRI surfaces. This is best achieved by supplementing the current rail replacement programme (RNGIM) and the national grinding programme.
- Recommendation 3: All new rails are ground to the intermediate profile as soon after installation as possible. This is best achieved by establishing a minimum rail grinding capability in New Zealand.

Notes, grinding.

- The grinding processes needs to include:
  - Remedial grinding (remove all known rail defects where this is economic to be done by grinding rather than re-rail).
  - Full network preventative grinding. All rail, including new rail, be ground to an agreed uniform profile. Noting the profile chosen for Pukekohe to Papakura may be different to the rest of AMRN.
  - Grinding an artificial 1:20 rail inclination on all existing track structures in the AMRN.
  - Any new track structure proposed be purchased with a factory applied 1:20 inclination head profile or site ground after installation.
  - Before completion, the AMRN grinding programme is peer reviewed.
  - Review of the process of specifying, planning and delivery of grinding which appears to be somewhat fragmented between the National Grinding Programme team, Professional Head of Track, the Network Services Team, the AMR project and RNGIM.
- Recommendation 4: The AMRN grinding programme be managed to a formal plan. This is best achieved by the parties preparing a 30-year plan for rail grinding in the AMRN as part of a comprehensive AMRN maintenance and renewals regime. As a minimum the plan should include:
  a. Experience gained during the current National Grinding Programme.
  b. A philosophy for grinding, noting that the AMRN is heavily dominated by one vehicle type and one-wheel profile.
  c. Documenting and justifying the approach to be taken for identifying timing for grinding, (mix of visual inspection, internal rail flaw detection, and accumulated MGT since last grinding).
  d. The approach to grinding newly installed rail.
  e. Procurement issues (contract, own, dry hire, mix of own and hire) and assumptions used for the future.
  f. 30-year grinding programme with budget prorated on the 2020-23 contract.
  g. Lubrication philosophy and plan.

h. Assumed wheel profiles coming into the network, existing freight vehicles and future freight or passenger vehicles.
i. Wayside inspection systems to ensure wheel profile compliance. Noting that the EMU fleet are in the depot often enough to achieve profile management without trackside systems.
j. Vehicle mounted rail profile measuring systems to ensure rail profile compliance. For asset management planning it is important to be able to understand the overall health of the WRI rather than just identify sections that are out of code.
k. Emerging technologies (e.g., vision systems for inspection of early stages of RCF).
l. The plan should be in a format that will slot into the emerging AT and KR route asset management plans.

15.3 Works required to reposition the AMRN.

Recommendation 5: The key localised track contributors to accelerated RCF in the AMRN be removed. This is best achieved by KR preparing a scoping, funding and implementation plan to carryout deferred track renewal works where these are not included in other programmes. A gap analysis may be required to identify the scope of these. Specifically, the following situations need to be addressed:

1. Removal of all situations that can lead to rail roll, including removal of aged timber sleepers.
2. Removal of all causes of sudden vertical or lateral dynamic forces, including out of specification welds, historic wheel burns and squats.
3. Remedial work to remove areas of low track modulus (low combined stiffness of rail, sleeper, ballast, and formation, at times aggravated by poor drainage).
4. Removal of all areas of tight gauge, noting this will probably be removed as part of the removal of aged timber sleepers as the tight gauge is a legacy of historic track design on straights.
5. Correction of all areas of suboptimal cant. To achieve that analysis and cross-party discussions are required prior to implementation.
6. Progressive removal of bolted joints.
7. Identification and removal of the reasons that have created a culture of reactive maintenance practices that allow out-of-code situations in track geometry and gauge exceedances. The reasons are often under funding, limited windows for inspection and maintenance, and training issues.
8. Identify and review the current lubrication strategy (including on vehicle). Implement necessary changes. This may require routine monitoring of rail friction by use of a tribometer, to check for over lubricating the gauge face such that the top-of-rail becomes contaminated.

Notes, track upgrade

- It is certain that a comprehensive, ongoing rail management programme (grinding and rail replacement) will prevent the current issue (reactive focus on internal rail defects) occurring again. However, it is a costly approach and only remedies the effects of underlying issues, it does not remove the underlying issues. It is imperative that the underlying track asset is upgraded, and these issues are quantified for attention where they are not already part of an existing funded programme.

- Fundamentally the key recommendation of this assessment is little different to the intent of the recommendation of the WSP report (January 2020) and Network Rail report May 2014. This could be stated as: "To allow the Auckland Metro system to perform at an international standard, at current service levels and those proposed after CRL, three actions are needed":
  1. The track infrastructure needs to be repositioned; that is significantly upgraded; in a similar way but to a more extensive scope, than identified by the WSP report.
  2. Once the repositioning is complete (say over 3-years), there needs to be in place a funded asset management plan (AMP) that is implemented/managed by those most qualified to implement/mange it, and by following processes that simplify implementation.
  3. Vehicle causes have a material influence on RCF propagation, so vehicle design and maintenance need to be factored into the AMP. In the short-term changes are needed to the wheel profile. A change to the bogie primary yaw stiffness would provide longer term benefits.

Recommendation 6: The AMRN infrastructure asset be managed to a formal asset management plan (AMP). This is best achieved by the parties collaborating on the development of a multi-year asset management plan for the AMRN. The AMP should sit alongside AT's AMP for transport assets owned by AT, enabling exchange of knowledge and transparency of asset management and performance between KR and AT. The asset management plan needs to cover:

- Predicted service demands (vehicle frequency and ride quality)
- Emerging inspection and maintenance technologies (e.g., automatic vehicle inspection systems to detect out of specification wheels).
- Vehicle design acceptance criteria
- Funding
- Implementation

15.4 Vehicle Study

The AM class EMU characteristics have been studied in terms of its propensity to contribute to accelerated RCF. The wheel profile needs to be modified to balance TCO with ride quality for passengers. The vehicle stiffness has been shown to have little impact on RCF for perfect track. However, logic, literature, and the Matangi design experience indicate that a vehicle of high stiffness, on low modulus track with maintenance tolerances that are more suited to a freight railway is likely to accelerate RCF.

The following approach is suggested:

- Engage with vehicle stakeholders to assess their acceptance of the recommendations on wheel profile and vehicle stiffness.
- If necessary, commission further studies including to assess "RCF damage index" when perfect track in the model is replaced with representative track. The modelling

would be for the existing vehicle stiffness and the assessed minimum safe operating stiffness. [Note that the Vampire tool is weak in this area and is currently being upgraded].

- Wheel profile testing: see SNC-Lavalin recommended approach.
- Vehicle stiffness, see proposals from CAF.

<u>Recommendation 7:</u> That the AM class vehicle wheel profile and the AMRN rail profile be optimised. This is best achieved by the establishment of an inter-stakeholder technical WRI group. The group would be briefed to identify, and recommend, optimised wheel and rail profiles, possibly unique to the AMRN, and concurrently recommend agreed wear limits.

<u>Recommendation 8</u>: That the AM class vehicles be progressively modified to reduce their primary yaw stiffness, balanced against ride quality for customers. This is best achieved by the establishment of an inter-stakeholder technical group. The group would be briefed to establish the minimum allowable primary yaw stiffness (considering both dynamic stability limits and ride quality issues) and identify alternative approaches to achieving this. The brief needs to address how to minimise flange wear from wheel / rail contact on intermediate radius curves, while still allowing an RCF friendly wheel / rail profile combination.

15.5 Cross check for Recommendations

Magel, Sroba, Sawley and Kalousek provide a check list of areas track owners should consider minimising the formation of RCF. This has been used to test the recommendations provided above.

1. Install harder, cleaner rail steels since they are more resistant to both initiation and propagation of cracks that contribute to RCF: **This is current practice.**
2. Manage friction control at the top-of-rail to a value of 0.3-0.35. Avoid over lubricating the gauge face such that the top-of-rail becomes contaminated: **Included in the lubrication notes.**
3. Minimize dynamic loads, especially those associated with track geometry errors. **Recommended above**.
4. Control track gauge, especially in sharp curves. Curves should not exceed 13mm wide gauge and tight gauge should be avoided on tangent track. Noting that this has implications for flange wear limits as well. That is flange wear increases affect track gauge. This should therefore include a review of wear and back-to-back limits for wheels in this context **Recommended above.**
5. Rail flaw detection information should be used as part of the planning process for rail grinding. **Recommended to be included in the grinding plan above.**
6. Encourage self-steering bogies, ones that limit vertical dynamics and optimise stability. **Recommendation will be considered after modelling.**
7. Optimise Cant. **Recommended above.**
8. Enforce vehicle hollow wheel limits. **Recommended for inclusion in the AMP.**

9. Control rail roll. Key causes in AMRN appear to be aged sleepers and low track modulus. **Recommended above.**

16 MINOR ISSUES

During the assessment, the Group noted that there were several concerns raised by individuals and papers that were unlikely to be key influencers but still needed to be considered, understood and if possible “put to bed”. These are listed below with interim conclusions.

16.1 Could CAF’s on-board lubrication systems cause RCF?

There is no known mechanism where lubrication initiates RCF. Well-designed lubrication is recommended in conjunction with grinding to extend wheel and rail life and improve steering. This is noted in the report. In unidirectional traffic situations lubricants can accelerate the growth of RCF as does the presence of water. In Auckland’s wet climate water probably has a higher effect than friction modifiers. See also 16.4.

16.2 Can high carbon steel used in rail manufacture cause RCF?

This is discussed in “Rail metallurgy (1) and (2)” in Appendix 3.

16.3 Can the process of head hardening create rail susceptible to RCF?

This is addressed in the Autech report. The consultants advise that the hardness of the hardened rail restricts formation of RCF but without grinding head hardened rail will get to a stage where it will instead accelerate it.

16.4 Can improper and inadequate trackside lubrication cause RCF?

Having a low coefficient of friction cannot prevent RCF but it does slow the commencement of RCF. Literature routinely recommends both lubrication and grinding to extend rail life. However, Autech and AREMA publications warn that the lubrication plan needs intelligent design and regular monitoring. Autech does not directly say it, but they imply that if lubrication is not going to be managed it may be better not to lubricate. This seems to be a rather defeatist position to take, and KR and the EMU operator need to work together on a well-managed system. This is noted in the report.

16.5 Could the presence of welds every 12.8m cause a harmonic that causes RCF?

Rail used to be supplied in 12.8m lengths; it has since been welded up at these spacings. Such frequent welds can lead to challenges to maintaining good geometry. However, the bogie spacing is quite different to 12.8m or any multiple of 12.8m. The mechanical members on the group consider harmonics with the rail joint spacing to be unlikely but do have concerns about possible drive harmonics. In terms of welds a high-quality weld (alignment and geometry) and the correct hardness weld (+/- 30BH) are both important in avoiding localised RCF for reasons other than harmonics.

16.6 Does uni-directional running causes RCF?

This is a documented contributor to RCF, but uni-directional running is fundamental necessity for a high-capacity network so the knowledge cannot be applied in practice. SNC suggest bi-directional running as a possible solution, but the cost (signalling, cross overs, and passenger confusion) make it an academic solution only.

16.7 Are there fundamental codes and standards errors causing RCF?

Autech could not find any key concerns with the codes other than some typos. But they could find plenty of examples when the field did not reflect the code. Poor state of maintenance can be a result of many things including lack of funding, lack of suitable equipment, lack of training or lack of on track time. See the recommendations about the need for a formal, funded, AMP to identify these issues and allow them to be rectified.

16.8 Are there any fundamental operations that are wrong and are causing RCF?

Autech could not find any key issues with the operations but suggested the vehicle characteristics be modelled.

16.9 Is it the normal EMU characteristics causing the RCF?

Autech note that by their nature EMUs accelerate RCF; ARUP references the need for careful attention to RCF in EMU design and references the handbook "Passenger Rail Best Practices Handbook". The issue the RCF working group is looking at is not "do EMU cause RCF?" (They do) but "is there any unusual cause in the Auckland EMU?" That is the focus of the modelling.

16.10 Is it high traffic density causing RCF?

High density reflects in a mix of high numbers of wheels passing and annual MGT imposed; the AMRN has experienced significantly increased MGT (in percentage terms). Internationally this would not be considered "high", but in areas it is high considering the accumulated tonnage over historic formation. The current aspirations in Auckland lie below high density (e.g., 2 minute frequency), and below high speed (say below 130kph) but still above a basic low frequency, low speed network. Essentially the AMRN is a medium density network and needs to be funded and maintained as such.

16.11 Could the hardness of the EMU wheels be causing RCF?

Autech address this concern and says it is not an issue. There are reasons why rail and wheel hardness should be similar (say +/- 10%), but it cannot be considered a key cause of RCF. See the argument presented in the extracts in Appendix 3.

16.12 There is a poor freight vehicle design that is causing the RCF.

This was not studied as part of the modelling. AT members of the group propose this idea due to the presence of RCF Papakura –> Pukekohe. KR members consider it less likely to be a key cause due to the low levels of RCF in Wellington and the freight network in general.

16.13 The axle weight of the EMUs may be too high for Auckland rail.

Autech has expressed the view that the axle loads are suitable.

16.14 50kg rail has a profile that is susceptible to RCF.

Autech has expressed the view that the profile is suitable.

16.15 The narrow rail gauge susceptible to RCF.

Autech has expressed the view that 1067mm has no real difference to 1000mm gauge and both are acceptable.

16.16 Inclining the rail at 1:20 causes RCF.

Autech has expressed the view that 1:20 is normal. The incline is to reduce lateral forces on the rail. Once there is an incline then the rail profile must take this into account. If the inclined profile is put on “flat” rail, then it becomes the wrong profile, and a new artificial profile is needed. See recommendations regarding turnouts where rail is mounted flat.

16.17 Are the EMU’s “over sensitive” to slight changes in track geometry? Is the vehicle incompatible with the reality of AMRN?

There is speculation that the vehicle design assumed a higher standard of track or was designed for speeds well above 110km/hr, or assumed mainly straight track (not large numbers of small radius curves). The SNC modelling was not briefed to exactly answer this question, but data collected on the stiffness of the vehicle and modelling of the wheel profile indicates that insufficient attention was given to matching the vehicle with all the operating conditions.

APPENDIX 1: TOR

To:	Steering Committee
From:	Ted Calvert (Independent Group Co-ordinator)
Date:	1 October 2020
Subject:	RCF Working Group TOR
Response	Discussion and approval

DRAFT
TERMS OF REFERENCE
RCF (Rolling Contact Fatigue) Working Group

1.0 INTRODUCTION

KiwiRail (KR), as track infrastructure owner and maintainer, and Auckland Transport (AT), as specifier of passenger rail services are concerned about the rapid propagation of rail defects, initiated by RCF, in a significant percentage of the rails in the Auckland Metro Network. Of greatest concern is the imposition of a network wide 40km/hr speed restriction as a necessary risk management strategy while urgent rail replacement takes place.

2.0 BACKGROUND

As a response KR and AT have identified and initiated several work streams:

2.1 Study: Rail Consultants Autech and SNC were separately commissioned to study the rapid rise in RCF and identify any root cause.

2.2 Manage: Auckland Area resources were instructed to maintain passenger safety and passenger services (to the extent possible) and by inspection and rapid deployment carry out any immediately urgent rail replacement.

2.3 Plan: Auckland Area resources, with the Professional Head of Track (KR) were instructed to leverage two programmes already in place to ensure that they would prevent future unmanageable propagation of rail defects, from RCF. This included the RNGIM project and the Auckland Metro part of the national grinding programme.

2.4 Review, comment and recommend: A temporary technical group was created to (a) review information available, (b) create a clearer statement of root cause than provided by the Consultants in 2.1 above (c) recommend further actions and/or studies (d) resolve the importance of the many causes unofficially being identified as root causes.

3.0 RCF WORKING GROUP

All of the initiatives above other than 2.4 are being managed as part of “Business as Usual”. Action 2.4 however is being addressed by a temporary internal team, to be led by an independent coordinator, with a background in the NZ rail industry.

The coordinator will be independent with engineering technical expertise sufficient to coordinate the technical analysis and investigation activities of the working group, interrogate and analyse data sources and ensure collaborative and jointly developed causal analysis and future mitigations.

This memo provides the Terms of Reference for the group and its governance arrangements.

4.0 GOVERNANCE

The RCF working group reports to a technical “Oversight Group”. The Oversight group consists of:

Murray Burt	Chief Engineer (AT)
John Skilton	Chief Engineer (KR)
Adam Williams	Executive General Manager - Rolling Stock Asset Services (KR)
Israel Gómez	General Manager CAF NZ

The Working Group reports to the Oversight Group weekly or as required.

The Oversight Group reports to an Executive Group, Programme Control Group (PCG) which consists of:

Mark Lambert	Executive General Manager Integrated Networks (AT)
Todd Moyle	Chief Operating Officer (KR)
Rob Gibbes	Executive General Manager Construction (KR)
Jenny Chetwynd	EGM Planning and Investment (AT)
Greg Pollock	Transdev

5.0 COMPOSITION

The RCF working group is composed of technical experts with a focus on using that expertise to identify facts, and exercise technical judgement when facts are difficult, expensive or time consuming to obtain The RCF working group is a multi-stakeholder, multi-disciplinary technical group. The RCF working group is composed of:

Ted Calvert	Independent Coordinator

	Experience in managing multidisciplinary rail projects
Mark Fleet	KR, Track (civil) expertise
Mark Wilson	KR, Rail vehicle (mechanical) expertise; Data management
Andrew Hunt	KR, Rail vehicle (mechanical) expertise
Craig Inger	AT, Manager, Train Services
Damian Flynn	AT, Manager, Strategic Rail Development
Brendon Jones	CAF, Depot General Manager CAF New Zealand
Stuart Ferguson	CAF, Maintenance Manager CAF New Zealand
Gary Iddon	Transdev Auckland, GM Operations

5.1 KiwiRail is involved as track infrastructure owner and maintainer.

5.2 Auckland Transport is involved as specifier of passenger rail services and purchaser of access time to the track infrastructure to operate those services, acts as customer and end-user custodian.

5.3 Transdev is involved as the passenger rail train operator and access user, bringing experience in infrastructure maintenance internationally, driver behaviour and other operations related matters. Transdev will also contribute to the second task as track time is assumed to be a factor in remedial and ongoing works.

5.4 CAF is involved as the passenger train manufacturer and maintainer, bringing experience in wheel/track interface management and maintenance, international RCF experience and technical owner of the Auckland EMU units

6.0 AUTHORITY

Other than through business-as-usual lines, the group has no technical authority to modify codes and standards, or issue technical instructions.

Other than through business-as-usual lines, or as approved on a case by case basis by the Steering Group, the working group has no financial authority.

7.0 OTHER STAKEHOLDERS

7.1 Link Alliance: will transfer compliant assets from CRL and will enable increased services that may further stress the Network.

7.2 RNGIM Project; An initiative resulting from the WSP study and charged with outworking the recommendations of that report.

7.3 Central Government.

7.4 NZTA.

8.0 PURPOSE OF THE TERMS OF REFERENCE (TOR)

The goal is to retain the Working Group for as short a time as possible, reverting their activities to Business-as-usual resources and intergroup relationships as soon as the objectives have been achieved. The TOR guides the group and enables progress to be measured.

9.0 COMMON OBJECTIVES OF KEY STAKEHOLDERS

9.1 The primary task of the RCF working group, is to determine the root causes of Rolling Contact Fatigue (RCF) initiated defects in the Auckland metro area.

9.2 A second task of the group is recommendation of future maintenance practices regarding RCF management.

10.0 KEY ACTIONS AND DELIVERABLES

10.1 Root Cause

10.1.1 Review the work of SNC and Autech.

10.1.2 Identify probable key contributors.

10.1.3 Evaluate these as necessary from the body of knowledge of RCF.

10.1.4 With appropriate approvals engage with experts to conduct any studies required in areas where there is reasonable confidence that a key cause may exist; recognising that there may not be a single major cause but a combination of several major causes.

10.1.5 Report on the "Root cause" analysis and seek consensus beyond the working group. NB: an interim report may be required if modelling / studies / data collection have long lead times.

10.1.6 As a critical element, but of lower importance, identify and provide technical commentary on all potential cause issues known to be of concern to stakeholders.

10.1.7 The working group coordinator will be independent with engineering technical expertise sufficient to coordinate the technical analysis and investigation activities of the working group, interrogate and analyse data sources and ensure collaborative and jointly developed causal analysis and future mitigations.

10.2 How did we get here?

10.2.1 Deductive investigation into occurrence of RCF, how it was managed and possible learning.

10.2.2 Report on the issues.

10.3 Avoiding a repeat

10.3.1 Root / key cause reduction/elimination.

10.3.2 Recommendations regarding inspection / grinding / codes and standards.
10.3.3 Commentary on TCO of the "system".

10.3.4 Commentary on future alignment with "best practice".

10.3.5 Recommendations for future RCF maintenance and management.

11.0 PEER REVIEW

11.1 Any interim reports from the group will be reviewed by the oversight group and the executive PCG.

11.2 The final draft report from the group will be reviewed by the oversight group and the executive PCG. An independent engineering technical peer review will be required for the final report.

12.0 TIMEFRAME

12.1 The initial phase is expected to be complete by Friday 2 October 2020.

12.2 Should modelling be required the Group may continue to manage the consultant, report on conclusions from the study and integrate these into the final report.

12.3 In any case the final report must be complete by Friday 4 December 2020.

13.0 COSTS

13.1 Costs for staff time will lie where they fall.

13.2 Costs for the Working group co-ordinator will be funded by KR.

13.3 Costs for external consultants will be agreed as they are identified, noting that the Link Alliance may be willing to be a joint funder for some parts.

DRAFT

TERMS OF REFERENCE
With progress notes
RCF (Rolling Contact Fatigue) Working Group

1.0 INTRODUCTION

No action required.

2.0 BACKGROUND

No action required.

3.0 RCF WORKING GROUP

All of the initiatives above other than 2.4 are being managed as part of "Business as Usual". Action 2.4 however is being addressed by a temporary internal team, to be led by an independent coordinator, with a background in the NZ rail industry.

The coordinator will be independent with engineering technical expertise sufficient to coordinate the technical analysis and investigation activities of the working group, interrogate and analyse data sources and ensure collaborative and jointly developed causal analysis and future mitigations.

Ted Calvert was appointed to this position and was judged to have sufficient technical expertise to manage the process and to provide a synthesis of the information available.

This memo provides the Terms of Reference for the group and its governance arrangements.

4.0 GOVERNANCE

No action required; the governance arrangements adequately supported the process.

5.0 COMPOSITION

No action required; the composition of the group allowed the easy disseminating of drafts but the technical nature of the subject limited the opportunities for active collaboration.

6.0 AUTHORITY

The only requirement for financial authority was for the vehicle modelling and this was arranged through the DFA of Adam Williams | EGM – Rolling Stock

People from all stakeholders accepted requests for input without the need to seek authority to instruct them to accept tasks.

7.0 OTHER STAKEHOLDERS

Limited contact was made with “other Stakeholders”. The key one was the link alliance during the modelling phase.

8.0 PURPOSE OF THE TERMS OF REFERENCE (TOR)

The goal is to retain the Working Group for as short a time as possible, reverting their activities to Business-as-usual resources and intergroup relationships as soon as the objectives have been achieved. The TOR guides the group and enables progress to be measured.

It is proposed to disband the group once a final draft report has been provided (early March 2021).
Individuals from the group can be contacted as required by the Peer reviewer.
Individuals from the group may be approached to carryout activities recommended in the report, under a spate brief /TOR.

9.0 COMMON OBJECTIVES OF KEY STAKEHOLDERS

9.1 The primary task of the RCF working group, is to determine the root causes of Rolling Contact Fatigue (RCF) initiated defects in the Auckland metro area.

These are provided in the report.

9.2 A second task of the group is recommendation of future maintenance practices regarding RCF management.

The full detail of this task is beyond the capacity of the working group, but key recommendations are included in the report. The group is confident that implementing key recommendations will lead to suitable maintenance practices with regard to RCF management.

10.0 KEY ACTIONS AND DELIVERABLES

10.1 Root Cause

10.1.1 Review the work of SNC and Autech.

Completed – see summary in this report.

10.1.2 Identify probable key contributors.

Completed – these are noted in the body of the report and those with low or nil contributions are listed as “Minor issues” in section 16.

10.1.3 Evaluate these as necessary from the body of knowledge of RCF.

Completed – these are noted in the body of the report and those with low or nil contributions are listed as “Minor issues” in section 16.

10.1.4 With appropriate approvals engage with experts to conduct any studies required in areas where there is reasonable confidence that a key cause may exist; recognising that there may not be a single major cause but a combination of several major causes.

Completed – the only notable study was a Vampire model commissioned externally to examine the vehicle effects.

10.1.5 Report on the “Root cause” analysis and seek consensus beyond the working group. NB: an interim report may be required if modelling / studies / data collection have long lead times.

10.1.6 Report on the root cause analysis: Completed and reported in the body of the report.

10.1.7 Seek consensus beyond the working group: Feedback was sought from group members, RINGM and interested KiwiRail technical staff. Discussions with those with differing views were taken to consensus where possible but otherwise to a place of each understanding the other view. The views in the report are the views of the author, and generally the views of all involved in the group.

10.1.8 As a critical element, but of lower importance, identify and provide technical commentary on all potential cause issues known to be of concern to stakeholders.

Reported in section 16.

10.1.9 The working group coordinator will be independent with engineering technical expertise sufficient to coordinate the technical analysis and investigation activities of the working group, interrogate and analyse data sources and ensure collaborative and jointly developed causal analysis and future mitigations.

Ted Calvert was accepted as having the necessary competencies.

10.2 How did we get here?

10.2.1 Deductive investigation into occurrence of RCF, how it was managed and possible learning.

10.2.2 Heavy reliance was placed on the findings of the Autech reports and the report by SNC. These were extracted, tabulated, discussed, and debated by the group in a series of emails and video meetings. External technical references were researched as needed.

10.2.3 Report on the issues.

10.3 Completed and reported in the body of the report “Avoiding a repeat”.

10.3.1 Root / key cause reduction/elimination.

Completed and reported in the body of the report.

10.3.2 Recommendations regarding inspection / grinding / codes and standards.

Inspections / codes and standards: No recommendations have been made; it is understood that a RNGIM work stream will consider this as part of a new "Maintenance plan".

Grinding: Recommendations have been made in the report

10.3.3 Commentary on TCO of the "system".

Completed and reported in the body of the report. It is understood that this will be more comprehensively looked at during the preparation of a long-term comprehensive asset management plan

10.3.4 Commentary on future alignment with "best practice".

Limited commentary has been provided; it is understood that a RNGIM work stream will consider this as part of a new "Maintenance plan".

10.3.5 Recommendations for future RCF maintenance and management. Recommendations have been made in the report.

11.0 PEER REVIEW

11.1 Any interim reports from the group will be reviewed by the oversight group and the executive PCG.

This process has been followed since November 2020.

11.2 The final draft report from the group will be reviewed by the oversight group and the executive PCG. An independent engineering technical peer review will be required for the final report.

This process has been followed since November 2020. The PCG is considering suitable peer review groups. Options for peer review include National Research Council, Canada and WSP

12.0 TIMEFRAME

12.1 The initial phase is expected to be complete by Friday 2 October 2020.
The first draft report was issued for comment 26 September 2020. The group recommended modelling take place before finalising the report and sought an extension of time until December 2020. Delays in modelling suggest a final draft report will be available for peer review during March 2021. The recommendations related to track have been available for consideration and implementation from 4 November 2020.

12.2 Should modelling be required the Group may continue to manage the consultant, report on conclusions from the study and integrate these into the final report.

Modelling was requested and the results from that are in the final draft report.

12.3 In any case the final report must be complete by Friday 4 December 2020.

This deadline was missed (due to a delay in modelling) and a final draft report will be available for peer review during March 2021.

13.0 COSTS

13.1 Costs for staff time will lie where they fall.

This has occurred.

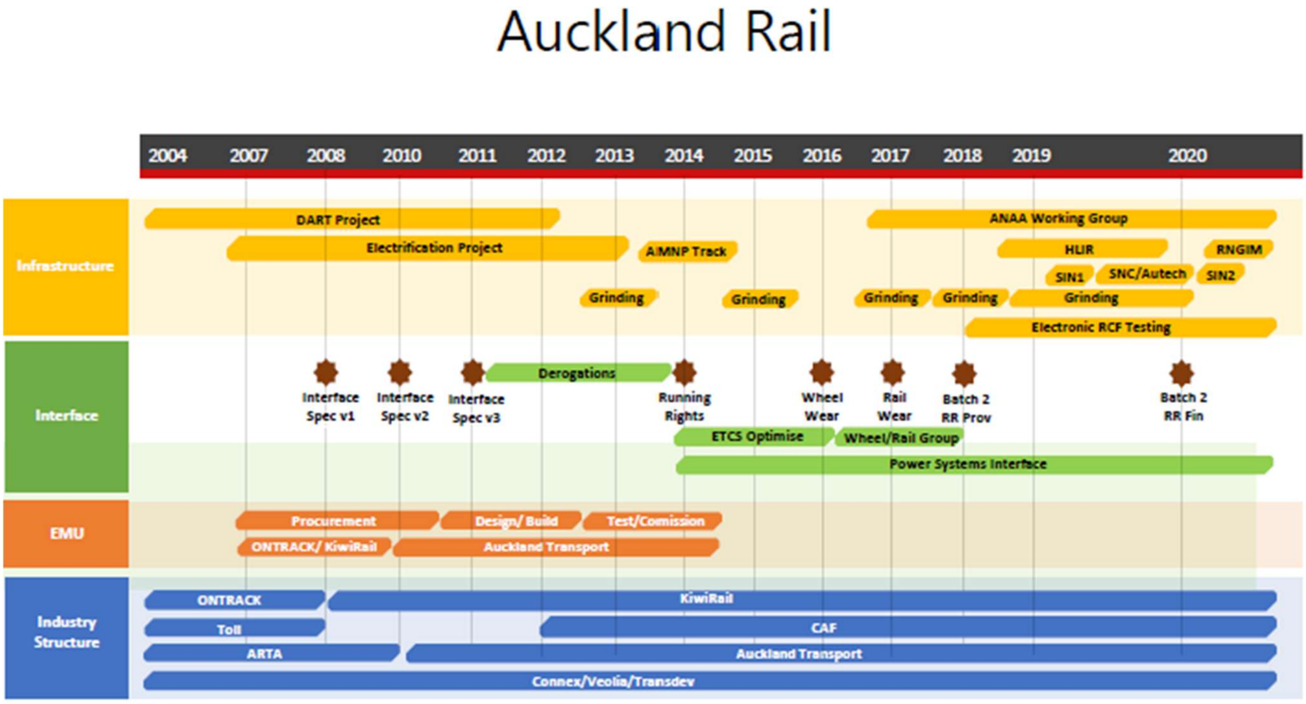
13.2 Costs for the Working group co-ordinator will be funded by KR.

This has occurred.

13.3 Costs for external consultants will be agreed as they are identified, noting that the Link Alliance may be willing to be a joint funder for some parts.

The key unknown cost was the cost of modelling. This was authorised by KR.

APPENDIX 2: DEVELOPMENT TIMELINE



DART Project	• Upgrade of Auckland Metro infrastructure to support increased capacity. Installed some new infrastructure (eg Western Line double tracking, Onehunga Branch rehabilitation, Newmarket Junction) but did not generally upgrade existing track infrastructure
Electrification Project	• Electrification of the Auckland Metro network. Primarily signalling and traction power focused with some track alignment and structures clearance improvements.
Infrastructure Condition and Renewal	• Auckland Metro Network Management Plan (AMNP) Track Study. Study undertaken by Network Rail consulting for Auckland Transport. The intent of this study was to identify renewal work required to improve the network condition to a level of long term sustainability • Auckland Network Access Agreement (ANAA) working group. This group includes representatives from Auckland Transport, Transdev Auckland and KiwiRail with the intent of assuring alignment for future service performance – particularly post CRL. • Auckland High Level Infrastructure Review (HLIR). Study undertaken by WSP-Opus for the ANAA working group. The intent of this study was to review the current specification and condition of Auckland rail assets, maintenance standards and maintenance plans for these assets, and provide an assessment as to whether these specifications and standards are fit for purpose for delivering the service and patronage task of the Auckland Metro Rail Network (AMRN) for the future. The output from this report fed into the Rail Network Growth Impact Management (RNGIM) business case for accelerated renewals funding. • RNGIM is a funded package of work targeted at ensuring that the Auckland Metro infrastructure is able to support required service levels post CRL opening.
Grinding	• NAL and MNK was ground in 2013, NIMT 2013 and 2015 using SPENO 24 stone grinder. • Then sporadic locations on network in 2017, 2018 and 2019 using Autech 6 stone grinder.
RCF Reports	• KiwiRail commissioned two reports to look at RCF on the Auckland Metro. The first of these was produced by Autech and the second by SNC – Lavalin.
KiwiRail Documentation	• Traditionally KiwiRail has managed RCF in the same way as other rail faults. As an initial response to RCF specific issues a Significant Information Notice (SIN) was issued to provide guidance on RCF tolerance and intervention levels. This SIN was updated post receipt of the Autech and SNC reports and was supported by a guidance document which provided information on how to identify and measure RCF related defects.
Electronic RCF Identification and Testing	• Traditionally RCF related defects were observed visually or via ultrasonic non-destructive testing (NDT). Phased Array Ultrasonic Testing (PAUT) is used to determine the depth of rail cracks but is a manual and very slow process. Alternating Current Field Measurement (ACFM) is also used to determine crack depth. Eddy Current Surface Mapping (ECSM) is undertaken by equipment installed on the NDT car and provides a relatively quick way of identifying RCF – ECSM needs to be followed by a subsequent visual, PAUT or ACFM inspection to determine severity.

Interface Specification	• Specification E1317 outlines the requirements for rolling stock to be compatible with the KiwiRail network. This specification covers several areas including clearance envelope, gauge, weight, wheel profile, signalling interface, traction power interface and telecommunications interface. During the procurement phase of the AM class EMU this specification was updated. Before the AM class entered service a number of derogations from this standard were requested.
Interface Issues	• Immediately after the implementation of the AM class EMU it became apparent that the interface with ETCS signalling was unnecessarily restrictive. KiwiRail, AT and Transdev worked together to optimise this interface with changes to both on-board systems and infrastructure. • As the number of EM class EMU in service increased a number of power systems issues were identified which affected the performance of the EMU. The Power Systems Integration Technical Working Group (PSITWG) was set up to address these issues. Most have been resolved for the current level of traffic and continual work is underway to provide future certainty. • In response to accelerated wear being noted on rolling stock and track a wheel/rail interface group was set up to determine and resolve any issues. This group included representatives from CAF, AT and KiwiRail.
Running Rights	• Before any vehicle can operate on the KiwiRail network it must have Running Rights. Running Rights for the AM class EMU were originally granted in 2014. Provisional running rights for batch 2 of the AM class EMU were granted based on being 'substantially similar' to batch 1 but noting that investigations into accelerated wear were in progress. Currently batch 2 has full running rights but total number of units able to operate simultaneously is 57

APPENDIX 3: TECHNICAL EXTRACTS

For the technical reader, the extracts below relate to recommendations and discussions in the Report. Source in brackets.

Importance of grinding new rail.

New rail is ground soon after installation to produce the optimal low stress profile and to remove the decarbonized layer that can rapidly produce rail surface cracks.

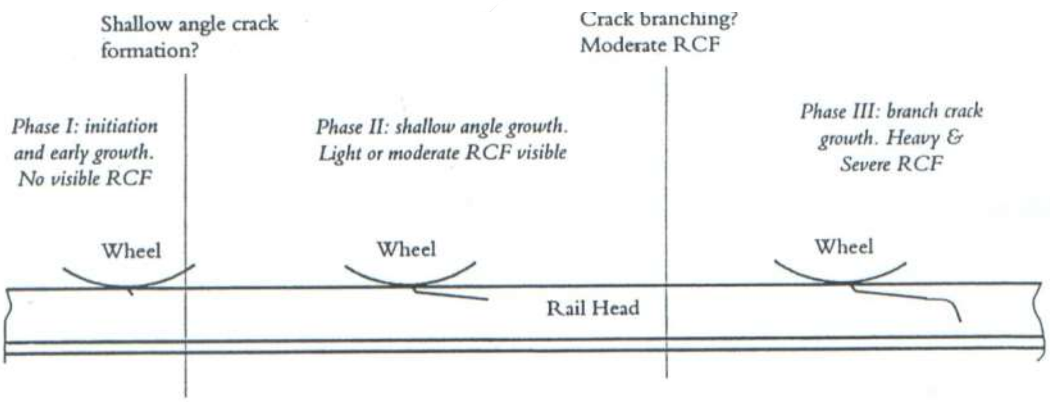
(AREMA rail grinding)

Benefits of preventative grinding:

Grinding of rails has evolved as a maintenance technique to insert controlled artificial wear and manage wheel / rail contact stress. This maintenance strategy reduces rail wear, controls rail surface and sub-surface fatigue, controls rail surface plastic deformation, improves truck steering, improves the dynamic stability of rolling stock and improves rolling stock wheel life.

(AREMA rail grinding)

The growth rate of rail surface (and subsurface) fatigue is influenced by the level of contact stress between the wheel and the rail. Micro-cracks develop at the most stressed portion of the rail surface. In their early phase the microscopic cracks grow quickly in a somewhat vertical direction (not visible) to a shallow depth in the rail surface. The cracks then enter a phase of shallow angle growth (planar growth) until they reach a branching phase. At this phase the rate of growth in the vertical direction accelerates. The preventive grinding strategy is designed to cycle the rail grinder at frequent intervals to remove a thin surface layer of metal from the rail to prevent the micro-cracks entering the rapid phase of growth.



Abbreviated from (AREMA rail grinding)

Lubrication

Lubrication substantially reduces the traction stress at the wheel/rail surface and therefore increases the number of contact cycles by wheel loads before RCF initiates. Preventive rail grinding (where surface cracks are eliminated) in combination with lubrication can significantly increase rail life. However, once formed, rail surface fatigue cracks grow fastest when contaminated by water, and to a lesser extent when contaminated with a mixture of water and lubricant. Optimum lubrication (face and top) needs careful design and monitoring. For example If the coefficient of friction (COF) on the high and low curve rail is controlled in the range 0.3 to 0.4 on both rails, it will reduce the anti-steering moment on the trailing axle, reducing RCF.

Abbreviated from (AREMA rail grinding)

Rail metallurgy (1)

Rail wear and rail surface fatigue occurs in soft (250 to 300 BHN), intermediate (300 to 340BHN) and hard (340 to 420 BHN) steels. Improved metallurgy, harder steel, profile grinding and proper lubrication can significantly reduce wear and RCF.

(AREMA rail grinding)

Importance of grinding new rail

Softer rails plastically deform more rapidly and therefore must be ground more often and more metal needs to be removed each grinding cycle. Harder rails are more resistant to plastic flow and will require less frequent grinding and less metal removal each cycle. However, soon after installation, harder rail will require profile correction to a worn (KR intermediate profile) conformal profile to compensate for the harder steel tendency to resist natural wearing. This resistance to plastic flow can cause the rapid initiation of RCF cracks. Also, when new rail is installed into track the thin surface decarbonized layer should be removed as it is very soft and will rapidly produce RCF cracks.

(AREMA rail grinding)

Optimal grinding point

The optimal wear rate is the rate of rail wear required to just control rail surface fatigue. Insufficient wear results in rail fatigue, while excessive wear reduces rail life. Preventive grinding is an optimized rail surface maintenance process that achieves the required optimal rail profile and removes the RCF cracks. The optimal wear rate is tonnage and track specific and depends on some of the following; accumulated tonnage since the last grinding cycle, the axle load, type of traffic, rail metallurgy, track curvature, environment / season, track gage, lubrication standards, etc.

(AREMA rail grinding)

Understanding the optimum grinding point needs detailed assessment and understanding of AMRN parameters.

Track gauge and RCF

Track Gauge, changing the distance between the two rails modifies the position and geometry of the wheel/rail contact. Tight gauge in tangent track promotes gauge corner contact, hunting and RCF, whereas at correct gauge more of the contacts will be carried towards the crown of the rail where contact conditions are usually less severe.

In curves, controlling wide gauge is essential for mitigating low rail damage associated with hollow wheels (wheels are termed hollow when they wear such that the centre of the wheel tread is worn below the level of the end of tread). Wide gauge curves are also more susceptible to dynamic rail rotation, which often contributes to unfavourable contact geometry.

Abbreviated from (Control of Rolling Contact Fatigue in Rails; Magel, Sroba, Sawley and Kalousek)

Welds and RCF

The steel in welds invariably has hardness different from that of the parent rail steels, even with the best post heat-treating efforts. In welds where this difference is large (say 30 points Brunel), either softer or harder, the weld will deform greater or less, respectively. Softer welds typically produce a dip with accelerated development of RCF and harder welds produce high spots that excite vertical wheelset dynamics and are responsible for RCF damage that develops adjacent to that weld.

Abbreviated from (Control of Rolling Contact Fatigue in Rails; Magel, Sroba, Sawley and Kalousek)

Other factors

Other factors that affect contact stress include cant excess and cant deficiency, hunting of wheelsets in tangent track and mild curves, track geometry errors, situations where rails can rotate, uneven vehicle loading, skewed trucks and mismatched wheel diameters.

Abbreviated from (Control of Rolling Contact Fatigue in Rails; Magel, Sroba, Sawley and Kalousek)

Rail metallurgy (2)

The effect of rail metallurgy on RCF is complex. In laboratory studies two conclusions generally recur. First, for a given level of hardness, pearlitic steels are more resistant to RCF than are other structures such as bainite and martensite. Second, for any given type of steel structure, resistance to RCF increases with hardness.

The problem is demonstrating these laboratory results in service tests, where many factors interact to influence RCF: rail hardness, detailed wheel and rail profiles, lateral and longitudinal wheelset dynamics (which depend on the vehicle design and state of wear), and possibly transient dynamic effects at small lateral track geometry deviations.

RCF is particularly sensitive to wheel and rail profiles, and inappropriate or uncontrolled profiles can completely mask effects of metallurgy. In the UK, the general experience has been that high strength steels are more prone to forming RCF – a finding that can be explained by the high stress rail section employed and the failure of the hard steels to wear or flow to a lower stress shape. It has also been their experience that if the rail is initially ground to a lower-stress shape, then it is much more resistant to RCF than the softer steels.

While there is no consensus on the effect of rail microstructure on RCF, the strength of rail steel in shear is understood to be the main factor that controls RCF in rails, and consideration of this parameter helps explain microstructure effects. The shear yield strength of as-manufactured rail is easily measured in the laboratory, and is seen to increase with hardness. However, it is the shear yield strength developed in the work-hardened rail surface layers that is likely to be critical, and different microstructures work-harden at different rates. As an example, laboratory tests indicate that bainitic steels work-harden less than pearlitic steels under rolling contact conditions. Thus, while bainitic steels may have higher bulk strength than pearlitic steels, pearlitic steels likely develop work-hardened layers with even greater strength. This may explain why tests with other microstructures, such as bainitic and martensitic steels, have produced conflicting results.

Crack propagation wet / dry situations

Once a crack has initiated, the rate at which it progresses into the surface is influenced by a large number of considerations. The crack propagation rates are dependent on the propagation stresses and on the ability of the steel to resist propagation. The presence of grease and water at the wheel/rail contact play a critical role in the rate and depth of surface crack propagation. If grease or other contaminants seep into the surface cracks, the reduction in crack-face friction allows the faces to slide past each other, contributing to moderate crack growth rates. Water, with its low viscosity and high surface tension, is drawn into the cracks by capillary action. (This supports the note above that water has a higher effect than grease). If the surface crack is oriented in a direction where it drops away from the approaching load, the rolling contact will first seal the crack entrance and then hydraulically pressurize the crack tip.

This provides a large tensile stress at the tip, promoting rapid crack propagation. For this reason, crack propagation in dry environments is very different from that in wetter environments. The shear stress in dry environments is intense and very shallow. Surface cracks propagate only about 3-mmdeep. Under wet conditions, those surface cracks propagate to a much greater depth (say 7-15 mm), largely due to the hydraulic crack propagation mechanism.

Note that once the crack reaches a depth of greater than about 8-15mm, it is out of the field of influence of rolling contact stresses. Beyond this depth cracks may continue to propagate due to thermal stresses in the rail (e.g. tensile stresses in cold weather), bending stresses due to wheel loads and residual stresses in the rail from manufacturing processes.

Abbreviated from (Control of Rolling Contact Fatigue in Rails; Magel, Sroba, Sawley and Kalousek)

Sub surface RCF (Control of visual RCF does not remove the need for ultrasonic testing).

Only one of the many subsurface defects that occur in rails can be considered a rolling contact fatigue defect. While vertical and horizontal split heads and tache ovales have sometimes been classified as RCF defects, they are more appropriately dealt with as metallurgical defects since contact stresses have little influence on their initiation or propagation. In contrast, deep-seated shells are a direct response to excessive contact loads at the extreme gauge corner that cause the rail to fail along a shear or “slip” line. In steels with metallurgical imperfections, the deep-seated shell can initiate a transverse defect. Since rolling contact stresses are only active near the surface, the transverse defect must be propagated by bending, residual and thermal stresses.

Deep-seated shells can be minimized through the use of harder steel and rail grinding. Grinding to shift load from the extreme gauge corner is one obvious approach. Rail grinding can also be used to progressively shift the location of greatest subsurface shear stress through the railhead so that the stress does not have an opportunity to dwell at any given weak spot for an extended period of time. This is especially important in well-lubricated environments where the lack of wear only exacerbates the problem of shear-stress dwelling on vulnerable steels.

(Control of Rolling Contact Fatigue in Rails; Magel, Sroba, Sawley and Kalousek)

APPENDIX 4: SUMMARY OF KEY REPORTS

I. SUMMARY OF AUTECH

For the technical reader the extracts below attempt to summarise the observations, findings, technical comments and recommendations of Autech; see DE01-00662_KiwiRail-Wheel-Rail-Study-Auckland-Transport_Report_08-03-00299-2-00_191217c-DVS.pdf. Note these sections are “copy paste” with occasional additions but no attempt has been made to correct poor English.

Extracts from “Summary” starting at page 16
In the past years, KiwiRail experienced an increased appearance of Rolling Contact Fatigue (RCF). Since RCF can have a variety of causes, an onsite-inspection was agreed in order to understand the local system properties of the network and rolling stock, operational conditions, maintenance regimes and wheel/rail-related issues (including lubrication).

The works [A-001] started with a query of theoretical data from KiwiRail [P-004]. Preparations of works were discussed in a kick-off-meeting [P-003, P-006, P-007] and were followed with local visits to pre-selected inspection sites [P-005] in the Auckland Metro related tracks of KiwiRail. The rolling-stock workshop of KiwiRail in Westfield and the Wiri-depot of the AM-class EMUs, which are manufactured and maintained by the Spanish company CAF on behalf of Auckland Transport (operator), were visited, too.

Onsite inspections (week 43/2019) included measurements of profiles as well as documentation of visual appearance of wheels and rails. For this purpose, some 10 locations in the Auckland Metro network were visited. Concerning rolling-stock, the profiles of locomotives, DMUs and EMUs were measured and/or obtained by KiwiRail as coordinate data files.

…
There were no definitive hints that the state of the profiles correlates with the development of RCF.

The wheels have just some slight tendency to wear out in the central tread with the development of a more inclined inner tread zone. It has been determined that the profile change of the CAF-wheels is more intense as it is for the KiwiRail-wheels.

…
• Rail Grinding Profiles
o The Intermediate Rail Grinding Profile shows good contact conditions at least with wheel profiles in wear state. It shows a continuous displacement of the contact patches and pressures reach a global minimum value below 600 MPa (considering all conducted simulations).

o The Ultimate Rail Grinding Profile did not show any advantage over the Intermediate Rail Grinding Profile at all. It has some two-point contact and the pressures are generally higher.

…….

The development of Rolling Contact Fatigue is discussed in the report with its variety of possible causes. Concerning the state at KiwiRail it was found that at cross sections of the track with identical rail profiles, in some situations RCF occurs and in others not. This is a clear sign that the wheel rail-combination (even though it is one of the points of influence) cannot the sole decisive factor.

For the Auckland Metro Network of KiwiRail, it was frequently found that RCF occurs in such situations with noticeable vertical motion of the tracks. Examples are given in the report.

Therefore, the stabilization of the foundation of tracks must be in focus of KiwiRail.

As discussed in sec. 14.5, according to [L-001] the metallurgical properties of the rail steel are secondary. Harder rails certainly increase the resistance against the initiation of cracks. However, once initiated the higher brittleness of harder rails can become a drawback.

The hardness of the wheels does not affect the contact stresses, since those are (apart from geometry and loads) not determined by the strength but by the stiffness of the contact partners.

This means in particular, that the RCF will not disappear by application of a (probably) different rail grinding profile. The impact from the trackwork are too intense and situations were found, with similar contact conditions but varying RCF-state.

It must be concluded that in the past years, the maintenance of the surface of the rails was not as required. That means that RCF cracks could freely develop without being stopped. Since RCF cracks have a progressive rate of growth, the number of cracks seemed to explode once traffic was increased.

This leads to the uncomfortable situation that many locations exist, were the rail is irreparable.

Consequently, refurbishment (stabilisation) of the track-substructure, combined with preventive grinding particularly of those track sections, where RCF has not yet reached critical levels, should be the main steps for KiwiRail.

Due to the scope of this survey the report does not cover any analysis on vehicle running dynamics and bogie characteristics. PROSE has a profound background in the analysis of vehicle system dynamics in terms of wheel/rail-simulation and measurements. Therefore, such an analysis on the impact of differing bogie characteristics (e.g. influence of suspension characteristics) on track loads and contact stresses can be conducted. Of course, this would require mandatory intense co-operation from Auckland-Transport/CAF.

We can conclude:

- Wheels and rails were inspected at place.
- Some visited rails are partly in a serious RCF condition.

- Development of RCF at KiwiRail/Auckland Metro is not strictly correlated with the state of rail profiles (in terms of the geometry of the cross-section). Factors like “stability of track foundation” and “lack of maintenance in the past” are more relevant.
- To prevent or at least to retard the development of RCF, more preventive grinding than in the past is mandatory.
- Rails with huge amount of RCF are considered to be dead and need replacement.
- Rail profile in wear state tends towards the Intermediate Grinding Profile.
- Therefore, the application of the Intermediate Grinding Profile is recommended for future grinding procedure at KiwiRail/Auckland Metro.
- In turnouts the application of inclined rail profiles is recommended to reduce contact stresses.
- Recommendations on KiwiRail specifications were given with this report.

12.4 Further Observations concerning RCF

12.4.1 Rolling Contact Fatigue

The inspections of the rails in Takanini (MP05DM-1/-2/-3, MP05-4/-5, MP05-6/-7) showed at several cross sections heavy RCF defects which were related to welded rail joints. Fig. 16-85 shows how RCF defects start immediately at a welding joint and lasted for approximately 5 to 10 m until they fade. Concerning the section of fig. 16-85 the RCF might have been initiated either vertical due to dynamics due to a dip in the welding point or due to a change of material both is possible.

However, in fig. 16-86 RCF definitively does not start at the joint but occurs around it, before and behind. That leads to the conclusion that there not a change of material is reason for RCF but vertical dynamics of the track.

The correlation between vertical motion of the track and occurrence of RCF was also found close to MP05DM-6/-7. There, the foundation of the track was in such a bad condition that the rails did “pump” with a very visible amplitude (guess: certainly more than one centimetre). Fig. 16-87 shows, that the motion already led to a lack of ballast so that the overall stability of the track is even more reduced. Exactly in this track section (including some meters ahead and behind) the rails showed severe RCF. The tracks on the opposite track (upmain, fig. 16-88) were in the same state (so, the discovered state was not an exception).

As mentioned in section 12.1.10, also lateral misalignments can contribute to the development of RCF. This is shown in figure 16-89.

Apart from wheel/rail contact geometry, axle loads, materials, vertical motion of the tracks much simpler reasons exist to cause RCF. Figure 16-90 shows a wheel burn as an initial spot for the development of cracks. It is clear, that such issues must be resolved by maintenance of the surfaces (i.e. by preventive grinding).

14 Assessment and Conclusion

14.1 Conduction of Works

In week 43/2019 AUTECH and PROSE did inspect the tracks, measured profiles of rails and wheels and discussed with the technical staff of KiwiRail and CAF about the wheel/rail interface.

14.2 Nominal State

The wheel-rail system of KiwiRail/Auckland Metro shows hardly any striking issues. The Newmarket junction and the entrance-curves towards Britomart tunnel with their curve radii of 95 m are extreme for metros. However, these are not specifically related to the problem of RCF. The track alignment (curve radii) is (apart from the Newmarket- and Britomart-Curves) unimpressive. Curve-radii are in general above 400 to 500 m and at the inspected locations there was no significant (if any) gradient.

In the network the CAF-AM-class EMU-trains are dominant. Freight traffic performs some trains per day and should be neglected here.

With exception of the Newmarket-Britomart line the loads (trains per hour) on the tracks can be considered as normal.

The configuration of the AM-class EMUs is a classic four-axle coach configuration with an axle distance of 2200 mm and axle loads of some 13.5 t. These data are in a very normal range for a metro train.

The rail profile NZR50 is very similar to European profiles UIC60, UIC54, 60E1, 54E1, 49E1, etc. with a sequence of radii in the crown of R300 and R80 with a gauge corner radius R13.

The Cape Gauge of KiwiRail is considered as normal since it can be compared to the huge amount of metric gauge systems in Europe.

The same is valid for rail inclination 1:20.

The reference level A = 16 for track gauge measurement differs from known values in Europe (A = 14 mm) but this is irrelevant for the task.

The wheel profiles of KiwiRail and CAF differ slightly. Whereas the wheel profile for CAF matches rail profile even better than the KiwiRail wheel profile TLA1 does.

14.3 Grinding Specification

Rail Grinding Profiles (Intermediate and (more relevant) have some formal issues in confusing arrangement within appendix 1 and 2 of [KR-005] and concerning their alignment. This is mentioned in sec. 15.1.

14.4 Classification of permissible Crack Depths

The classification depths of surface cracks in the rails of KiwiRail as referred to in section 11.7 is considered not to be strict enough [L-007]. At German railways crack depths up to 2.7 mm rails can be correctively ground (timescales to take measure range from 18 months to 3 months, depending on crack depth). For deeper cracks, rails are to be replaced within 6 months or 6 weeks (here speed restriction to 20 km/h applies), depending on the magnitude of the readings of the testing device.

14.5 Rolling Contact Fatigue, Wear and Lubrication

Rolling Contact Fatigue is caused by a variety of reasons. It is often found, that the identified reasons often depend on the field of application of the railway engineer, who is concerned with the investigation. It is comprehensible, that engineers who deal with high-speed trains will claim that RCF occurs with high speed traffic. Operators of cargo tracks will notice that higher axle loads are responsible for the development of RCF. Others insist on the fact that rail material is relevant, whereas again others name the traction capacities of the motor-units, and again others clearly indicate narrow gauges as reasons. All of them are right to some extent, but the main reason and therefore the solution will vary from case to case.

The wheel rail contact itself contributes to the development of RCF (no contact -> no defect). However, other aspects could be as important or even more important than the wheel/rail contact itself.

- Load
- Load Cycles
- Dynamic response of the track
- Traction
- Material
- Lubrication
- Lack of Maintenance

The topic itself is not new. In the mid-1990s the development of RCF in its various forms of appearance (squats, shells, headchecks, etc.) came into the focus of railway-engineers who dealt with rolling contact (although the question if the introduction of harder rails is reasonable was already discussed a decade before, see [L-008]).

Most significant appearances of RCF at KiwiRail (as far as demonstrated during the inspections) are Headchecks.

These headchecks are small cracks which appear parallel to each other with spacings between them ranging from few millimeters to some centimeters [S-005, S-004]. They get initiated in or very close to the surface where, depending of the friction state, equivalent stresses become maximal [L-003] (see fig. 14-1) From there they grow and reach the surface very quickly. Initially they grow with shallow angle under the surface before they bend downwards and may lead to a transverse defect (TD) of the rail. This is in conjunction with an increased rate of propagation.

Due to the number of following cracks, this failure can get extremely dangerous as demonstrated by the Hatfield crash in the United Kingdom in the year 2000.

Once one single crack leads to a TD, the dynamics response when subsequent wheelsets pass will lead to TDs of neigbouring headcheck-cracks – leaving some dozens of rail fragments.

Headchecks are assumed to occur in particular in high rails [S-005] in situations when wear is not sufficient to remove initial cracks[S-005]. Initially they grow fairly slow but have progressive propagation rate.

Grinding and rail replacement are considered as countermeasures [S-005] – if headchecks are not removed on time their number will “explode”. Then the only option is a change of the rail.

According to [L-001] Rolling Contact Fatigue like headchecks or squats are a common failure at tracks for passenger and cargo traffic, whereas transverse rail defects were observed at high speed-tracks, too (that means, effectively all tracks are concerned).

GRASSIE reported that headchecks start to grow at the surface of rails as a consequence of ratchetting (see figure on pg. 16 of [KR-011]), propagate with shallow angle under the surface and finally fork and divert down into the rail. Of course, the presence of liquids (water, grease) can penetrate into the cracks and lead to a mode-I-cracking due to hydraulic pressure of the passing wheel (see [L-005]).

Already in [L-001] it was stated, that in dry conditions (with augmented coefficient of friction) the wear would erase newly initiated cracks before they can start to grow.

According to [L-001] the metallurgical properties of the rail steel are secondary. Harder rails certainly increase the resistance against the initiation of cracks. However, once initiated the higher brittleness of harder rails can become a drawback. As consequence, in 1998 GRASSIE strictly proposed regular preventive grinding.

The reasons are easy:

- The wheel/rail loads are always present since transport services are to be provided
- The load cycles cannot be reduced since the demands for transport services require them
- Traction is always present and cannot be avoided. Traction is always present even for undriven wheelsets due to wheel/rail contact geometry (rolling radius difference leads to longitudinal creepage, angle of attack leads to lateral creepage, contact angle leads to spin creepage)
- The material will suffer RCF, it is just a question of time how long it lasts for the first defect
- Lubrication is required in order to protect the wheels.

At this stage it is to be recalled that each wheel suffers magnitudes of the load cycles of the rail, since each wheel re-enters the contact region approximately all 3 m. That means, a six-axle train which runs from Pukehohe to Britomart has touched each cross section of the rails six times –

but each wheel has suffered 52960 m / (2π 0.425 m) = 19832 contacts. This is a ratio of 1:3305 in favour of the rail, against the wheel.

Therefore, the lack of wear needs to be balanced by regular smooth preventive grinding.

The RCF-cracks have a progressive rate of propagation. That means, once they propagate fast, measures need to be applied quickly and intensively. It is not sufficient to grind “just a little bit”.

However, as long as initiated cracks which have already turned downwards remain in the rail, they need to be completely removed too. The slow rate of propagation occurs only in case that the cracks have a shallow angle.

…….

14.6.3 Vertical Track Motion

At KiwiRail/Auckland Metro RCF is often related with tracks which have higher vertical dynamics. The vertical dynamics of the foundation are in some European countries considered as a safety relevant issue. It shall be recalled that a wheelset, which passes a vertical dip or top (summit) achieves a vertical acceleration az of $\hat{u} = (2\pi v/\lambda)^2$ (sinusodial excitation assumed). For a speed of v = 30 m/s, a wavelength of the through/summit of λ = 4 m and an amplitude of û = 5 mm (i.e. top/bottom=10 mm) occurs. This leads to a vertical acceleration of az = 10 m/s². That means, in the extreme case, the axle load is doubled, in the best case the axle load is increased by the ratio of the unsuspended wheelset mass to the axle load (depending on the vertical stiffness of the bogie suspension).

Consequently, as a prerequisite, in the KiwiRail-Network of Auckland Metro, the track foundation must be intensively improved. This was always related to “pumping” of rails. That means, as long as those bad track foundations are not treated, the RCF will re-start even if grinding measures took place.

It should be checked why the NAL is affected by RCF in particular in upmain direction and not in downmain direction (see [KR-011]). Probably the downmain-track was refurbished with NZR50 rails and the upmain track was not. This can be proofed by checking the KiwiRail-records.

14.6.4 Effect of Lubrication

As discussed in sec. 14.5, lack of wear [S-005] is considered as one reason. Therefore, all measures related with lubrication should be handled with care.

This is in particular valid if hardened rails are introduced. These have a higher resistance against the initiation of cracks but once a crack exists, those rails are more sensitive due to reduced ductility. The problem is increased by the fact that rails of higher strength have (naturally) a reduced wear rate. In turn, this increases again the propagation-rate of the cracks.

14.6.5 Wheel Hardness

Concerning the wheel hardness it is to be recalled that cracks are developed due to the normal and tangential stresses which act in the wheel/rail-contact patch. These stresses depend on the geometrical properties (i.e. curvatures) of the contact partners, on the load (i.e. normal force and slip) and on the elastic stiffness (Youngs modulus) of the related materials. The Youngs modulus of steel is nearly independent from its hardness. Therefore, material properties as “hardness” (or strength in terms of yield stress) do not contribute to the stress-field in the contact patch. Only the hardness of the rail itself can contribute to RCF, but not the hardness of the wheel.

Of course, the hardness of the wheel affects its own wear and thus its developing cross section (geometry!). Only in a back-loop the hardness of the wheel may be considered to be related to the development of RCF but not with direct contribution. The geometry of the wheels in wear state was even found to have better contact properties than in new state (see section 14.10). Therefore the hardness of the wheels should be excluded as a reason for RCF.

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14.11 Conclusion

The nominal state of the KiwiRail/Auckland-Metro-wheel/rail-system does not show unusual facts.

RCF occurs at specific track sections and vanished some meters later with the same profiles and the same traffic passing by.

RCF cracks at KiwiRail/Auckland Metro often show by their visual appearance that they have propagated for too long without countermeasures.

RCF at KiwiRail/Auckland Metro occurs frequently in vicinity of pumping rails, voids (sleepers with lack of ballast), welded rail joints or rails with abnormal vertical or lateral alignment. That means, often when abnormal dynamics are introduced into the track, the RCF occurs.

The wheel/rail properties show (at least for the inclined rail 1:20) good conditions for the CAF-AM-class EMUs.

Specifications at other railway operators consider lack of wear as reasons for and grinding respectively replacement of rails as countermeasures against headchecks.

Therefore, the focus to avoid RCF must be set to preventive grinding. Those rails which have already deep cracks are lost and need to be replaced. It must be considered that intensified lubrication would even increase the risk of RCF since it reduces the “healing” wear.

15 Recommendations

The initial state of the wheel/rail-system does not give many reasons for major objections, however some minor issues remain. The following points are, as the scope of this complete report, valid for the KiwiRail Network which is used for Auckland Transport Metro train operations, only.

15.1 Nominal Data

The following recommendations refer to nominal data, documents and specifications of KiwiRail.

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- The choice of high strength rail grades should take into consideration: Even though those rails have a higher resistance against the initiation of cracks, once they were initiated, countermeasures need to be taken quickly. The reason is that such rails have less ductility (i.e. they are more brittle) than rails with lower strength.

- Classification of permissible crack depths:

Specifications concerning classification of cracks in [KR-011] (which varies from given information in [KR-004]!) (5 mm/8 mm-limit) is, according to our point of view, much too broad. Cracks with depths of up to 5 mm should not be considered as "light" but as severe! According to our experience and common practice at railway and suburban operators rails with crack depths of more than 5 mm are to be considered to be dead.

For further recommendations on permissible crack lengths and -depths the inspection specifications (related to RCF) as they are used at operators of railways and suburban train-systems in Europe could be reviewed and compiled. This task (which is certainly beyond the scope of this report), should also include a survey of the state of knowledge on RCF development and treatment.

15.2 State of Tracks and Rail Surfaces / Grinding

There were no specific issues found in the nominal data of the KiwiRail/Auckland Metro-system which would (compared to other operators) explain the high amount of RCF. The inspections of the tracks did show that the rails simply need more maintenance. This affects, as far as in was in the focus to our inspections, the state of the track foundations as well the state of the surfaces of the rails.

- Generally a relation between bad track foundations and development of RCF was apparent. Even though the main focus of this report was on the cross profiles of wheels and rails as well as the wheel/rail interaction, it was apparent, that alignment of tracks/rails and restoration of ballast, sleepers, rail fixations and welded rail joints with dips and cracks need to be in the scope of works (see figures concerning MP01UM, MP05DM).

    - Vertical alignment errors of the tracks immediately induce vertical oscillations of the trains which lead to amplifications of axle loads.
    - Missing ballast leads to local instabilities of the track with isolated "weaker" parts of the "continuous beam" of the track which again increase motion and forces.
    - Mud spots underneath tracks generally reduce the total stability of the complete track. They need to be properly drained or to its extreme completely removed what implies a re-installation of the track. Even though this is a high effort, the safety aspect of a correctly aligned track needs to be kept in mind.

- Scruffy wooden sleepers also reduce the total stability of the track what leads to increased vertical accelerations (and thus stresses)
- Dips at worn welded rail joints lead to high impacts what damages the track substructure and the rail surfaces at the same time.

- The state of the surfaces of the rails leads to the assumption that in the past maintenance of their surfaces was not sufficient. Since it was concluded in this report that the wheel/rail-interface cannot be considered as the primary cause for the development of RCF at KiwiRail (AT-network), maintenance has to gain the focus.

The development of Rolling Contact Fatigue Faults destroys, if not counteracted at time, rails (and thus assets). Once the cracks have grown too deep, the only remaining option is the replacement of rails. As long as cracks are shallow under the surface, they can be removed, and the lifetime of the rail can be preserved.

It shall be recalled that RCF is not just an economical question as for instance the Hatfield-crash in the United Kingdom (year 2000) unfortunately demonstrated (4 fatalities in a train derailment, caused by broken rails due to RCF).

- This leads to the clear recommendation that more grinding needs to be conducted in the Auckland Metro network of KiwiRail. This must be seen with the background of increasing traffic.

- The Infrastructure needs to be refurbished since (apart from neglection of preventive grinding) vertical motions of the tracks contribute significantly to the development of RCF.

- As discussed in section 14.5, to remove and avoid RCF at KiwiRail a combination of measures is mandatory. An action plan should include:

  - The state of the track vertical and lateral foundation must be improved, especially those locations with intense vertical motions of the tracks. The tracks must be stabilised; vertical and lateral alignment must be restored. If this is not applied, then the causes of RCF will not vanish.

  - The life of those rails, whose RCF-cracks are not too deep (e.g. up to 2 mm) can be preserved:

    ▪ they need to be ground initially deep enough that all (tips of) cracks are removed (otherwise, the stress concentration is not removed)
    ▪ then, they must be preventively ground regularly in order to save the life of those rails.

  - Those rails with deeper cracks should be scheduled for replacement since as long as the cracks remain in the bulk material, the growth rate will not decline with grinding. Therefore, such rails need to be replaced.

- New rails should definitively be ground after installation. This is common practice in order to remove the softer decarbonized layer and the milling skin.
- According to the information of KiwiRail, the state of the NAL tracks in northbound and outbound direction are very different concerning RCF. Both tracks should be precisely compared for issues which may cause the significant difference in the development of RCF. One simple possibility is the case that the downmain tracks were simply re-equipped with new rails – if this should be true, then the age of the rails is found as one more reason for the development of RCF at KiwiRail:
- Check rail gauge L of guard rail:
  AM-class operator CAF reported unusual contact marks (wear) at the back-face of the flanges of the EMUs. Inspections at the entrance-curve towards the ramp to Britomart station (MP03, MP04) give reason to assume that the flangeway-width between the rail and the guard rail was not increased about the amount of track gauge widening (from 1068 mm to 1074 mm). This leads to an increased check rail gauge (nominally about 6 mm) what will lead to early contact of the back-faces of the flanges.

This is not a fatal issue to the back-faces of the flanges. However, it intensively affects the emission of noise. This concerns at least the Britomart entrance heading from the Newmarket line and the Newmarket junction itself. Both have 95 m curve radii and noise abatement (especially at Newmarket) should have primary relevance.

15.3 Grinding Profile

According to the wheel rail contact analysis, the Intermediate Grinding Profile shows even better contact conditions as the Ultimate Grinding Profile. Therefore, a distinction between both is not considered to be required.

The Intermediate Grinding Profile has in particular good contact conditions with the worn CAF-wheel profile. This is reasonable since the majority of the fleet will run in this profile state.

In turnouts the application of inclined profiles is recommended in order to reduce contact stresses. At least at German Railways this is best practice.

15.4 Wheel profiles

Concerning the wheel profiles the following recommendations are result of the survey:

- There was no clear indication that the wheel profiles do not match to the rail profiles. Therefore, there is no need to modify them. According to the wheel/rail contact analysis the CAF profile has some benefits compared to the KiwiRail wheel profile TLA1.
- Workshop staff of KiwiRail should be informed about effective wheel profiles. We had the impression, that the TRA-1 is absolutely unknown. Instead, the Series-A-profile is still applied. Presciptions from the engineering unit should be executed at the workbench.
- From our point of view the AM-class EMUs of CAF are well maintained, and the wheel profile is intensively monitored. A reprofiling interval of 100000 km is very small for railways. While tramways are used to have reprofilation intervals of 20000 km to 80000 km (sometimes 100000 km), railway-like trains should run some hundred thousand kilometers before returning to the lathe (as long as not flats occur).

- As KiwiRail reported that the wheels are not machined after a definite mileage, this measure should be considered to improve the surface characteristics of the wheels. It is common practice, that after defined mileages the profiles are measured and confirmed to match limit values concerning flange height, flange thickness, qR-value and sharpness of the tip of the flange. For guttering a limit value can be determined, which typically varies from operator to operator by experience. Values around 2 mm to 4 mm are common.

The definition of a complete limit profile (as set of X,Y-coordinates) is not helpful since its definition, measurement and analysis creates more questions than answers.

II. SUMMARY OF SNC

For the technical reader the extracts below attempt to summarise the observations, findings, technical comments and recommendations of SNC; SN0193488 _KiwiRail Independent Review of RCF Damage Issue A(draft2)(Final).pdf"

1. Executive Summary

KiwiRail is concerned about emerging rolling contact fatigue (RCF) on tight radius curves, some tangent tracks and switch and crossing (S&C) in the Auckland Metro rail network that has occurred during the last two years. KiwiRail has requested support from SNC-Lavalin Rail & Transit Pty Ltd (SNC-Lavalin) to investigate the root cause(s) of this RCF and to find potential solutions to this problem. It was agreed in the first instance that a five-day fact-finding visit should be made as a first step with the objective of identifying the root cause of the problem. SNC-Lavalin visited Auckland from Monday the 23rd to Friday the 27th of September 2019.

This report details the observations and findings that were made during the visit and recommends some changes for KiwiRail to consider and some aspects to investigate further in the Section 7 of this report.

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4. Background Information

The Auckland Metro network comprises of different rail types, namely NZR 50 kg/m standard carbon, NZR 50 kg/m head hardened, NZR 50 kg/m mill heat treated and 91 lb/yd standard carbon rail. Some of the rails have been in service for more than 45 years. KiwiRail is currently replacing old NZR 50 kg/m and 91 lb/yd standard carbon rails with NZR 50 kg/m mill heat treated rail. The standard rail section adopted in the network is according to the KiwiRail's NZR 50 kg/m rail section as per CE 88232/1 [Ref 1] (see Figure 1). The rails are manufactured according to AS1085.1 Australian Standard [Ref 2] to meet the mechanical requirements specified for the 340-350 BHNgrade rail.

KiwiRail's NZR 50 kg/m rail section has a 13 mm gauge corner radii and 91 lb/yd has a 9.5 mm gauge corner radius. The 91 lb/yd NZR rail section has a relatively flat rail crown compare to 50 kg/m rail section and is shown in Figure 2.

The track gauge is 1068 mm and the rails are inclined at 1 in 20. It is noted that some gauge widening was applied to curve radii less than 250 m to allow locomotives to negotiate tight radius curves.

The S&C installed in the rail network was supplied by several different suppliers (e.g. VAE, CRSBG). The rails of all S&C are laid vertically. The rail profiles of some (13) VAE S&C differs from the standard NZR 50 kg/m rail section by having an AS50 kg/m section, which has 15.5 mm gauge corner radii, rather than 13 mm on NZR 50 kg/m section.

The wheels of the DMUs and locomotives operated by KiwiRail were manufactured according to AAR Class B. AAR class C was used for the wagon wheels. TLA-1 (A - series) wheel transverse profile with the double taper is specified for all new 135-145 mm wide wheels and TRA-1 (B/C - series) transverse profile (see Figure 3) is specified for 114-128 mm wheels according to M6000-101 [Ref 4].

The CAF EMUs have a transverse wheel profile (see Figure 4) which is a modified version of the standard TRA-1 KiwiRail's transverse wheel profile. The modification is intended to improve the vehicle steering characteristics (i.e. by avoiding two-point contact). The modified transverse wheel profile has a R13.5 mm flange root and changes to transition radii leading into a 1 in 20 central tread section. The CAF EMU transverse wheel profile, across the flange root, is slightly different from the KiwiRail's TRA-1 transverse wheel profile.

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6. Discussion

It is not unusual for rails to suffer from rolling contact fatigue. The RCF originates due to development of excessive shear stresses at the wheel/rail interface and can be manifested in severe scale especially if not controlled. If RCF is not properly managed, the cracks can grow exponentially after certain perturbation period and can develop into a transverse defect combined with material inclusions, hence becoming a potential risk of derailment.

During the inspection, it was observed that a broad spectrum of RCF is evident on the Auckland Metro rail network. Heavy RCF was observed near Otahuhu station and the rails of the Up Main track were poorly supported by degraded timber sleepers and loose clips. It is important to note that RCF was observed for poor track conditions as well as fully supported rails with concrete sleepers. Light to moderate RCF was observed on other sites and some of rails have already been replaced due to heavy RCF (e.g. Puhinui station). There was a very little wear at the locations that were inspected during the visit.

Some tight radius curves where wear was dominant on the high rail showed no or very little RCF. Wear at the rail surface acts to prevent the development of RCF by wearing away the incipient cracks before they are able to grow. The increased use of hardened rails will reduce the rail wear further permitting growth of the RCF cracks. Where RCF is the prominent wear mechanism, implementing cyclic rail grinding (light skimming the rail at regular intervals) that introduces artificial wear is beneficial to eliminate RCF initiation sites.

With hardened rails, the frequency of grinding needs to be increased to provide artificial wear. For the nature of the Auckland Metro network's track conditions, cyclic grinding is required to control RCF after removing existing RCF via remedial grinding.

It was noticed that prominent RCF was discovered on rails that had been ground. The tracks on Onehunga branch, where only the CAF EMUs are operating, were not ground and no RCF was observed.

Another potential contributing factor is bi-directional traffic on the branch line which weakens the work-hardening mechanism, as work-hardening leads to crack initiation. It also weakens the hydrostatic crack propagation mechanism (water / grease trapped inside the crack).
The same principles apply to the Mission Bush line where freight trains are operating (low traffic 0.9 MGT). KiwiRail confirmed [Ref 6] that there was no RCF on the Mission Bush line either.

Therefore, bi-directional traffic seems to delay RCF crack initiation.

It was reported that the Auckland Metro network rails have been ground in 2012 and 2017 and some localised areas with known issues in 2018/2019, by installing the interim ground profiles, except for the Onehunga and Mission Bush branch line where the rails have not been ground and subjected to bi-directional rail traffic.

Section 5.1 of this report described that the X-Y coordinates of the ground rail profiles as specified in the KiwiRail Standard [Ref 8] can be misleading, i.e. the ultimate rail profiles are defined relative to a vertical rail profile but the interim profiles were found to be defined relative to a 1 in 20 inclined rail. This is not clearly stated in the standard. In addition, location of the profiles relative to the rails is unclear. If the EN 13231-3 method is applied to locate the profiles, their range of definition is a little short. It was recommended to clarify the defined rail grinding profiles by including the 1 in 20 rail inclination in their definitions (and to clearly state this), to extend the profiles to just beyond the 45-degree contact point, to align the data for the interim and ultimate profiles to common axes and to consider adding a location lug to the low rail and tangent rail profiles. These steps in the KiwiRail grinding standard [Ref. 8] would ease use of the templates and should avoid their miss interpretation.

The contact bands of the S&C that were inspected were different from the anticipated contact conditions. It was noted that the top of the switchblade near tip of the switch had contacted with the wheel and led to development of lipping on the field side of the switchblade. The switch no. 20 was laid with vertical rails and had very sharp contact bands near the rail gauge corner which generates higher stress. The observed contact bands align with the findings of the contact point analysis of the vertical NZR 50 kg/m rail. It is understood that KiwiRail installs 1 in 20 rail inclination by grinding after turnout installation. However, the turnout that had been installed recently (10 months ago) had not yet been ground to 1 in 20 rail inclination at the time of the inspection. KiwiRail intends to implement an artificial 1 in 20 inclination to the S&C rails as a goal for the 2020 rail grinding project.

All the wheels observed on CAF EMUs, DMUs, wagons and locos looked to be in good condition and no wheel flange wear issues were reported. Wheel flats are the dominant wheel damage reported. Flange back wear on the CAF EMUs from check rails was reduced by increasing wayside lubrication but now grease is covering the underside of EMUs requiring them to be cleaned prior to wheel profiling or routine inspections. Section 5.2.3 of this report described that the CAF EMUs suffered from rapid flange root wear within the first couple of months of operation, as well as development of an RCF band near the flange root. To rectify these issues, frequent wheel turning and bogie rotation had been introduced. Currently wheels are skimmed every 110,000 to 120,000 km. If the wheel profiles are causing stresses to the rail gauge corner, by turning the wheels on a frequent basis and not allowing the wheels to adapt to the rail profiles could be a contributing factor to the RCF on the Auckland network.

This analysis in this report has focussed on the contact points of the new wheel and rail profiles and ground rail profiles. If further work is undertaken to compare the TRA-1 and CAF wheel profiles, this analysis could be extended to consider the contact areas, wheel-rail forces and contact stresses.
Some measurements of worn wheel and rail profiles taken during the Auckland visit have not yet been analysed. If further analysis work is undertaken, the worn profiles that were measured could also be of use in those studies.

7. Conclusions and Recommendations

The key findings from SNC-Lavalin's visit to the Auckland Metro network to examine the rail RCF are as follows:

1. It was noted that there was very little wear on the rails of the Auckland network. Wear is beneficial in that it wears away cracks before they can develop into RCF. Despite the increased frequency of the EMUs, overall traffic tonnage remains low. Remedial grinding is required to remove existing RCF damage, then cyclic grinding introduced as artificial wear to control RCF.
2. It is understood that KiwiRail has standardised to hardened rails. Their use on the Auckland Metro network will reduce rail wear further, necessitating an increase in cyclic grinding frequency to control RCF.
3. It is recommended to clarify the defined rail grinding profiles by including the 1 in 20 rail inclination in their definitions (and to clearly state this in Ref. 8), to extend the profiles to just beyond the 45-degree contact point, to align the data for the interim and ultimate profiles to common axes and to consider adding a location lug to the low rail and tangent rail profiles. These steps in the KiwiRail grinding standard [Ref. 8] would ease use of the templates and should avoid their misinterpretation.
4. The contact patch position with vertical rails is undesirable, as explained in this report. If S&Cs are bought as vertical rail, then they should be ground to represent the NZR 50 kg/m at 1 in 20 rail inclination immediately after installation. Alternatively, KiwiRail could consider purchase of S&C that is already inclined to 1 in 20 for the Auckland network.
5. It is recommended to improve the blending of rail profiles around the rail weld and rail joints.
6. There is evidence of the benefits of running bi-directional traffic on the single line sections of the network to control the build-up of RCF. If possible, Auckland Transport and Transdev could consider the feasibility of running trains frequently in both directions on dual track sections of the network.

7. CAF uses a wheel profile that is slightly modified to the TRA-1 wheel profile. It is not certain at this stage how the CAF wheel is a contributor to the RCF, but it remains possible if the additional contact points in the flange root area are of small area and cause higher stresses. Further simulation work could be done to assess the wheel-rail forces and stresses for the CAF wheel profile and its contribution to RCF compared to the TRA-1 profile. In addition, the feasibility of a change of the wheel profile could be investigated in parallel. This would require a simple study to ensure the CAF EMU's dynamic performance is not compromised by the use of the TRA-1 profile.
8. If the study shows that the TRA-1 profile is compatible with the CAF vehicle, a sensible option is to conduct a trial with, say, two EMUs to ensure that there is no detrimental wheel wear issues prior to the change being rolled out onto the whole CAF EMU fleet. The above items are considered to be actions that could help towards reducing the rail RCF.
9. The following aspects are considered as useful measures to support these actions:

10. To review the corrective maintenance strategy for rail RCF management and review the intervention limits given in the KiwiRail RCF document.
11. Rail grinding requirements and actions for RCF are spread across several KiwiRail documents [Refs. 5, 8, 14 & 15]. Section 6 of Ref. 5 states that Ref. 5 is in addition to part of Ref. 14 and it supersedes part of Ref. 15 and that "The policy will remain in place until amended Track Standards are issued". Ref. 14 section 12.4.5 states "When an interim rail profile is established" as it was written prior to Ref. 8. An update of these documents for consistency, together with cross-references, should improve consistency and ease their use.
12. Lastly, the following aspect could be considered as a useful measure but probably not be implement at this time to avoid making too many changes at once. However, the feasibility of this activity could be considered to be done in parallel to the above activities:
13. The CAF EMUs are known to have high primary yaw stiffness and a high secondary yaw stiffness. Both of these factors have been found in UK studies to be detrimental to RCF performance. A study could be made to look at the benefits of reduce primary and secondary stiffness in reducing RCF. If that study shows that there are worthwhile benefits, then a feasibility study could be made to find how these changes should be implemented into the CAF bogie design.