Institute of Railway Technology

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VLOCITY WHEEL WEAR INVESTIGATION FOR V/LINE PTY LTD

by

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Circulation: Restricted to V/Line and Monash University (Institute of Railway Technology)

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EXECUTIVE SUMMARY

The Institute of Railway Technology (IRT), Monash University, was commissioned by V/Line Pty Ltd (V/Line) to investigate the root cause(s) of accelerated wheel wear on VLocity passenger rolling stock operated by V/Line, and provide recommendations on possible remediation strategies.

Based on the inspection and analysis work undertaken for this investigation, the following key points (listed in order of importance) are considered to represent the most significant contributors to the high wheel and rail wear issue, which developed at V/Line in late 2015.

i. Curve radii on the Regional Rail Link (RRL): The tight curves (i.e. curves with R<300 m) introduced to the mainline system as part of the RRL project are considered to be extremely sharp for broad gauge conditions. Moreover, without mitigation, such curves are unsuited to the curving behaviour of the VLocity bogies which utilise a relatively stiff suspension designed to provide increased stability at higher speeds.

ii. High friction: High friction conditions, such as those associated with the absence of any gauge face lubrication in the above curves prior to mid-January 2016, resulted in higher traction (tangential) forces and increased wear.

iii. Wheel and rail materials: The wear resistance characteristics of the material grades currently used for both wheels and rails is considered low by comparison with other grades that are available and may be more suitable. This resulted in higher wear rates, which was particularly significant in the tight curves.

While any one of the above could potentially cause a higher wear situation, it is the combination of these conditions that is considered to be the root cause of the wear issues that developed in late 2015.

An increase in wheel wear rates first occurred soon after commencement of services on the RRL. Wheel wear rates then remained relatively constant until late 2015, at which time wear rates progressively increased as the contact region between worn rails in the tight curves and worn wheels extended over the full depth of the wheel flange. In the absence of any lubrication, this resulted in severe wear damage.

A number of strategies can be used to reduce or control wheel and rail wear on the V/Line network, of which the following are recommended:

i. Lubrication and friction management:

- Continue lubricating the high rail in the sharp curves (R<300 m), but identify and implement a more suitable method of applying lubrication as the current method of manual application is not sustainable in the longer term.
- Investigate the benefits and potential risks of using a combination of friction management methods in sharp curves (R<300 m), which include application of grease to the gauge face of the high rail and a top-of-rail friction modifier (TORFM) on the low rail.

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ii. Wheel and rail materials:

- Replacement of the existing material grades for both rails and wheels to harder (and more wear-resistant) grades. In particular, use of a harder rail grade in the tight curves (R<300 m) should, when used in conjunction with gauge face lubrication, reduce the rate at which the rail profile progresses to a high-wearing (full flange contact) condition.
- For rails, the options which are considered suitable include the standard head hardened grade (nominal hardness 380 HB), or an intermediate strength (~320 HB) grade, noting that the latter may require the use of imported rails.
- For wheels, use of the RS8T or R9T grades can be considered; this would provide a moderate increase in rim hardness levels of up to a maximum of 311 HB. Alternatively an AAR Class B grade, with a maximum rim hardness of 341 HB, can be considered.
- Altering the wheel material grade represents a change to the design specification for the VLocity trains, and hence Bombardier may need to be consulted regarding in any proposed changes.
- An assessment of the expected wear versus rolling contact fatigue behaviour of the alternative rail grades should be performed to identify the maximum curve radius in which the harder rail grade should be used so as to not increase the probability of rolling contact fatigue damage

iii. Wheel machining:

- The surface roughness on the as-machined VLocity wheels should be reduced to increase the effectiveness of any lubricant applied to the gauge face of the high rail in the sharper curves.

iv. Management of the wheel/rail interface:

- Initiate a review of wheel-rail interface management on the V/Line network to:
  - Examine the suitability of current wheel and rail profiles and (where required) identify revisions to help improve wheel/rail contact conditions.
  - Develop a comprehensive network-wide wheel-rail interface management plan.

v. Design:

  - Investigate the feasibility of easing sharp curves along the RRL section, in particular the North Melbourne ‘Flyover’ and any other curves below 300 m radius, which would significantly reduce wear and the need for on-going control measures.
  - While not a preferred option, there is scope to investigate the feasibility of altering the primary suspension characteristics of the VLocity in order to improve curving performance. However, the need for a change in bogie design should be reassessed following the implementation of some of the other control measures noted above.

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PURPOSE:

The purpose of this document is to report on investigative works undertaken for V/Line Pty Ltd regarding wheel wear issues on their VLocity rolling stock fleet.

AUDIENCE:

The work described in this review was carried out for V/Line Pty Ltd and the report is intended for use within V/Line Pty Ltd.

ASSUMPTIONS/QUALIFICATIONS:

All results, conclusions and recommendations made in this report are based on measurements taken directly by Institute of Railway Technology (IRT) personnel and data supplied by V/Line Pty Ltd and/or authorised parties.

To ensure its contextual integrity, this report must be read in its entirety and should not be copied, distributed or referred to in part only.

FURTHER INFORMATION:

Further information can be obtained from Mr. Ravi Ravitharan at the Institute of Railway Technology.

EXTERNAL SOURCE MATERIALS:

The Institute of Railway Technology and/or Monash University do not accept responsibility for the validity, accuracy or quality of any source material or data used in this study that was not generated by IRT.

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1 INTRODUCTION

1.1 PURPOSE OF THIS REPORT

The Institute of Railway Technology (IRT), Monash University, was commissioned by V/Line Pty Ltd (V/Line) to investigate the root cause(s) of accelerated wheel wear on VLocity passenger rolling stock operated by V/Line, and provide recommendations on possible remediation strategies.

This report summarises the activities that were performed in this investigation, the results obtained, possible root causes for the increased wheel wear, and outlines a number of recommended strategies which, if implemented, should lead to a reduction in wheel wear rates on VLocity trains.

1.2 BACKGROUND

V/Line operates VLocity rolling stock for passenger services between Melbourne and Geelong, Ballarat, Bendigo, Traralgon and some other regional centres. The highest proportion (~40%) of service operations are to Geelong, followed by Ballarat and then Bendigo.

The VLocity rolling stock design was first introduced into service in late 2005 and currently comprises a fleet of 59 trainsets. The rolling stock was manufactured by Bombardier, who also provides ongoing maintenance services. Reprofiling of wheels is primarily performed by Downer on an underfloor lathe at Newport Workshops.

Based on information provided by V/Line, average wheel flange wear rates on the VLocity fleet were 0.2-0.3mm per month prior to mid-2015. In July 2015 the fleet average wheel flange wear rates increased to 0.7-1.0mm per month, and remained at this level until late 2015.

In late 2015 a rapid increase in wheel flange wear rates was detected by Bombardier. The highest figure reported by V/Line was 2.6mm per month for freshly-machined wheels, based on the normal measurement regime in which each VLocity train is inspected at intervals of 6-8 weeks. In early January 2016 the measurement frequency was increased, and a further increase in flange wear rates was subsequently recorded.

In mid-January 2016 the increase in wheel flange wear rates had reached a stage where it affected the availability of VLocity rolling stock for service, prompting urgent action to identify the root cause(s) and implement remediation measures.

Based on information provided by V/Line, the changes in VLocity wheel wear rates during 2015 coincide with (but were not necessarily directly related to) alterations to the operational or service profile which included:

- Commencement of passenger services on the Regional Rail Link (RRL), including the dual gauge track sections on the flyover at North Melbourne in mid-2015.
- Complete separation of VLocity services from Southern Cross Station to Geelong Ballarat and Bendigo from Metro Trains Melbourne (MTM) passenger services

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once the RRL was fully operational. VLocity services to Traralgon have continued to use MTM track from Southern Cross to Pakenham.

- Increases in the number of train services in the second half of 2015.

Based on information provided by V/Line at the commencement of the IRT investigation:

- The wheel profile used on the VLocity rolling stock is the MP2 profile originally developed for use on the disc braked passenger rolling stock which operate on the MTM network.
- Apart from the RRL, and the previously-constructed Regional Fast Rail (RFR) track sections, there has been no systematic grinding or milling of rails.

  A gauge-widening rail profile was previously introduced in the RFR high speed track sections to compensate for an as-constructed tight gauge.

  The RRL track sections were profiled to the following rail profiles:

    - For curves below 1000m radius: RPH2000/RPL2000
    - For curves greater than 1000 m radius and tangent track: RFR101
- The VLocity rolling stock is not fitted with any wheel flange lubrication systems.
- No rail gauge face lubrication systems are installed on the on any of the curves in the RRL track sections.

In early 2016 V/Line commenced lubrication of the rail gauge face in the sharp radius curves, particularly those on the North Melbourne 'Flyover' (NMFO), to alleviate the wheel wear. This involved manual application of a rail curve lubricant containing a graphite extreme pressure (EP) additive.

1.3 Scope of Works

The scope of works for this study was based on an immediate need to inspect, measure and assess current wheel and rail conditions, with the aim to develop the most likely cause (or causes) of the recent wear issue and provide recommendation(s) regarding rectification and mitigation options.

It should be noted that the scope of works did not include the development of any new or revised wheel and/or rail profiles, nor in-depth detail regarding rectification or mitigation processes. Such items will require further investigation and development outside the scope of the present study.

1.4 Works Undertaken

The investigation by IRT involved the following major activities:

i) An assessment the current service conditions, including:

   - A preliminary review of the track and rolling stock data provided by V/Line;
   - Inspection and measurement of typical rolling stock and selected track locations, including measurement of wheel and rail profiles, and measurement of friction levels at the running surface and gauge face of rails (the latter on the NMFO only).

ii) Analysis of the collected data in conjunction with an assessment of wheel-rail interaction characteristics and vehicle-track interaction behaviour using a multi-body simulation (MBS) package.

   The analysis included examination of the following aspects:

   - Specified and actual wheel and rail profiles, and the extent of wear loss;
   - Current wheel/rail contact conditions based on the measured profiles;
   - Application of friction management products to the wheel/rail interface;
   - Wheel and rail material characteristics;
   - Rail profiling (by milling or grinding);
   - Wheel machining quality.

   The primary objectives of the analysis were:

   - To identify possible root causes of the accelerated wheel flange wear
   - To examine options for reducing wheel flange wear rates in the VLocity fleet.

iii) Reporting, including preparation of interim reports summarising preliminary results, attendance at meetings arranged by V/line to report on progress and discuss relevant aspects of the investigation, and preparation of a final report.

   Two interim reports were provided during January 2016 [1, 2]. In addition, two separate reports on the proposed changes to track layout on the NMFO [3], and the influence of flange friction levels on the probability of a flange climb derailment [4] were prepared as part of the investigation.

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2 NETWORK AND OPERATIONAL CHARACTERISTICS

2.1 INFRASTRUCTURE NETWORK

V/Line predominately operates passenger train services to regional Victoria on a broad gauge rail network. All services depart Melbourne from Southern Cross Station to numerous regional cities in Victoria along five main railway lines. They are the Geelong, Ballarat, Bendigo, Seymour and Gippsland Lines as illustrated in Figure 1 and summarised in Table 1.

The Geelong, Ballarat and Bendigo services now run on the Regional Rail Link (RRL) illustrated in Figure 2. This new double track and infrastructure was built through the western suburbs of Melbourne between Southern Cross and West Werribee dedicated for regional train services. The Gippsland and Seymour services continue to use the broad gauge Metropolitan rail network managed by Metro Trains Melbourne (MTM), and thus an access agreement is in place for the provision of regional train services.

The Geelong Line serves the south west region of Victoria. It consists of a broad gauge double track to Geelong (~73 km) operating through the Regional Rail Link, with a majority of services terminating at either South Geelong (~74 km) or Waurn Ponds (~88 km). Some services continue further, where beyond this point is a single track with passing loops until terminating at Warrnambool (~ 267 km).

The Ballarat Line serves the western region of Victoria. It consists of a broad gauge double track to Deer Park West (~19 km) operating through the Regional Rail Link and then a single track with passing loops to Ballarat (~113 km), with a majority of services terminating at Wendouree. From this point, some services continue further where the line branches off to either Maryborough (~ 187 km) or Ararat (~ 211 km).

The Bendigo Line serves the northern region of Victoria. It consists of a broad gauge double track to Kyneton (~ 92 km) operating through the Regional Rail Link and then a single track with passing loops to Bendigo (~162 km). From this point, some services continue further where the line branches off to either Echuca (~233 km) or Swan Hill (~345 km).

The Seymour Line serves the north east region of Victoria. It consists of a broad gauge double track extending the Craigieburn Line to Seymour (~99 km), where a majority of services terminate. From this point, some services continue further where it is a single track with passing loops until terminating at Shepparton (~182 km). In addition to this, a single standard gauge track also runs to Seymour which then splits into a double track thereafter until terminating at Albury (~307 km) in New South Wales.

The Gippsland or Traralgon Line serves the eastern region of Victoria. It consists of a broad gauge double track extending the Pakenham Line to just west of Moe (~129 km). A single track with passing loops then continues to Traralgon (~158 km), where a majority of services terminate, whilst some services extend all the way to Bairnsdale (~275 km).

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In addition to being a regional public transport operator, V/Line is responsible for the condition and maintenance of over 3420 kilometres of railway track and infrastructure used by both passenger and freight services running on standard and broad gauge track.

TABLE 1: V/LINE PASSENGER RAILWAY LINES

Line	Region	Terminates	Length	Stations	Track Gauge	RRL
Geelong	South West	Warrnambool	267 km	22	Broad	Yes
Ballarat	Western	Ararat	211 km	12	Broad	Yes
		Maryborough	187 km	13	Broad	Yes
Bendigo	Northern	Echuca	233 km	18	Broad	Yes
		Swan Hill	345 km	19	Broad	Yes
Seymour	Eastern	Shepparton	182 km	16	Broad	No
		Albury	307 km	21	Standard	No
Traralgon	North east	Bairnsdale	275 km	23	Broad	No

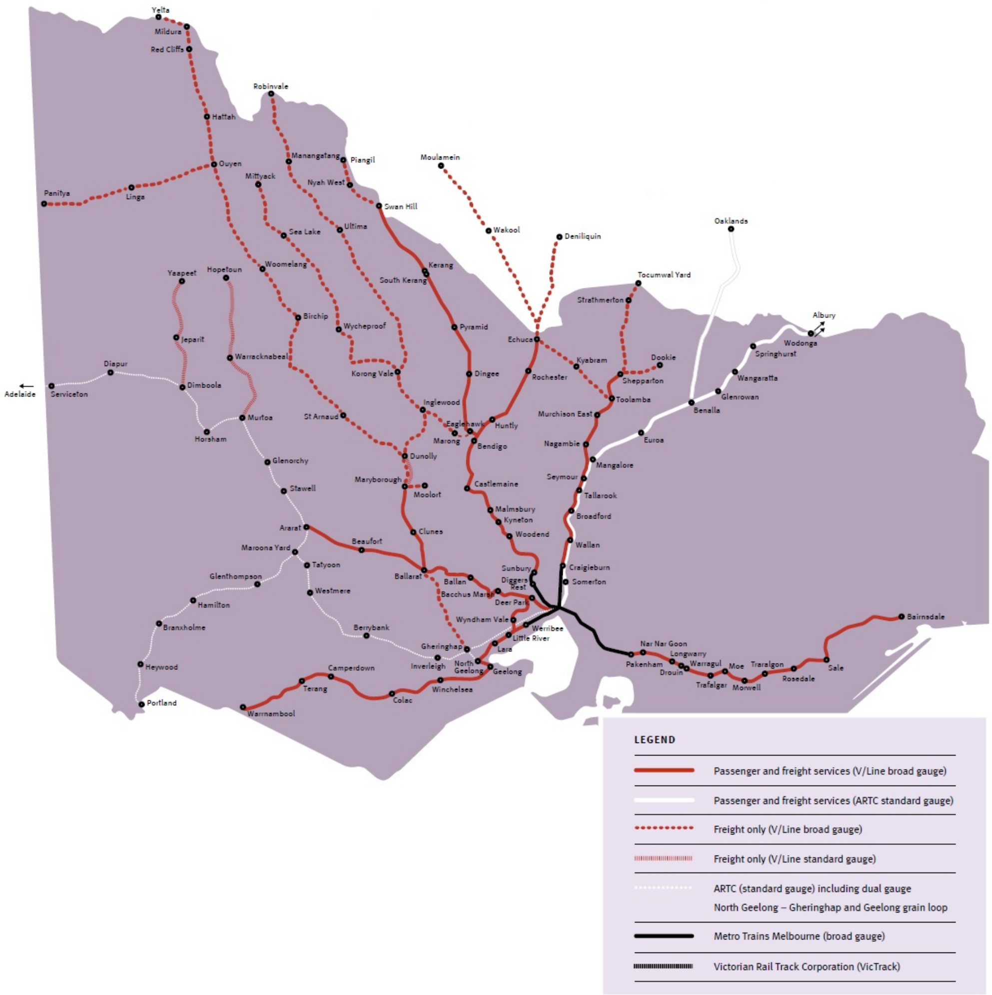

FIGURE 1: VICTORIAN COUNTRY RAIL NETWORK MAP [5]

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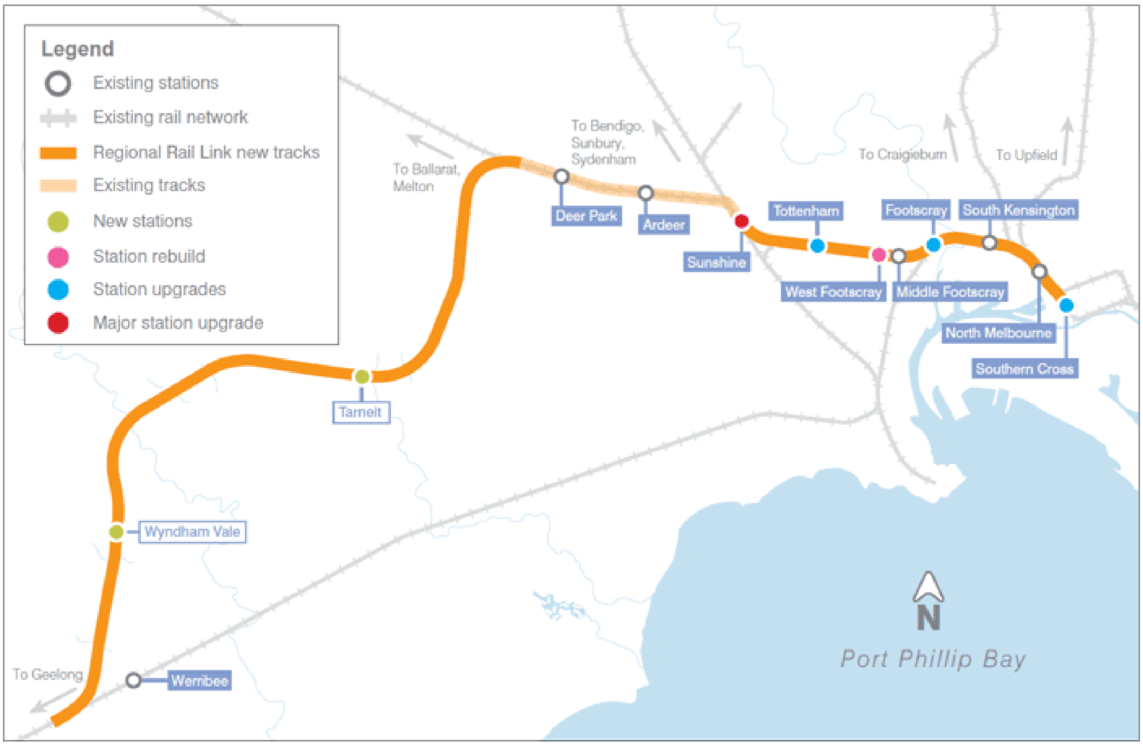

FIGURE 2: REGIONAL RAIL LINK (RRL) MAP

[HTTP://ECONOMICDEVELOPMENT.VIC.GOV.AU/TRANSPORT/RAIL-AND-ROADS/PUBLIC-TRANSPORT/REGIONAL-RAIL-LINK]

2.2 ROLLING STOCK CHARACTERISTICS

V/Line operates many different types of rolling stock for its passenger services including a range of locomotives, coaches and diesel multiple units (DMU).

The following sections provide details and characteristics of the types of rolling stock pertinent to this investigation, including VLocity, Sprinter, N Class locomotives and N type coaches. There are other rolling stock types within the V/Line fleet, such as the older A class, P class and Y class locomotives, as well as the H type and Z type passenger coaches, which were not considered in this study.

2.2.1 VLOCITY DMU

The VLocity (Figure 3) is the newest rolling stock in the current V/Line fleet and is manufactured by Bombardier Transportation. This Diesel Multiple Unit (DMU) first entered service in December 2005 on the Ballarat Line, followed by the Geelong, Bendigo, Traralgon and Seymour lines in 2006. There were also extended VLocity services to Ararat, Maryborough, Echuca and Sale.

FIGURE 3: VLOCITY 3-CAR DMU

VLocity units are powered by one 559 kW Cummins diesel engine (per car) and have a maximum design speed of 160km/h. There are currently 59 sets in service on the network, with seven more VLocity trainsets currently under construction. Each VLocity trainset can be configured as two or three semi-permanently coupled sets (Figure 4). There are also three types of cars, each identified by a different series number:

- 1100 Series – DM(D) = Driver Motor with Disabled Access (66 seats)
- 1200 Series – DM = Driver Motor (74 seats)
- 1300 Series – TM = Trailer Motor (82 seats)

FIGURE 4: VLOCITY TRAINSET CONFIGURATIONS

Pertinent details of the VLocity rolling stock are listed in Table 2, while a general drawing of the bogie arrangement is provided in Figure 5.

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TABLE 2: VLOCITY DETAILS AND SPECIFICATOINS [6,7]

Type	Diesel Multiple Unit (DMU)
Manufacturer/Location	Bombardier Transportation, Dandenong, Victoria
Constructed	2004-Present
Introduced	December 2005
No. in Service	52 sets (3VL); 6 sets (2VL)
Fleet Numbers	VL10-11,VL13-18 (2VL); VL0-9,VL12,VL19-28,VL30-59 (3VL)
Capacity	140 (2VL); 222 (3VL)
Maximum Speed	160 km/h
Power Output	559kW (750 hp) per car
Track Gauge	Broad – 1600 mm
Services	RFR: Geelong, Ballarat, Bendigo, Traralgon Seymour, Ararat, Maryborough, Echuca, Sale

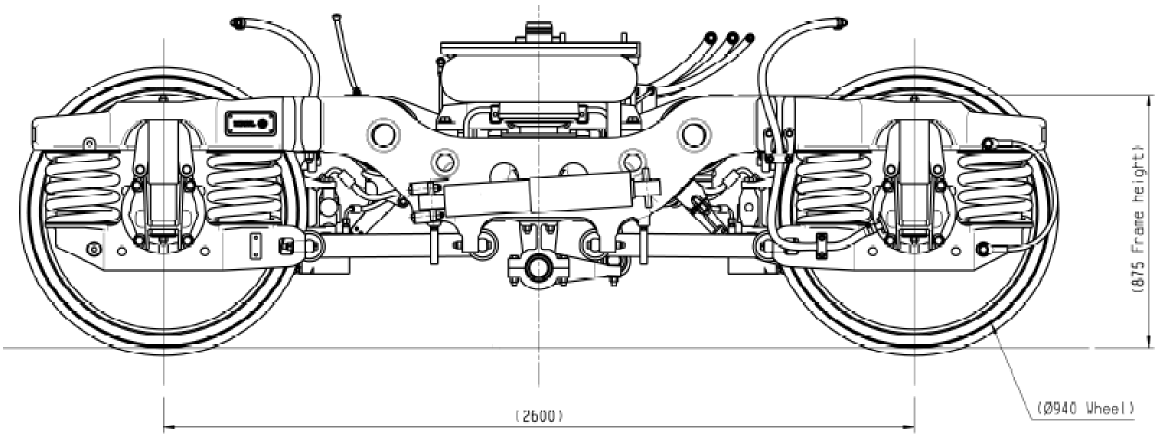

FIGURE 5: VLOCITY BOGIE [8]

2.2.2 SPRINTER DMU

The Sprinter (Figure 6) is a DMU manufactured by A Goninan & Co. in the mid-1990s. 22 single railcars originally entered service between 1993 and 1995 and were subsequently refurbished between 2007 and 2011. These vehicles now mainly run on short haul trips on the Seymour and Stony Point Line (for MTM) following the introduction of the VLocity stock. The Sprinter has a maximum speed of 130km/h and is powered by a two Deutz-KHD 235 kW diesel engines. Up to eight Sprinter cars can be coupled together at a time.

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FIGURE 6: SPRINTER DMU

[HTTPS://C1.STATICFLICKR.COM/3/2719/13210046005_BC628FFA33_B.JPG]

Pertinent details of the Sprinter are listed in Table 3, while a general drawing of the bogie arrangement is provided in Figure 7.

TABLE 3: SPRINTER DETAILS AND SPECIFICATIONS [9,10]

Type	Diesel Multiple Unit (DMU)
Manufacturer/Location	A Goninan & Co., Broadmeadow, New South Wales
Constructed	1993-1995
Introduced	December 1993
No. in Service	21
Fleet Numbers	7001-7022
Capacity	90
Maximum Speed	130 km/h
Power Output	470 kW (630 hp)
Track Gauge	Broad – 1600 mm
Services running	Geelong, Ballarat, Bendigo, Seymour, Traralgon, Stony Point (MTM)

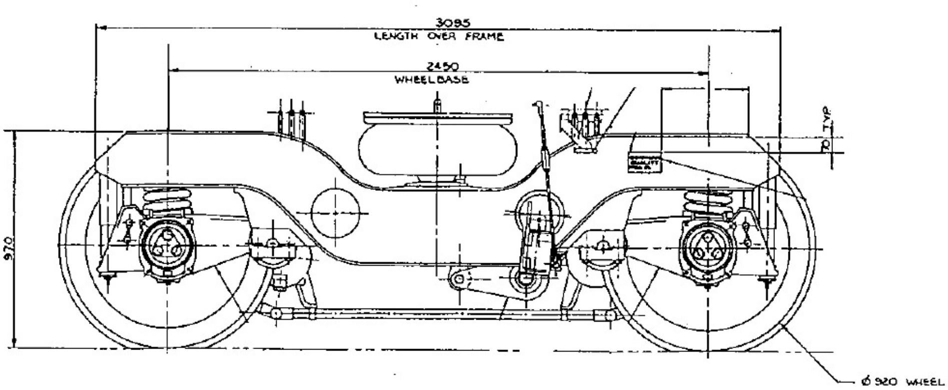

FIGURE 7: SPRINTER BOGIE [11]

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2.2.3 N Class Locomotive & N Type Coaches

The N Class locomotive is a diesel locomotive manufactured by Clyde Engineering. These six axle locomotives entered service between 1985 and 1987 and have a power output of 1846 kW and operate at speeds of up to 115 km/h. There are currently 25 N Class locomotives in service.

The N type coaches are used on predominantly longer haul services to Warrnambool, Swan Hill, Shepparton, Albury and Bairnsdale. These passenger carriages were originally manufactured by Victorian Railways at Newport Workshops between 1981 and 1984. 56 of these carriages are currently in service; these are arranged in 3, 4 or 5 semi-permanently coupled sets.

Figure 8 shows a typical N class locomotive and N type coaches in operation on the V/Line network.

Figure 8: N Class Locomotive Hauling N Type Coaches
[https://c2.staticflickr.com/4/3734/12179734704_fb0e47a28b_b.jpg]

Pertinent details of the N Class locomotives and N Type coaches are listed in Table 4.

TABLE 4: N CLASS LOCOMOTIVE AND N TYPE COACH DETAILS AND SPECIFICATIONS [12,13,14]

Stock	**N Class Locomotive**	**N Type Coaches**
Type	Diesel Electric Locomotive	Locomotive Hauled Carriages
Manufacturer	Clyde Engineering	Victorian Railways
Location	Somerton, Victoria	Newport Workshops, Victoria
Constructed	1985-1987	1981-1984
Introduced	September 1985	October 1981
No. in Service	25	56
Fleet Number	N451-N475	ACNXX-BRNXX-BNXX
Capacity	-	52 (ACN); 67 (BRN); 88 (BN);
Power Output	1846 kW (2476 hp)	-
Maximum Speed	115km/h	115 km/h
Track Gauge	Broad – 1600 mm, Standard – 1435 mm	
Services	Warrnambool, Swan Hill, Shepparton, Albury, Bairnsdale	

2.2.4 VLOCITY AND SPRINTER PRIMARY SUSPENSION

Of interest to this study were the comparative differences between the design and operation of the primary suspension on the VLocity and Sprinter bogies. The main aspect of interest was the method of longitudinal restraint of the wheelsets in each design.

The term primary suspension refers to any suspension components acting between the wheelset and bogie, which are generally quite stiff when compared to the secondary suspension elements located between the bogie and the body of the car.

The VLocity primary suspension design (Figure 5) employs a traction rod between each axle box and the bogie frame; this rod contains two load bearing elastomer bushes, one at each end, that facilitate the required vertical and lateral motion of the axle while providing longitudinal stiffness.

The Sprinter primary suspension design (Figure 7) does not have this type of rod and instead directly couples the axle box to the bogie frame by a single, and much larger, elastomer bush. The larger size and greater area of elastomeric rubber in the Sprinter design means that primary suspension (in particular longitudinal) stiffness is significantly lower (approx. 4 times lower) than the VLocity design.

In addition, the wheelbase differs between the two designs, with the VLocity having a larger spacing between axles than the Sprinter on both powered and trailer bogies. The two designs also differ in the arrangement of powered and unpowered wheelsets; in the VLocity design each car has one powered and one unpowered bogie, whereas in the Sprinter design one wheelset in each bogie is powered and the other unpowered.

Specific values, as provided by Bombardier [8, 11], for both stiffness and wheelbase for the two designs are shown in Table 5.

TABLE 5: COMPARISON BETWEEN VLOCITY AND SPRINTER PRIMARY SUSPENSION CHARACTERISTICS [8,11]

Stock	VLocity	Sprinter
Primary Longitudinal Restraint	Trailing Link coupling between Axle Box and Bogie Frame	Axle Box and Bogie Frame directly connected through Elastomer Bush
Longitudinal Stiffness	At least 3 x 10^7 N/m	7 x 10^6 N/m
Wheelbase	2.6 m	2.45 m

2.2.5 WHEEL PROFILES

The current target wheel profile to be supplied with new wheels and installed on machined wheels for the VLocity fleet is the PTC-V MP2 wheel profile (Figure 9). The Sprinter rail cars are the other rolling stock within the V/Line fleet that also use the MP2 wheel profile, while the N type coaches use the MP1 wheel profile and the N class Locomotives use the ANZR1 1:40 wheel profile.

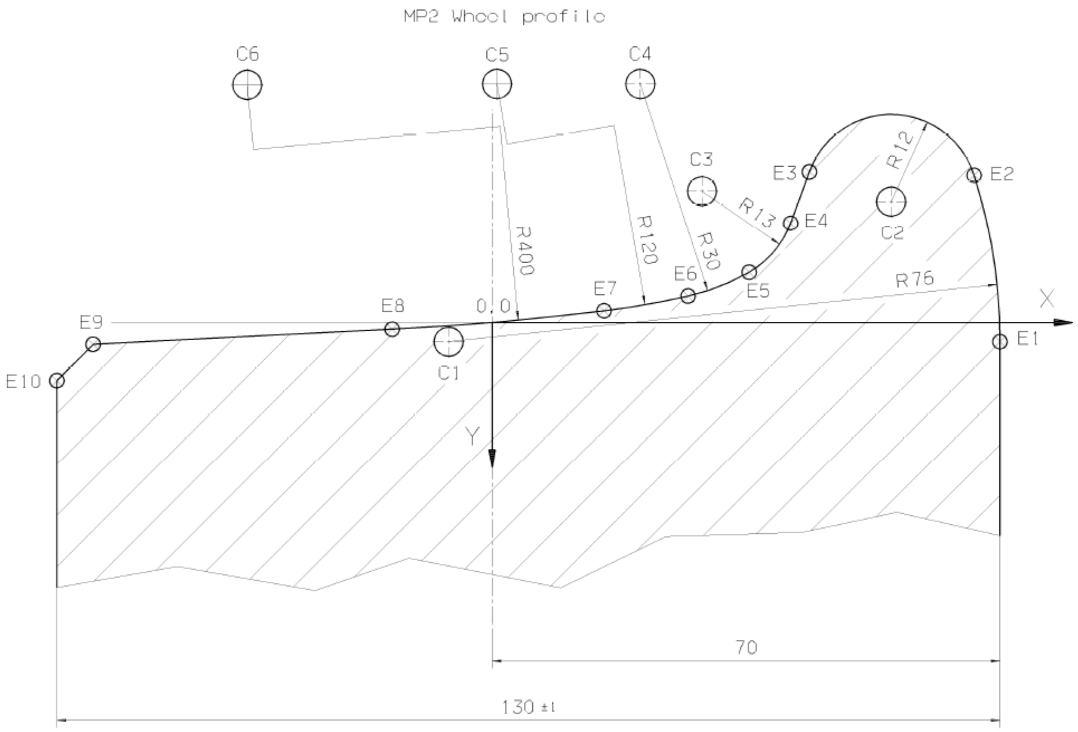

FIGURE 9: MP2 WHEEL PROFILE [15].

2.2.6 WHEEL MATERIAL

Wheels fitted to the VLocity rolling stock are currently manufactured for Bombardier by Comsteel to BS 5892-3:1992 grade R8T [16]. The characteristics of the wheel material grade, as summarized in the relevant Bombardier drawing and Comsteel product data sheet [17], are reproduced in Table 6.

TABLE 6: VLOCITY WHEEL MATERIAL CHARACTERISTICS [17]

New diameter	940mm
Condemning diameter	857mm
Rim width	130mm
Material grade	BS5892 R8T
Rim hardness	255 -285 BHN
Grain size	5-8 ASTM
Tensile strength: Rim Web	 860 - 980 MPa 820 MPa max
Elongation: Rim Web	 13% min 16% min
Impact tests (Rim)	15 J min @ 20°C (Charpy U notch)
Ultrasonic inspection	AAR M107 Latest Revision.

2.3 TRACK

The track sections of relevance to the current investigation are those over which the main VLocity services operate, i.e. Melbourne to Geelong, Ballarat, Bendigo and Traralgon. Figure 10 shows the distribution of curved track across all track sections, based on the details included in the curve summary provided by V/Line.

Figure 11 shows the corresponding details for all individual curves up to and including a minimum radius of 3000 m. A subset of these, for curves ≤800 m radius, is shown in Figure 12. Figure 13 shows the overall distribution of curved track of radius ≤800 m by radius and total length.

Rail size across the above track sections include primarily 60kg/m on the RRL and RFR track, with 50kg/m in some sections, such as the dual gauge track at the North Melbourne flyover, and older 53kg/m outside of these areas. All new rail is standard carbon (or As-Rolled) grade according to AS1085.1-2002. Nominal hardness levels in these rails vary between ~250HB for the older rails produced by BHP Steel at Pt Kembla, to ~280HB for rails from OneSteel at Whyalla.

V/Line have indicated that only a limited number (~17) of trackside lubricators are installed across the entire V/Line network, and none of these were in the track sections of primary interest in the current investigation.

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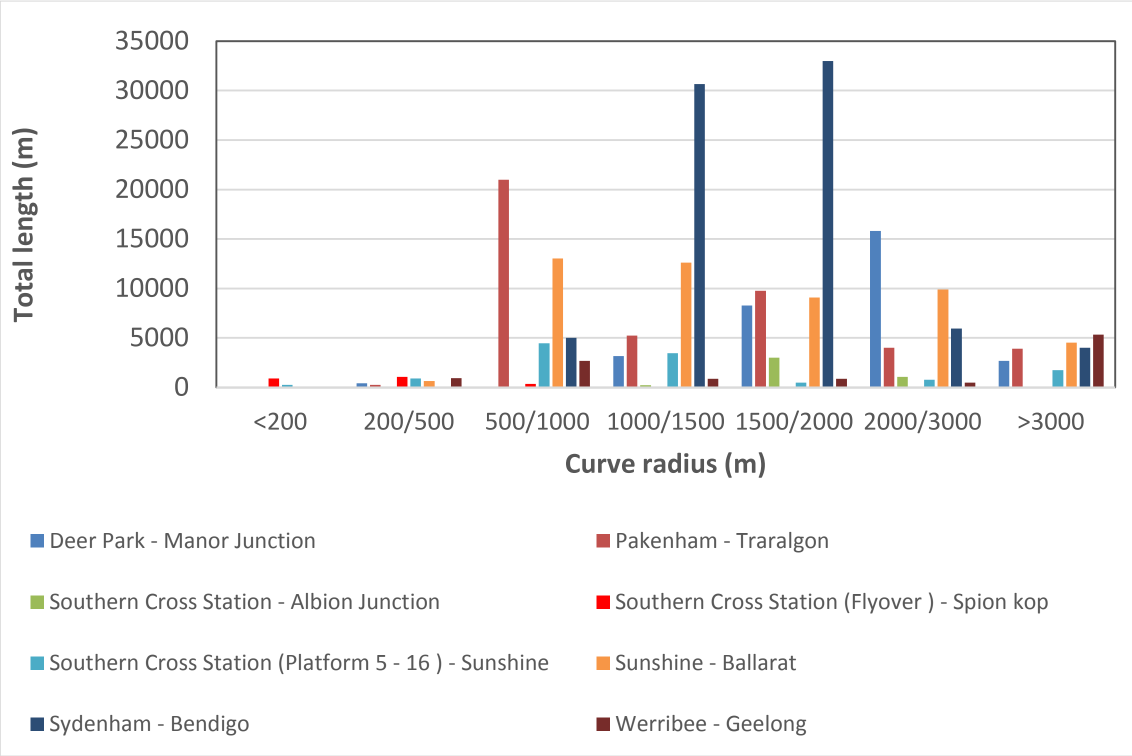

FIGURE 10: DISTRIBUTION OF CURVED TRACK BY RADIUS AND TOTAL LENGTH

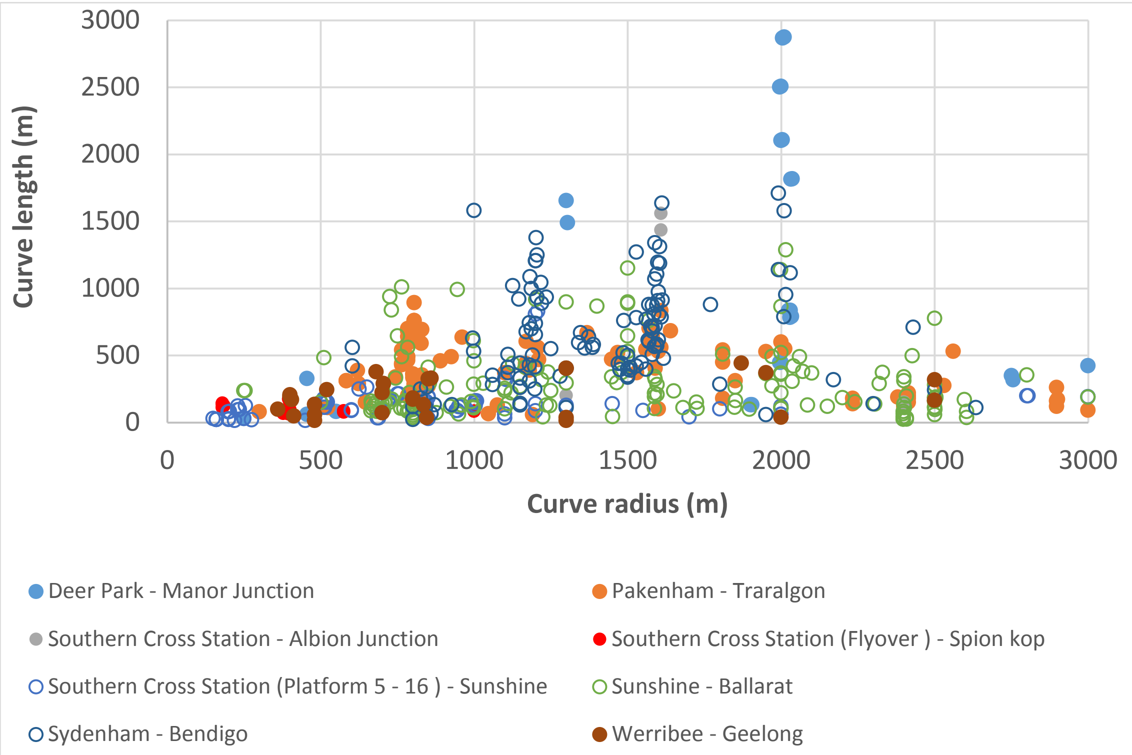

FIGURE 11: DISTRIBUTION OF CURVED TRACK BY RADIUS AND INDIVIDUAL LENGTH, ALL CURVES ≤ 3000 M RADIUS

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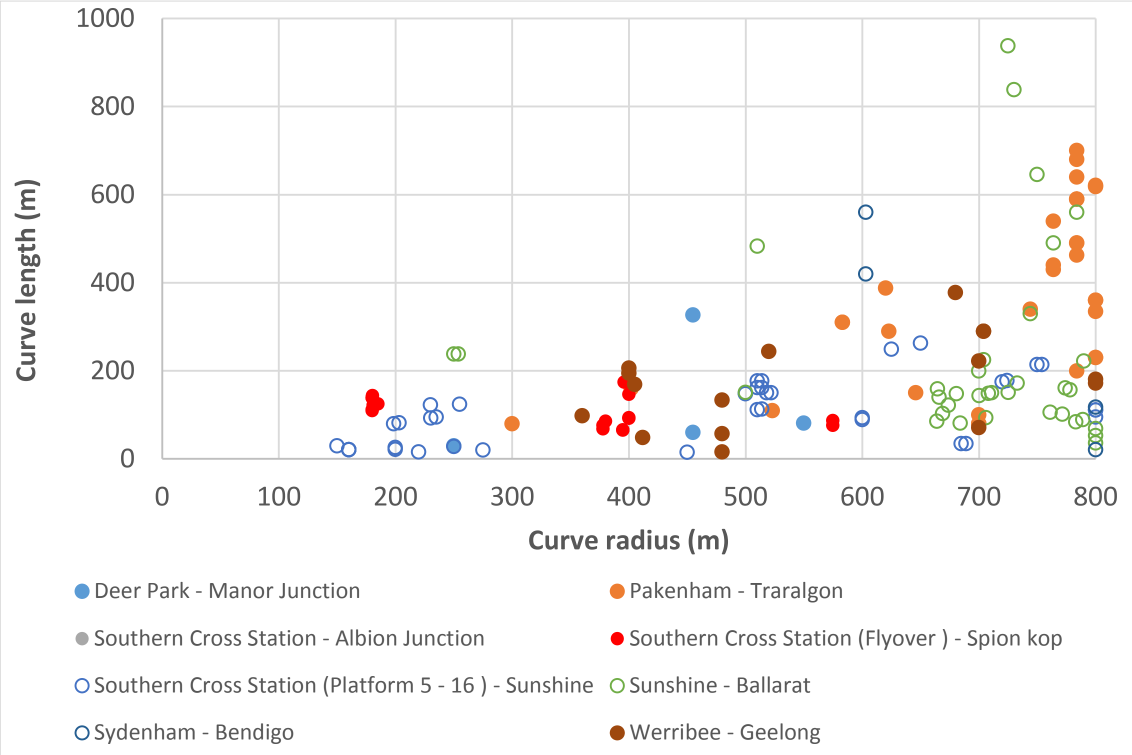

FIGURE 12: DISTRIBUTION OF CURVED TRACK BY RADIUS AND INDIVIDUAL LENGTH, ALL CURVES ≤ 800 M RADIUS

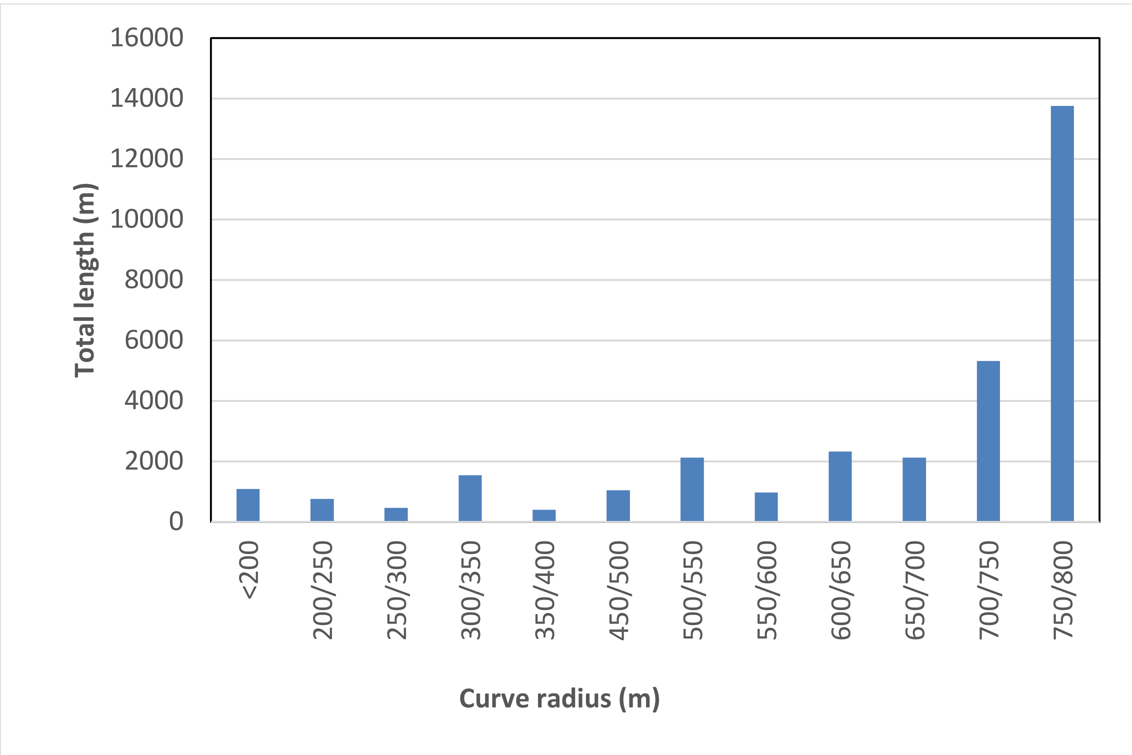

FIGURE 13: DISTRIBUTION OF CURVED TRACK OF R ≤ 800 M BY RADIUS AND TOTAL LENGTH

3 SITE INSPECTIONS AND MEASUREMENTS

Several site inspections were undertaken by IRT personnel between mid-January and early February 2016. The aim of the site inspections was to examine and measure current vehicle (wheel) and track (rail) conditions. This included the inspection of relevant rolling stock and track features on the V/Line passenger network.

3.1 ROLLING STOCK

3.1.1 OVERVIEW

Inspection of V/Line rolling stock was carried out by IRT personnel on 4 separate days in January 2016. During the mornings of 16th and 17th of January, VLocity sets 18 and 42 were scheduled for wheel machining on the Hegensheidt underfloor lathe at the Downer Newport Workshops. Upon arriving, some wheelsets of VLocity 18 had already been machined. However, a full set of pre-and post-machining measurements was taken from VLocity set No. 42. A number of new wheels supplied by Comsteel in Bogie Overhaul were also inspected and measured; these wheels were identified with the measured rim hardness level in each case.

During the mornings of the 19th and 21st of January, inspections were performed at the Bombardier West Melbourne Depot. Due to availability and access constraints, selection of vehicles was primarily based on the relevant rolling stock available within the depot at the time of inspection. Wheel measurements were taken from a variety of different rolling stock types including a total of 10 VLocity cars, 1 Sprinter, 2 N Class Locomotives and 3 N Type Coaches.

A summary of the completed rolling stock inspection program is provided in Table 7. A full list of inspected rolling stock is provided in Appendix A.

TABLE 7: COMPLETED ROLLING STOCK INSPECTION PROGRAM

Inspection Date	Location	Stock	Vehicle No.	No. of Cars
16/01/2016	Downer Newport Workshops	VLocity DMU	VL18	2
17/01/2016			VL42	3
19/01/2016			VL24	2
	Bombardier West Melbourne Depot		VL57	3
		N Type Carriage	N18	3
		N Class Loco	N452	1
21/01/2016			N459	1
		Sprinter DMU	7008	1

3.1.2 MEASUREMENTS

Measurements taken during rolling stock inspections included:

- Transverse wheel profile before and after machining
- Running surface hardness of wheel tread
- Photographs of wheel tread/flange conditions

Transverse wheel profiles were measured using a Miniprof® instrument, manufactured by Greenwood Engineering A/S (Figure 14). The Miniprof® instrument captures an electronic profile of the wheel flange and tread, which is then saved onto a laptop computer for further analysis. In addition to transverse profile, the Miniprof® instrument is also able to estimate the diameter of the wheel at the tapeline.

FIGURE 14: MINIPROF® WHEEL INSTRUMENT

Surface hardness of selected wheels was measured using a hand held rebound Equotip Piccolo 2 instrument (Figure 15) made by Proceq SA. Measurements were conducted on the throat, centre and field side region of the wheel tread.

The accuracy from the rebound hardness tester cannot be assured on machined wheels as the running surface of these wheels is not smooth. All measurements were recorded using the Brinell hardness scale (HB).

No independent assessment of the new wheels to confirm if the wheels comply with the specified requirements has been performed to date as part of the investigation. This will be completed once a new wheel is available for testing.

FIGURE 15: SURFACE HARDNESS INSTRUMENT ON A WHEEL

The convention used to identify the different V/Line rolling stock wheel measurements with respect to their position on the vehicle is shown in Appendix B.

In addition to the data obtained by IRT, upon request Bombardier provided a set of wheel wear measurements for the entire VLocity fleet, covering the period April 2015 to early February 2016.

3.2 TRACK

3.2.1 OVERVIEW

The track data provided by V/Line was analysed to determine the distribution of curve radii in sections over which the VLocity trains operate, and to identify suitable inspection locations. Site selection was primarily based on the need to inspect rail condition covering a wide range of track geometry conditions. Priority was given to sharper or tighter curves where it is expected that VLocity trains will flange continuously, as well as some intermediate radius curves with higher normal track speeds. Of particular interest were the Regional Rail Link (RRL) sections and the line from Sunshine to Ballarat, as these contained the sharpest curves. In addition, locations containing known wear issues, as advised by V/Line, were also considered.

Arrangements were made with V/Line personnel to travel in the leading cab of a VLocity to observe the vehicle response during curving. The cab rides were primarily conducted to survey the track sections of interest as well as identifying any pertinent locations that may not be obvious from the curve register. Return trips from Southern Cross Station to Ballarat were completed on 29th January and Geelong on 2nd February, respectively.

Track inspections were carried out by IRT personnel under the supervision of V/Line representatives during non-operating hours on nights of the 4th and 5th of February.

A total of 21 mainline sites were inspected in areas including North Melbourne, Footscray, Sunshine, Deer Park, Wyndham Vale, Manor and Bacchus Marsh.

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Where possible, curved track inspection points were established near the centre of the curve. All inspection sites were set up well clear of any other track features, such as road crossings, turnouts and insulated joints.

A summary of the completed track inspection program is provided in Table 8 and a full list of inspection sites is provided in Appendix A. Figure 16 shows the distribution of inspection locations by curve radius and line, separating up and down tracks. All of the sharpest curves with a radius below 200 metres were located between Southern Cross Station (SCS) and Spion Kop over the NMFO.

TABLE 8: COMPLETED TRACK INSPECTION PROGRAM

<table>
<tr><th>Inspection Date</th><th>Line</th><th>Location</th><th>No. of Sites</th></tr>
<tr><td rowspan="4">05/02/2016</td><td>SCS (Flyover) – Spion kop</td><td>North Melbourne</td><td>8</td></tr>
<tr><td rowspan="2">SCS (Plat. 5-16) – Sunshine</td><td>Footscray</td><td>4</td></tr>
<tr><td rowspan="2">Sunshine</td><td>1</td></tr>
<tr><td>Sunshine – Ballarat</td><td>1</td></tr>
<tr><td rowspan="4">06/02/2016</td><td rowspan="3">Deer Park – Manor Junction</td><td>Deer Park West</td><td>2</td></tr>
<tr><td>Wyndham Vale</td><td>1</td></tr>
<tr><td>Manor</td><td>1</td></tr>
<tr><td>Sunshine – Ballarat</td><td>Bacchus Marsh</td><td>3</td></tr>
</table>

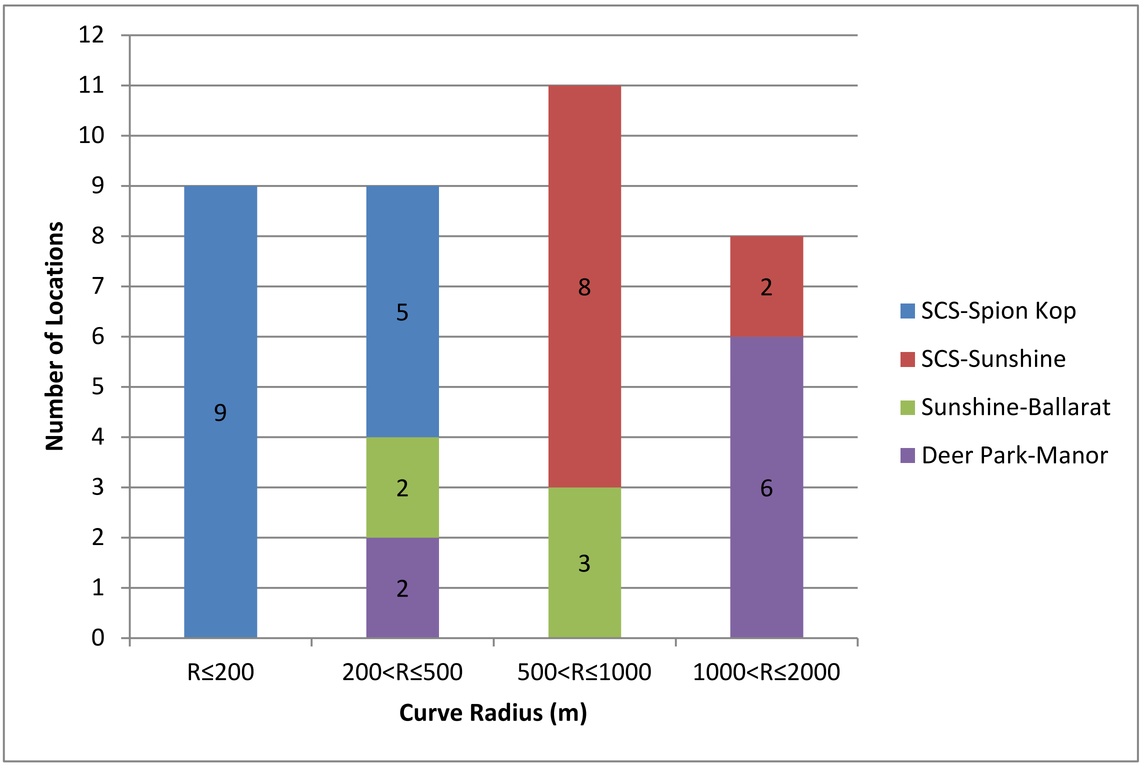

FIGURE 16: NUMBER OF LOCATIONS MEASURED FOR DIFFERENT CURVE RADIUS

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3.2.2 MEASUREMENTS

Measurements undertaken at each site during the inspection included:

- Transverse rail profiles
- Surface hardness
- Running surface friction using a Tribometer instrument
- Photographs of running surface condition
- General notes

Transverse rail profile was measured using a MiniProf® rail profile instrument, manufactured by Greenwood Engineering A/S (Figure 17). The MiniProf® instrument captures an electronic profile of the rail head which is then saved onto a laptop computer for further analysis. In addition to transverse rail profile, the MiniProf® instrument is also able to measure track gauge by using a calibrated telescopic bar attached to the measurement head.

FIGURE 17: MINIPROF® RAIL INSTRUMENT

The Equotip Piccolo 2 portable instrument (Figure 15) used for measuring the surface hardness on wheels was also used to measure surface hardness on rails at selected sites. Measurements on rails were taken from varying positions across the main contact band.

Surface friction levels at the running surface and gauge corner of rails in curves on the NMFO (i.e. the only track section in which lubrication was being applied) were measured during the track inspection. These measurements, which were performed using a Salient Systems Push Tribometer (Figure 18), provide a measure of the maximum or limiting friction from both gauge face and running surface.

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FIGURE 18: SALIENT SYSTEMS PUSH TRIBOMETER [18]

4 RESULTS

4.1 WHEEL WEAR & CONDITION

4.1.1 WHEEL WEAR

Wheel wear was assessed using a combination of both measured (by IRT) and wheel inspection records for the VLocity fleet, supplied upon request from Bombardier. The latter covered standard measurement parameters including, flange height, flange width, flange angle, rollover, width, hollow tread, tyre thickness groove, rolling circle diameter and arris. Although the data did not include dates of wheel machining or replacement, inspection dates with large changes in wheel diameter provided an estimate on the period during which these activities were carried out. In addition, measurements that indicate an increased flange thickness or wheel diameter were excluded from the results.

4.1.1.1 Supplied Wheel Data

Analysis of the supplied wheel data was limited to the period from June onwards, i.e. from just before the introduction of the RRL services. The data included odometer readings for all data obtained at Ballarat, but not for the data obtained at West Melbourne. In addition, the inspection and measurement interval for each train was typically in the range 6-8 weeks during 2015, and hence not all trains were inspected each calendar month.

The analysis primarily focused on the main wear parameters, flange thickness (Sd), flange height (Sh) and tread hollowing, with full results for these parameters presented in Appendix C.

Flange wear was calculated by taking the difference in flange thickness between inspection dates and then determining the loss per month (taken over an average of 30.5 days). As not all vehicles in the VLocity fleet were inspected during any individual month, the resulting data reflected the overall wear behaviour and not the performance of any individual trainset. In addition, the absence of odometer readings for some data sets meant that it was not possible to normalize the wear rates against the distance travelled.

Average flange wear rates (mm/month) for each month between the period June 2015 and January 2016 for the entire VLocity fleet are shown in Figure 19. The results showed flange wear rates averaged 0.27 mm/month in June 2015, then increased to ~0.5 mm/month in July 2015. This wear rate remained fairly stable until December 2015 when it rapidly increased to 0.7 mm/month and up to 1.3 mm/month in January 2016. There was also a considerable increase in the spread of flange wear rates in January 2016, as indicated by the error bars in Figure 19. This overall trend is consistent with the information provided by V/Line on the wheel flange wear rates of the VLocity fleet[1].

[1] V/Line subsequently advised the VLocity fleet distance travelled increased from 3,946,490 km average per month for the period January 2015 to June 2015, to 4,454,499 km between July 2015 and December 2015 (a 12.9% increase)

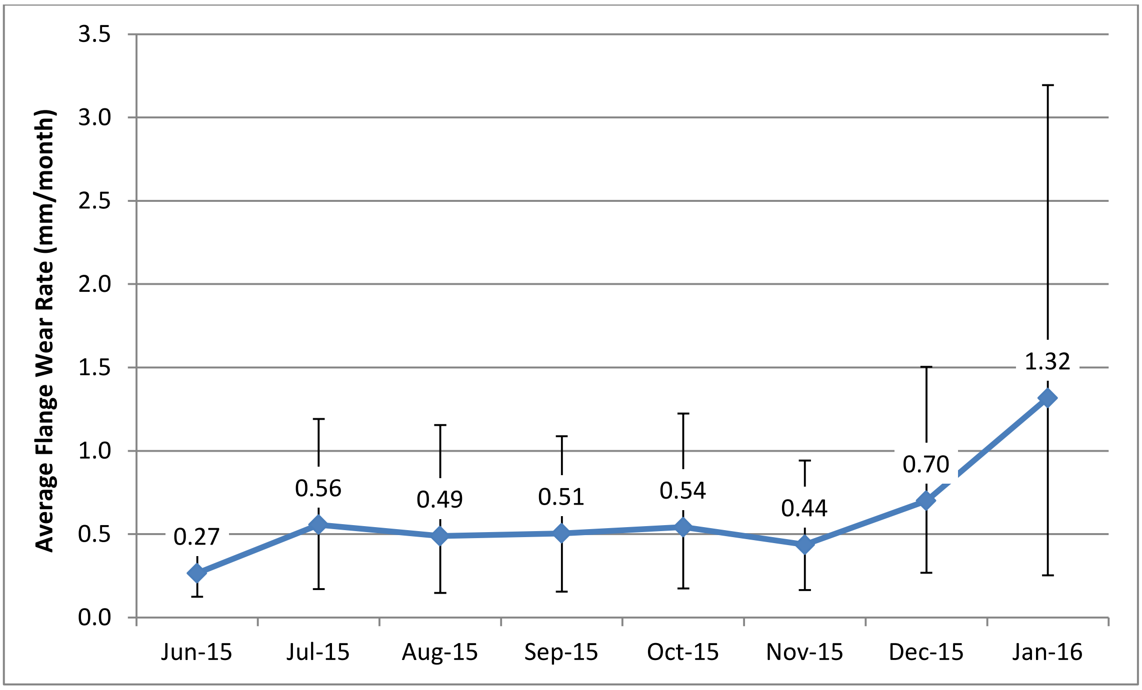

FIGURE 19: VLOCITY FLEET AVERAGE FLANGE WEAR RATE BY MONTH

To further analyse the trends in flange wear rates, the VLocity fleet data were separated by car series, bogie type and side. Figure 20 shows the average flange wear rate of wheels for each of the three different cars i.e. 11XX, 12XX and 13XX series, with negligible apparent differences.

Figure 21 shows the average flange wear rate of wheels separated by the left versus right side of the car. The right side of the VLocity (i.e. Side A of 11XX/13XX series car and Side B of 12XX series car) clearly showed a higher wear rate after July 2015 compared to the left side (i.e. Side A of 12XX series car and Side B of 11XX/13XX series car). However, the margin or difference did not appear to change significantly in the later months.

Figure 22 shows the average flange wear rate of wheels separated by bogie type for all cars (i.e. motor vs. non-driven trailer bogie). The results show that flange wear on the motor bogie is consistently higher than the non-driven trailer bogie, although the margin between them is less than that between the left and right sides (Figure 21). This characteristic is generally typical of railway vehicles since wheels on the driven motor bogie are subjected to greater tractive forces than non-driven wheels.

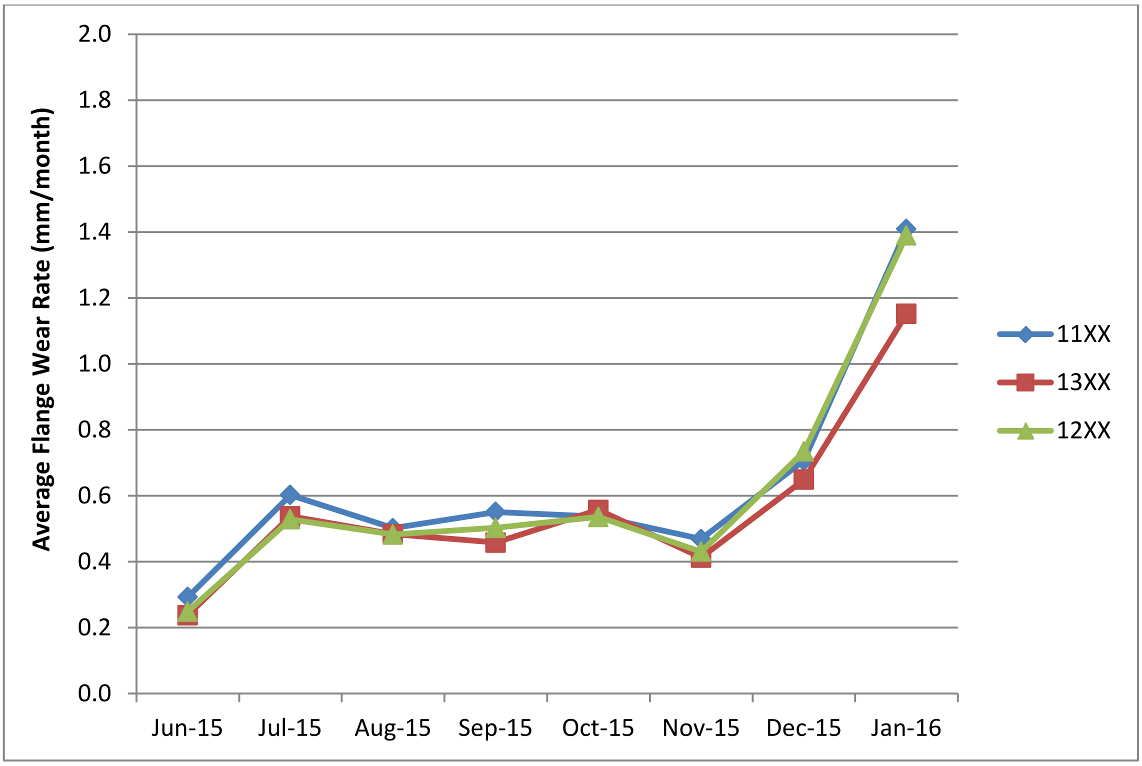

FIGURE 20: VLOCITY FLEET AVERAGE FLANGE WEAR RATE BY CAR SERIES

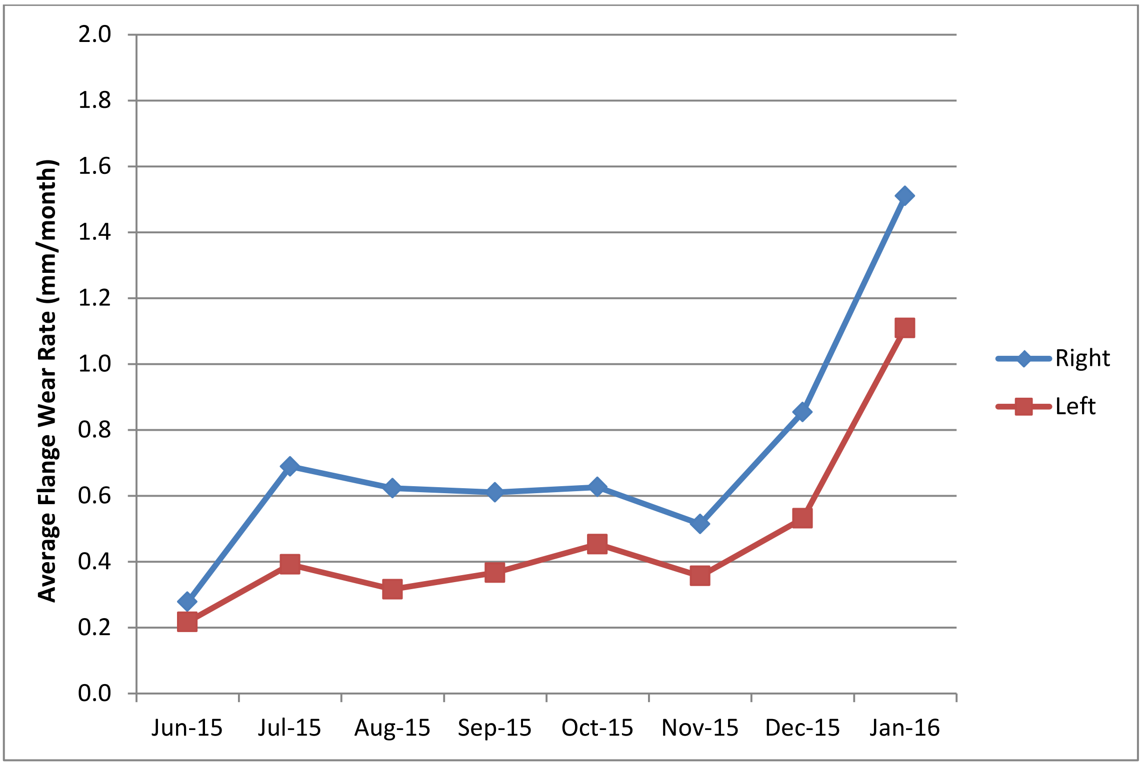

FIGURE 21: VLOCITY FLEET FLANGE WEAR RATE BY SIDE

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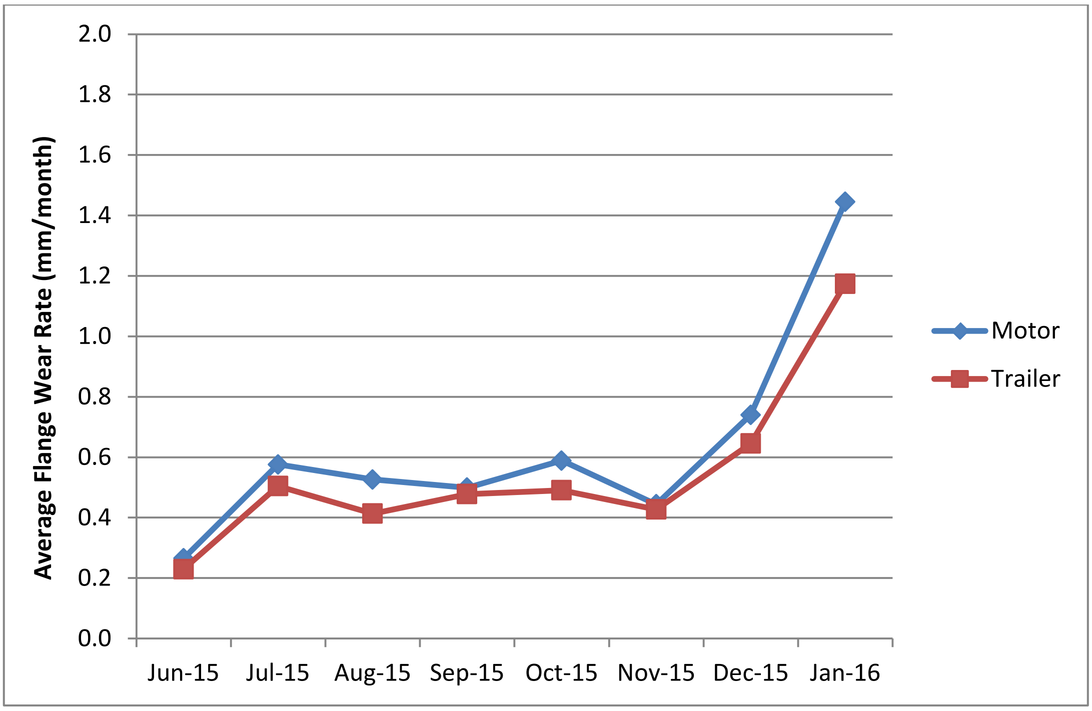

FIGURE 22: VLOCITY FLEET FLANGE WEAR RATE BY BOGIE TYPE

Wheel flange height and hollowing parameter results from the supplied data (presented in Appendix C) were generally unremarkable. These results show a steady increase in flange height for all wheels with increasing service, which is to be expected as the tread wears. Hollowing, measured using the wheel wear gauge, was generally found to increase slightly with increasing service; however most recorded values were around 1 mm. Greatest recorded hollowing was found to be approaching 2 mm.

4.1.1.2 IRT Measurements

The wheel profile measurements taken from 9 VLocity cars by IRT during vehicle inspections were analysed to provide statistical data reflecting the extent of flange wear (in terms of remaining flange thickness). The analysis was performed using the MiniProf® software and calculated in accordance with Figure 23; where L1 = 2 mm, L2 = 70 mm and L3 = 10 mm

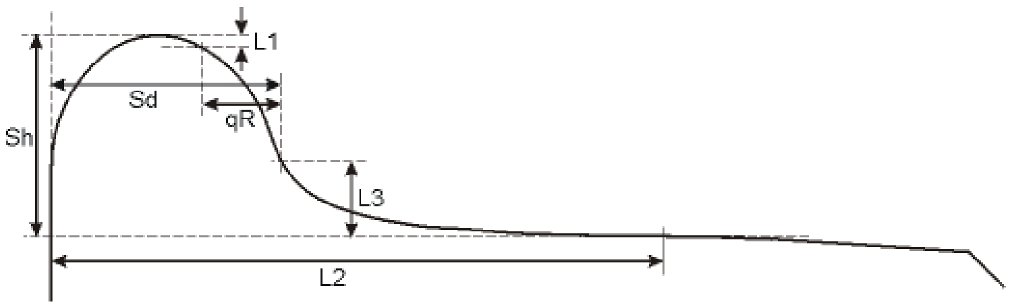

FIGURE 23: FLANGE WEAR CALCULATION

Figure 24 shows flange thickness (Sd) values of all measured VLocity car wheels prior to machining. These results show flange thickness to vary between 19 and 30 mm, however it should be noted that VLocity sets 18 and 42 were measured immediately before machining, hence at the lower end of the wear spectrum. Conversely, VLocity sets 24 and 57 were still in service at the time of measurement and consequently show a higher overall flange thickness.

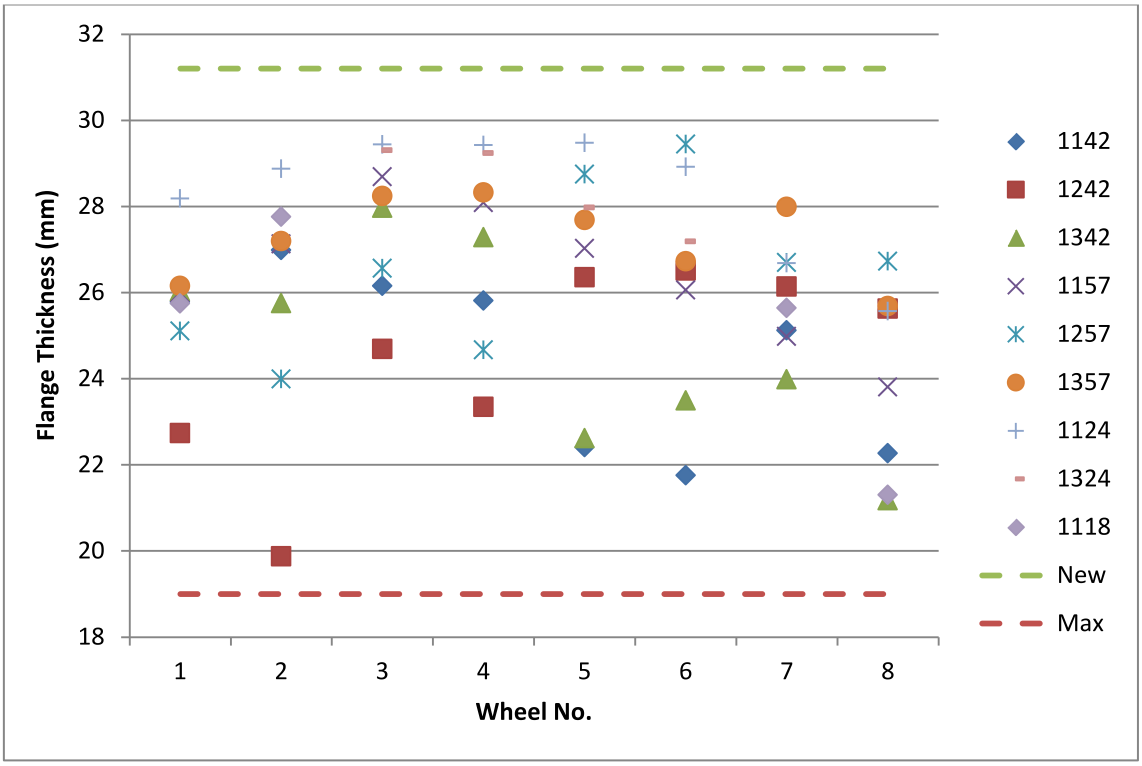

FIGURE 24: FLANGE THICKNESS FOR MEASURED VLOCITY CARS BY WHEEL POSITION

The average flange thickness for all measurements was calculated and separated by car orientation relative to the direction of travel. A full set of profiles for each car is presented in Appendix D.

The results in Figure 25 show a general right side flange wear bias for all cars (i.e. Side A for 1100/1300 cars and Side B for 1200 cars), which is consistent with a bias towards left hand curves in the RRL [2].

The above analysis was extended to include the additional measurements taken on two N Class locomotives, three N type coaches and one Sprinter car. It can be seen from Figure 26 that the level of asymmetric flange wear on the VLocity cars is generally not as prominent on the other rolling stock types. In-fact, N coaches and Sprinter vehicles show no significant wear bias.

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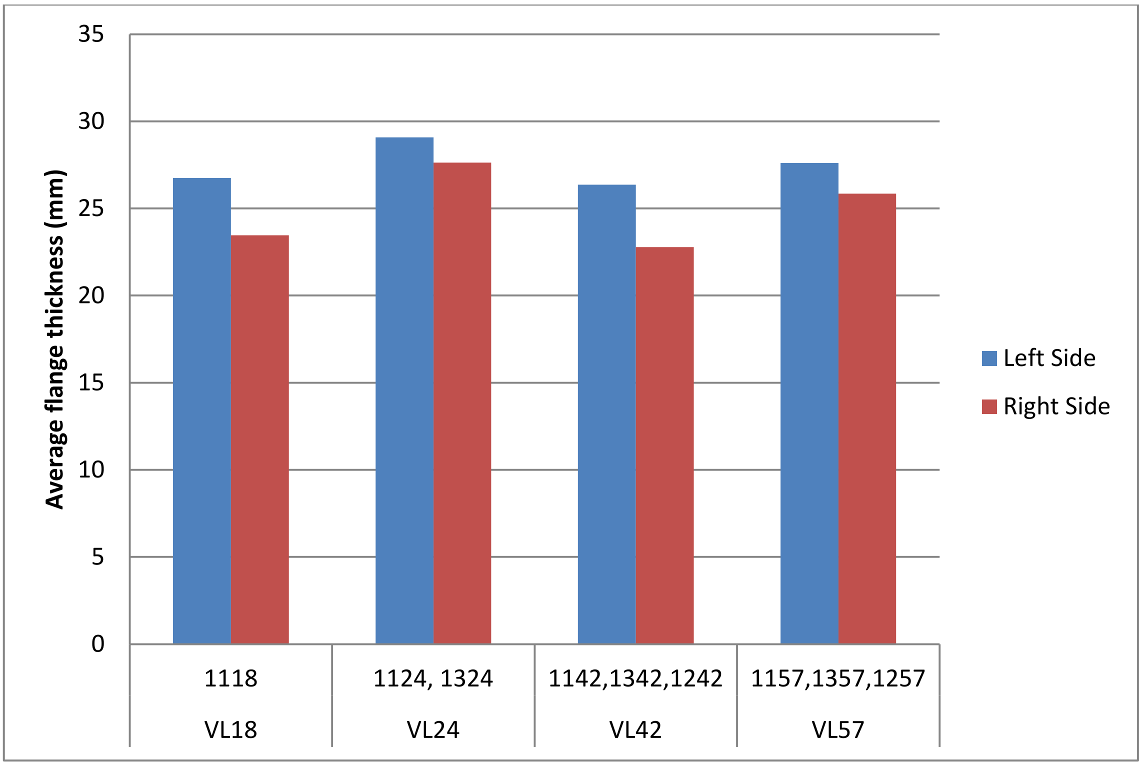

FIGURE 25: AVERAGE FLANGE THICKNESS FOR MEASURED VLOCITY CARS BY SIDE

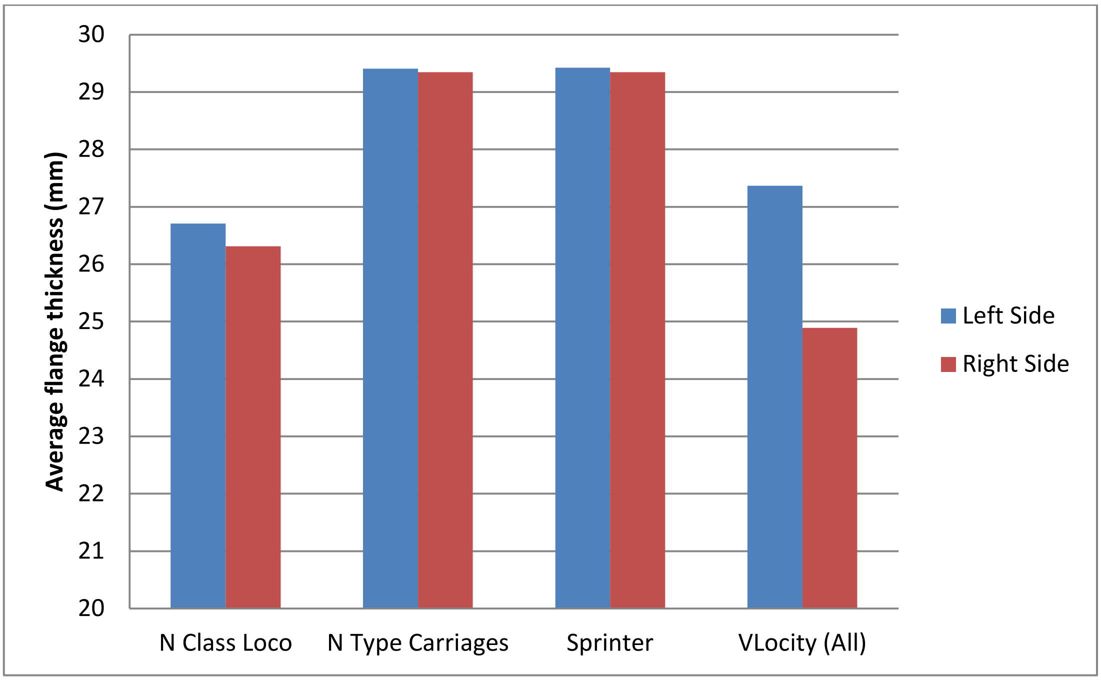

FIGURE 26: AVERAGE FLANGE THICKNESS FOR ALL WHEEL PROFILE MEASUREMENTS

4.1.2 WHEEL PROFILE AND CONDITION

The left/right wear asymmetry noted previously is clearly evident in Figure 27, which shows an overlay of worn VLocity wheels for each axle against the MP2 template. In this example, wheels 1- 4 represent left side of the vehicle, while wheels 5-8 are on the right.

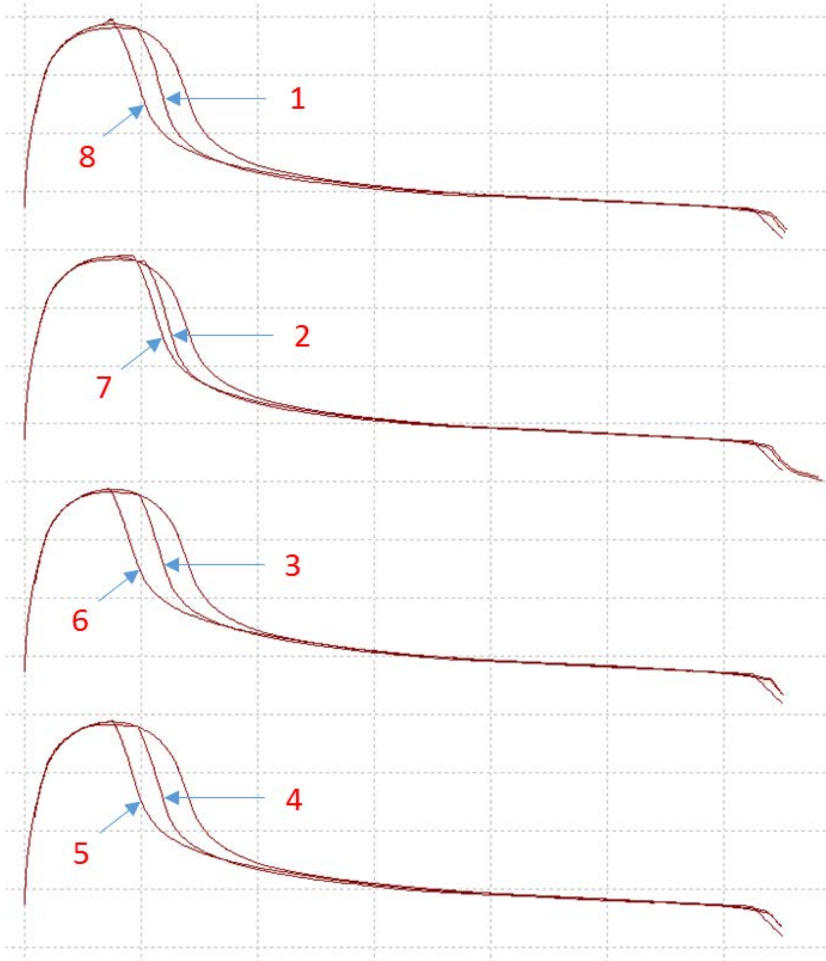

FIGURE 27: TYPICAL WEAR BIAS ON VLOCITY CAR

Also of interest is the worn wheel overlay with the MP2 wheel profile, when aligned within the throat region of the profile to see what changes have occurred as a result of wear. Figure 28 shows that the worn shape of the worn wheel matches well with that of the MP2 wheel in the throat area. Consequently, it could be said that high wear is not expected from a new/machined wheel due to any profile bedding in process. Note this does not include any adverse effects due to the roughened/machined surface (as discussed further in Section 6). The main change to profile, however, is the flange face angle which generally increases as the wheel wears. A new/machined MP2 profile contains a 70° flange face angle, which is typical of most Australian railway systems. Measurements of flange angle from worn wheels were on average around 72°, but as high as 75° (Figure 28).

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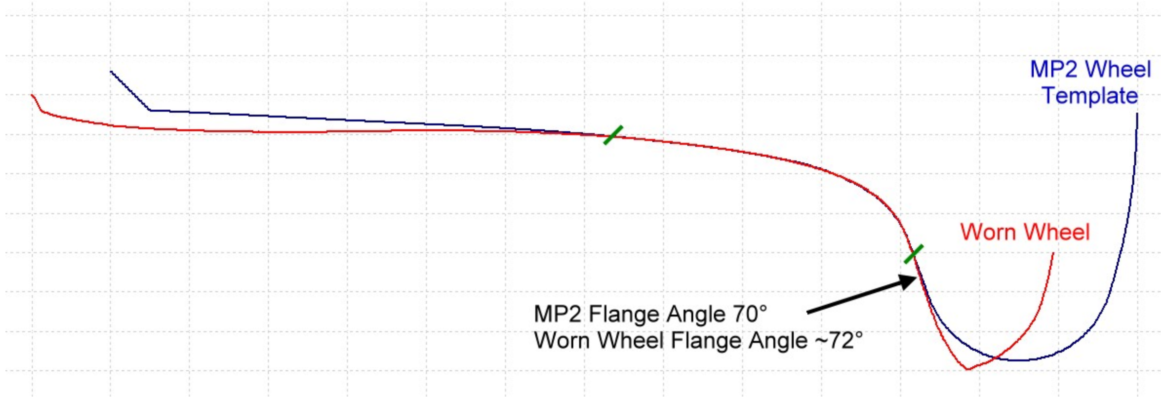

FIGURE 28: WHEEL THROAT ALIGNMENT - WORN VS. MP2 TEMPLATE

The appearance of the worn flange surfaces on VLocity wheels prior to machining was consistent with severe sliding contact and heavy adhesive wear, resulting in heavily gouged and roughened surfaces (Figure 29). None of the inspected wheels were found to contain any significant (visible) rolling contact fatigue (RCF) or other tread defects.

FIGURE 29: TYPICAL WORN VLOCITY WHEEL PRIOR TO MACHINING

Wheel tread surface hardness measurements were taken from each rolling stock type. Figure 30 shows average hardness results taken at three positions across the running surfaces of the wheel; throat, centre and field.

Average hardness levels ranged from 332 HB in the centre of the tread of the VLocity to 438 HB in the throat region for Sprinter. The hardness results for the VLocity are consistent with that expected for the specified (R8T) wheel material grade (255 – 285 HB), with some additional work hardening at the worn tread surface. The high hardness result on the throat of the Sprinter wheels indicates that this region of the wheel is under considerable strain and has significantly work-hardened as a result. This also indicates that wear in this area may not be particularly high.

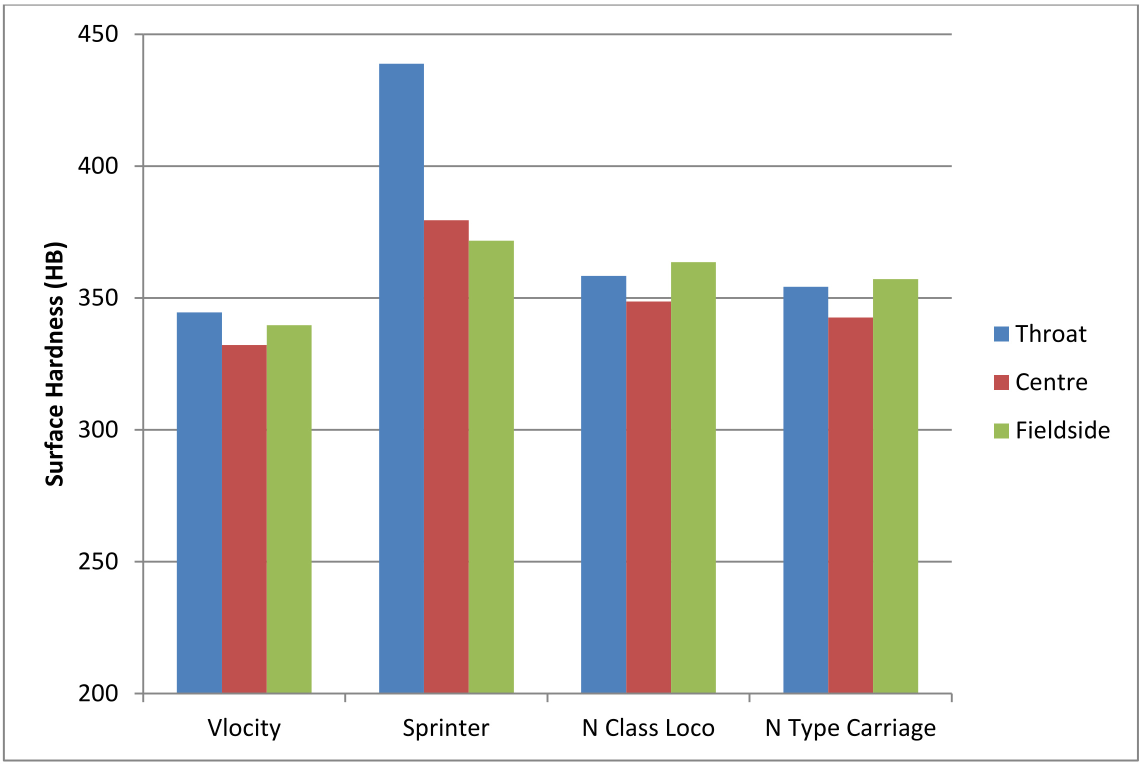

FIGURE 30: SURFACE HARDNESS FOR ALL WHEEL MEASUREMENTS

4.2 WHEEL MACHINING

The restoration of worn wheels to the correct profile (MP2 for VLocity rolling stock) is achieved through machining. This process is primarily undertaken by Downer at the Newport maintenance facility utilizing a Hegensheidt underfloor lathe, believed to have been installed in the mid 1980's (shown in Figure 31).

FIGURE 31: HEGENSHEIDT UNDERFLOOR WHEEL LATHE AT DOWNER NEWPORT WORKSHOPS

In order to examine the machining process a number of transverse wheel profile measurements were taken from VLocity cars before and after machining.

Allowable wheel diameter machining tolerances applicable to V/Line wheels are summarized in Table 9. Data obtained from the machine operator indicated that due to the thin flanges on worn VLocity wheels between 30 mm and 33 mm was removed from the diameter in order to restore profile. Measured diameter variations between wheels on the wheelset and across the bogie were recorded as within the applicable tolerances.

TABLE 9: WHEEL MACHINING TOLERANCES [19]

Location	**Allowable Tolerance**
Variance between Wheels Power Bogie	
On the same axle	0.25 mm maximum
On the same bogie	0.5 mm maximum
Variance between Wheels Trailer Bogie	
On the same axle	0.25 mm maximum
On the same bogie	13 mm maximum
Bogie to Bogie on same Vehicle	25 mm maximum
Vehicle to Vehicle	40 mm maximum

Figure 32 overlays a typical, post machining, measured transverse wheel profile with the MP2 template from which the variance between the two profiles is calculated. The resulting difference, known as the vertical residual, is plotted in Figure 33. From this, it can be seen the profile is generally within +/- 0.25 mm across the throat and tread region of the wheel, which is considered to be an acceptable accuracy.

Some variation in flange thickness between machined wheels and template was observed and it is understood that use of a 7/8 template (with a narrower flange) is permitted on last life wheels in order to reduce the machining requirement.

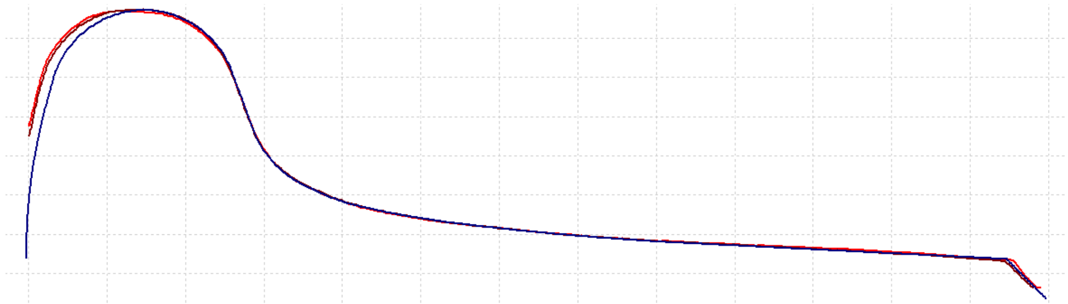

FIGURE 32: EXAMPLE OF MACHINED WHEEL PROFILE (VS.MP2 PROFILE)
[CAR 1118, WHEELS 2 & 7, MACHINED 16/01/2016]

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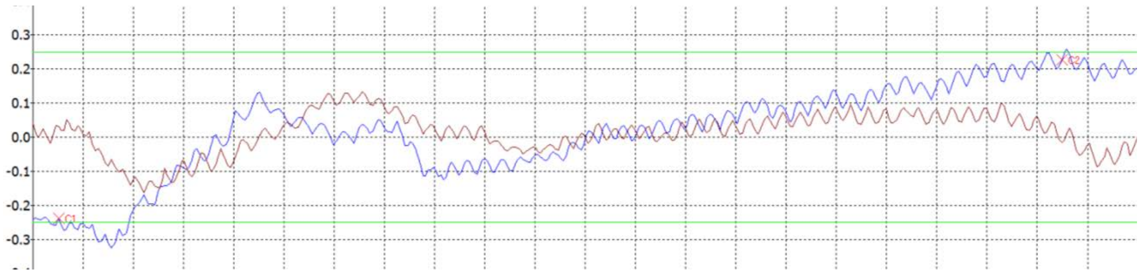

FIGURE 33: VARIATION BETWEEN MEASURED/MACHINED WHEEL PROFILE AND THE MP2 TEMPLATE.
[CAR 1118, WHEELS 2 & 7, MACHINED 16/01/2016]

While the above captures the results for typical post machining wheel profile, a limited number of measurements were observed contain atypical variations in profile (e.g. Figure 34). This was observed to occur mostly in wheels machined on one side of the lathe (though not on all) and may indicate that lathe components have some wear. In all cases, however, wheelset diameter matching was within the specified tolerance range.

As such, it is recommended that the lathe be inspected and calibrated in order to maintain sufficient target profile conformance. In the context of this report, the level of profile error observed in the "atypical" case is not considered to be a contributing factor in the present wheel wear issue.

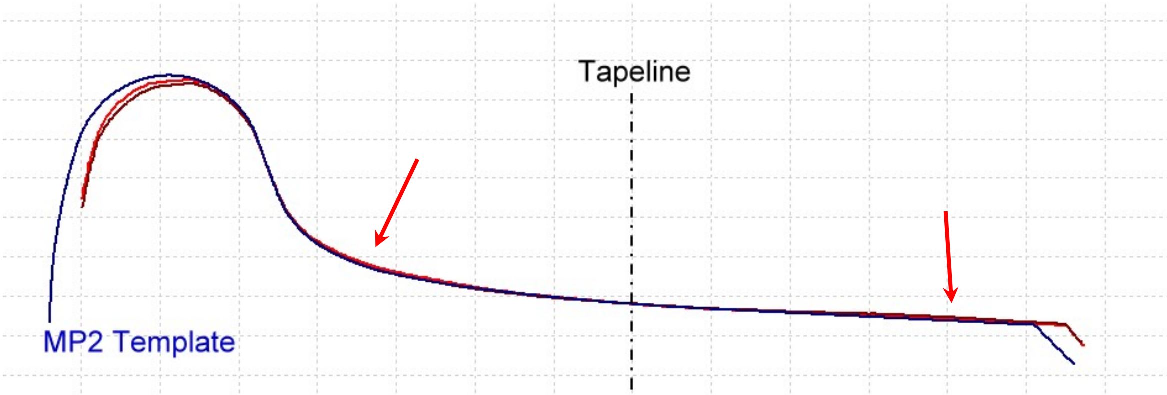

FIGURE 34: EXAMPLE OF ATYPICAL MACHINED WHEEL PROFILE (VS.MP2 PROFILE)

4.3 RAIL WEAR & CONDITION

4.3.1 RAIL WEAR

Analysis of measured rail profiles was undertaken using MiniProf® software. Calculation of rail wear was undertaken in terms of vertical (top), horizontal (side) and percentage head loss wear parameters. As shown in Figure 35, top wear (W1) is the vertical distance from the top of the reference (new) profile to the top of the measured profile along the rail centerline, while side wear (W2) is the horizontal distance between reference profile and measured profile at gauge point (L= 16 mm). The percentage head loss is calculated as the percentage area of worn material with respect to the full head section.

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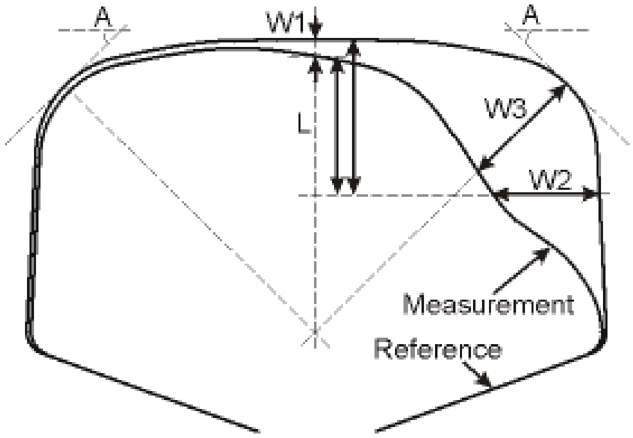

FIGURE 35: RAIL WEAR CALCULATION METHODLOGY

Figures 36 and 37 show the calculation methodology employed to calculate the rail gauge face angle at gauge point (L= 16 mm) and the maximum value, respectively. It should be noted that rail profile measurements include rail cant.

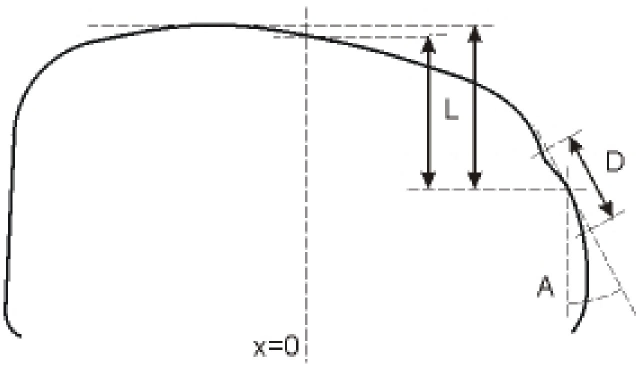

FIGURE 36: RAIL GAUGE ANGLE CALCULATION (AT GAUGE POINT)

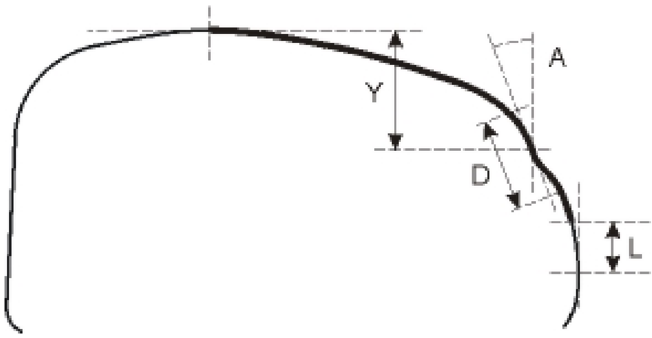

FIGURE 37: RAIL GAUGE ANGLE CALCULATION (MAXIMUM)

The assessment and response criteria for rail wear specified by V/Line [19] are summarised in Table 10. It is noted that limits apply to the worst location and not an average over the area being assessed.

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TABLE 10: ASSESSMENT AND RESPONSE CRITERIA FOR RAIL WEAR [20]

Parameter	Limit	Response
Gauge Face Angle	26°	Restore rail profile by grinding, or replace rail
Top Wear (e.g. Low rail)	40% Loss of head area	Replace rail
Side Wear (e.g. High rail)	30% Loss of head area	Replace rail
	24 mm Loss of head width	Replace rail

The rail wear results for all the measured locations were classified by four curve bands, as follows:

R ≤ 200 m
200 < R ≤ 500 m
500 < R ≤ 1000 m
1000 < R ≤ 2000 m

A full set of wear results for each measurement site are provided in Appendix E.

Average percentage head loss results for measured high and low rails are shown in Figure 38. These results show that high rails in moderate to very sharp curves have consistently higher wear than low rails. Furthermore, high rails show significantly increasing wear as curve radius reduces The sharpest curves (R<200m) yield the highest average percentage head loss at 11% and 4.7% for high and low rails respectively. Greatest high rail wear was found on the Up Track with 19% head loss on the 180 metre radius right hand curve on the NMFO. Conversely, the shallowest curves (R>1000m) yield the lowest average percentage head loss at just 1.6% and 1.5% for high and low rails, respectively.

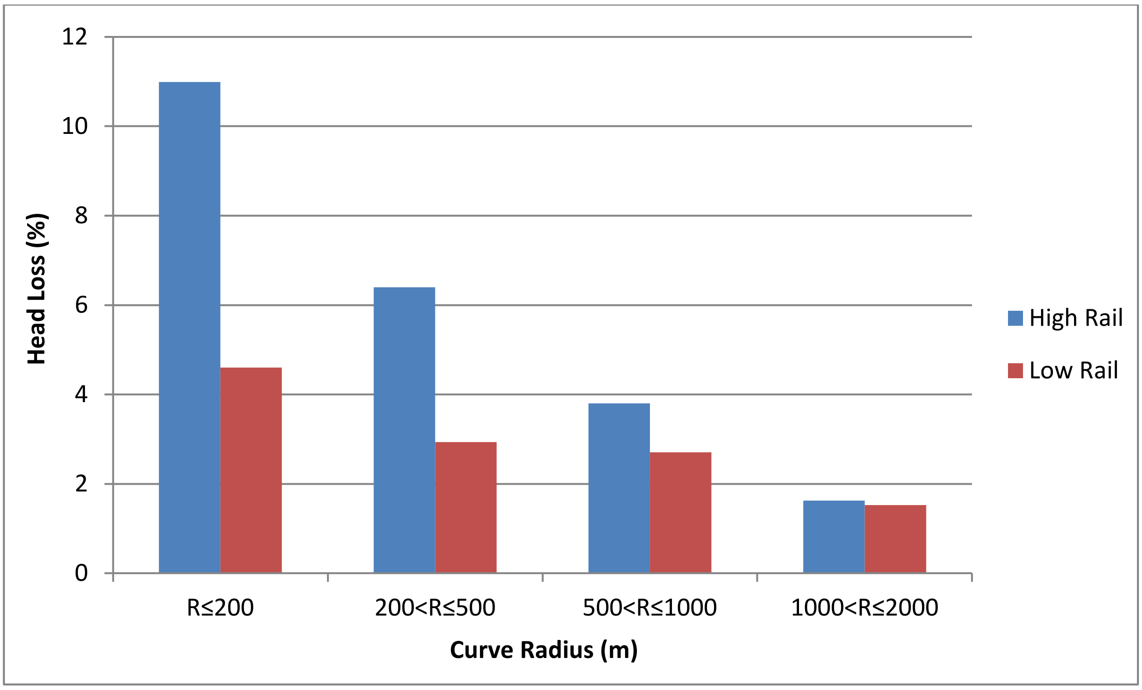

FIGURE 38: AVERAGE PERCENTAGE HEAD LOSS RESULTS (UP & DN TRACKS)

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Similarly, average vertical rail wear results are shown in Figure 39. While the results show rails in sharper curves have consistently higher top wear in comparison to shallower curves, there is little difference between high and low rails. The sharpest curves (R<200 m) yield the highest average top wear of around 2.3 mm for both high and low rails, while the shallowest curves (R<1000 m) showed the lowest average top wear at around 0.7 mm for both high and low rails.

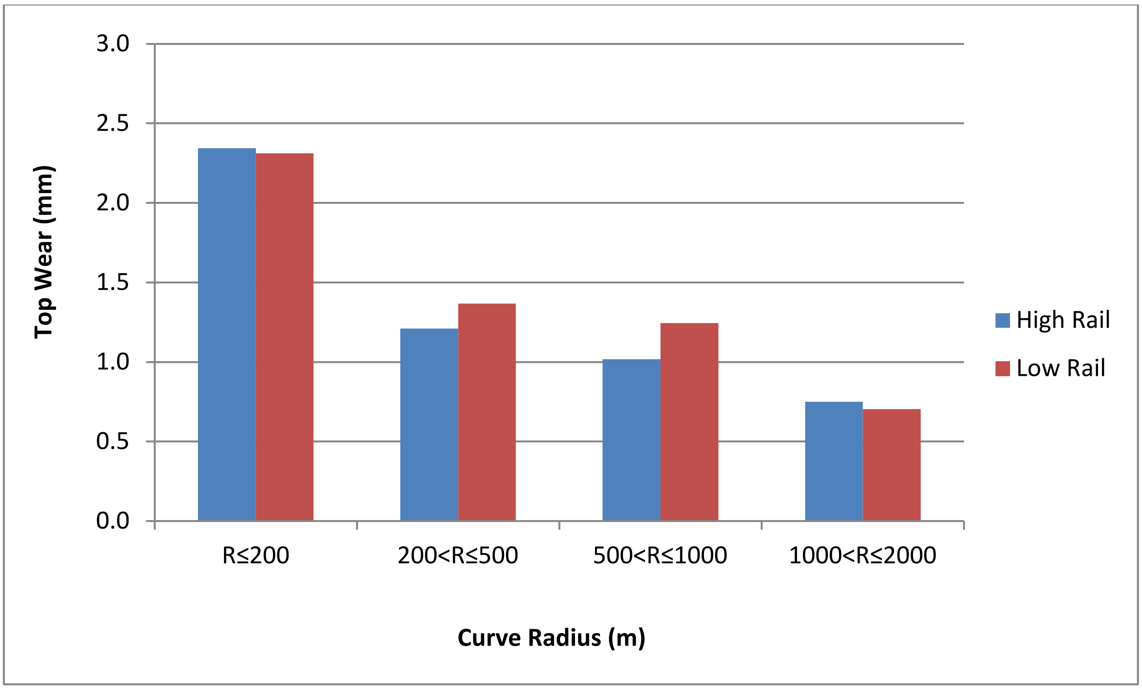

FIGURE 39: AVERAGE VERTICAL WEAR (W1) RESULTS (UP & DN TRACKS)

Average side wear results are shown in Figure 40, along with gauge angle. These results show that side wear generally only occurs in the moderate to very sharp curve ranges, increasing with reduced curve radius. The sharpest curves (R<200 m) showed the highest average side wear of around 7.4 mm, whilst the shallowest curves yield negligible side wear. The largest absolute wear was found on the Up Track on the North Melbourne Flyover with 13.8 mm side wear.

Gauge face angle results show increasing angles (gauge point or maximum) with increasing side wear and reducing curve radii. The greatest change appears to occur as side wear begins within the moderate curve range (500 < R ≤ 1000 m), then settling down once radius drops below 500 m. The largest gauge angle of 21.3° was found at the 1577.2 m measurement location on the Up Track (NMFO).

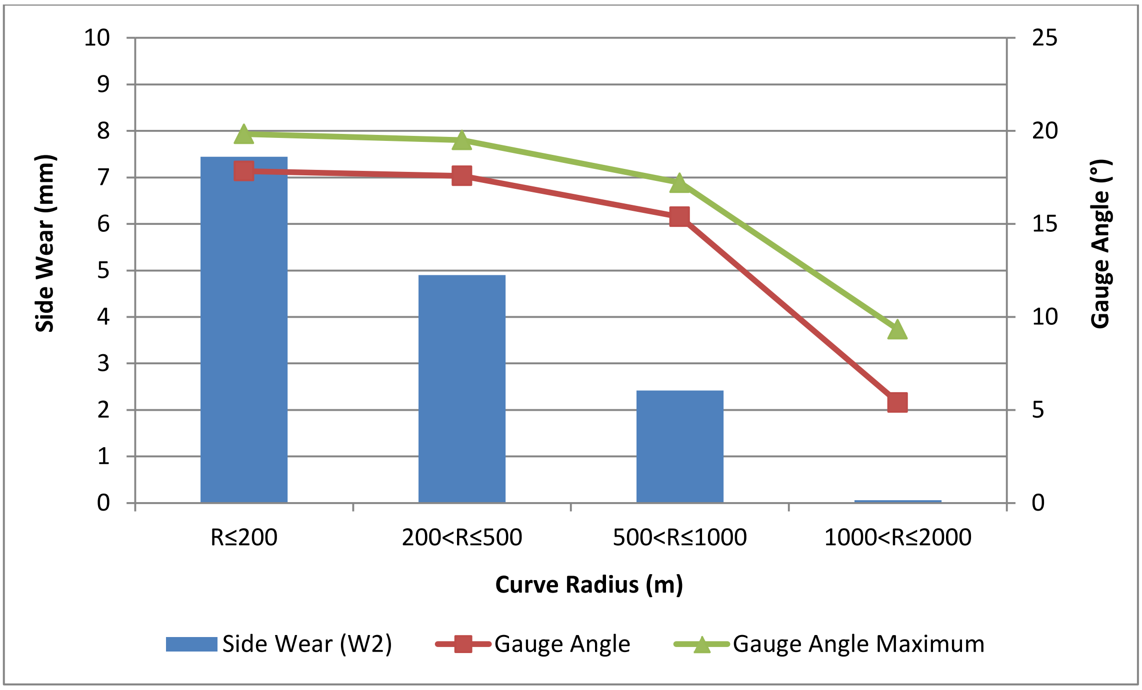

FIGURE 40: SIDE WEAR (W2) AND GAUGE FACE ANGLE RESULTS (UP & DN TRACKS)

4.3.2 RAIL PROFILE & CONDITION

Rail profiles understood to be installed on the V/Line network include:

RPH2000	NCOP High Rail Profile (R < 1000 m) [21]
RPL2000	NCOP Low Rail Profile (R < 1000 m) [21]
RFR101	Regional Fast Rail (RFR) Profile (tangent and curves R > 1000 m) [22]
T2_5GC	RFR Effective Gauge Widening Profile (160 km/h sections) [23]

It should be noted that the T2_5GC rail profile [23] was not specified for use on RRL track sections. This profile was designed for use on the high speed sections outside the metropolitan area in order to help alleviate tight gauge conditions in track constructed as part of the Regional Fast Rail (RFR) project in 2004/2005.

Rail profiles on the RRL track sections were installed with either a conventional rail grinder or rail milling machine, while outside the RRL sections rail profiles (if profiled) are understood to have mostly been installed by a rail grinder as part of the RFR project. Measured rail profiles were compared against the relevant templates above and the full results are provided in Appendix E. Pertinent findings of this analysis are summarised below.

The worn high rail profile from sharper curves (R < 600 m) show increasing flange contact as radius reduced. High rails in the sharpest curves, on the NMFO (R180 m), clearly matched the worn wheel shape in the main contact area (Figure 41). Of note is the difference between the original target RPH2000 profile and the worn profile. Further discussion on this issue is provided in Section 6.

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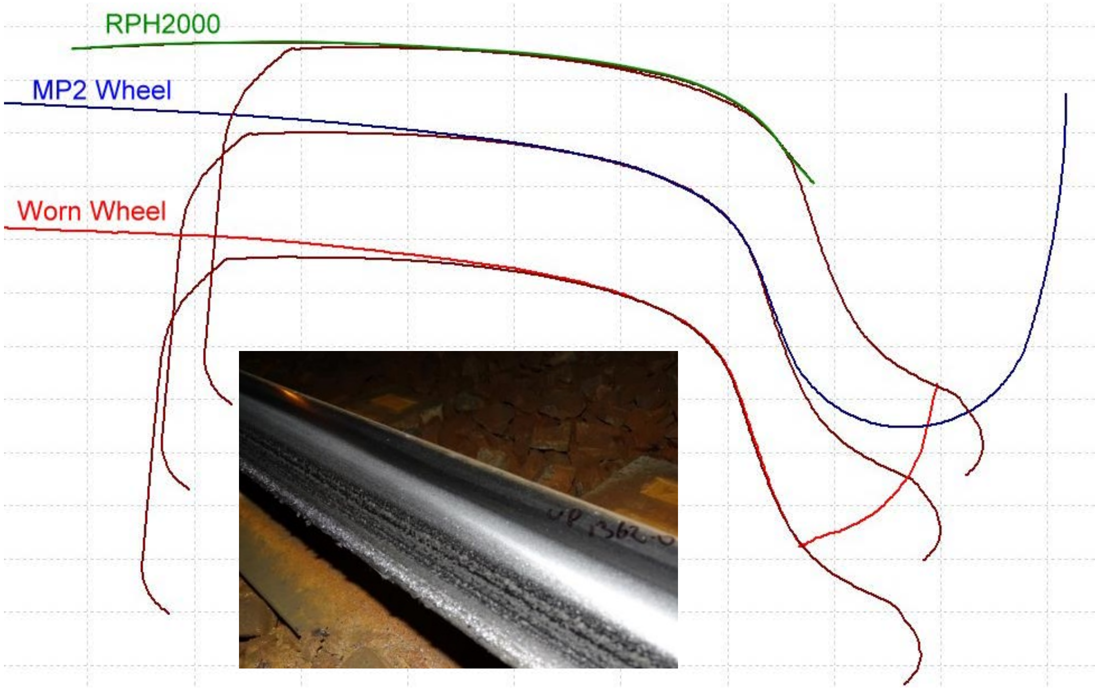

FIGURE 41: HIGH RAIL WEAR (NMFO)

Another issue identified on measured high rails was the observed peaking in crown of the rail (upper image of Figure 42). In this example the high rail of a 250 m radius curve was to be profiled to the RPH2000 rail profile, which is overlaid on the measured profile along with the RFR101 tangent/shallow curve profile for comparison. It should be noted that profiles were measured close to the centre of inspected curves and clear of transition curves which may otherwise affect the measured profile.

Since actual profile conformance at each inspection location before the start of operations on the RRL track is not known to IRT, it is difficult to comment on the quality of profiling works and whether this may have contributed to this issue. This is particularly true for locations such as this example where significant side wear appears to have occurred since profiling. However, it is considered likely that the peaks are probably associated with the change in profile due to wear rather than any profiling issue. As shown in the lower image of Figure 42, side wear effectively removes the material in the gauge to crown area and, in doing so, cuts away at the profiled shape. The apparent peak in the crown is hence a combination of the profiled shape on the field side and the worn wheel shape on the gauge side.

In this example the measured profile looks closer to the RFR101 profile since it has a higher crown than the RPH2000. However, the true starting profile (post profiling) cannot truly be determined without knowing the extent of side wear that has occurred since profiling – or through review of any quality records associated with profiling works.

Low rails of sharper curves (R < 500 m) were found to be suffering varying degrees of deformation and wear. The most severely affected low rails were found in the very tight (R 180 m) curves within the RRL section. Wear and deformation under these conditions

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has resulted in a typical ‘flat’ rail crown, extending out towards the field side edge. In the more severe cases, short pitch corrugations were observed through the main contact band (Figure 43).

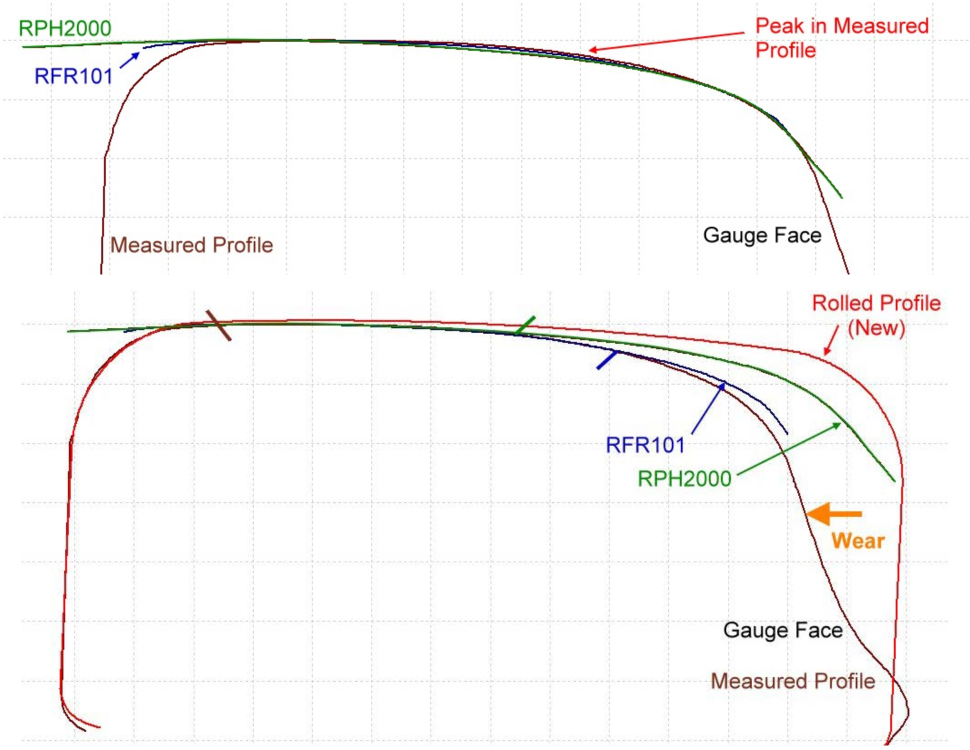

FIGURE 42: HIGH RAIL PEAKS

(12.5 KM BALLARAT LINE UP TRACK, R250 M)

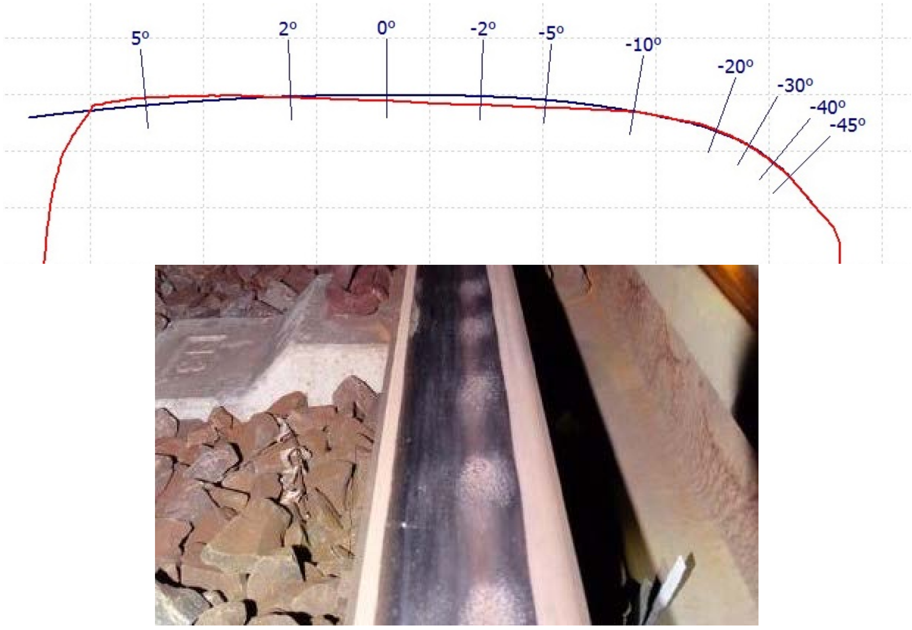

FIGURE 43: WORN LOW RAILS

(1.362 KM NMFO, UP TRACK, R180 M)

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In other less severe examples, the main contact band was close to the field side edge, rather than the desired central position. Measurements from these locations (Figure 44) showed substantial peaks in the field side of the profile. These peaks appeared to be the result of plastic flow, however residual profile anomalies (i.e. insufficient field relief during installation) cannot be ruled out without examining grinding/milling quality documentation.

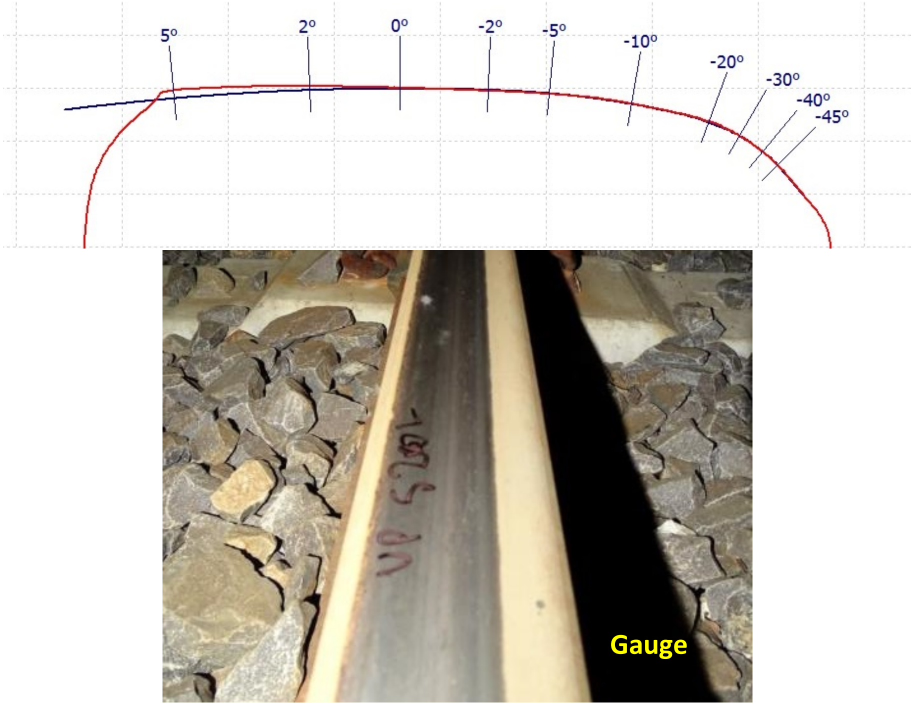

FIGURE 44: EXAMPLE OF FIELD BIAS ON LOW RAIL
(5.200 KM UP TRACK, R522 M)

Average surface hardness results are shown in Figure 45 for measurements taken from the contact band of rails on both Up and Down tracks on the NMFO. It should first be noted that the base hardness of the rail is approximately 280 HB.

Results show only mild work hardening on the gauge corner of high rails, primarily due to the severity of wear occurring in this region of the rail. Hardness generally increases once out of the severe wear zone.

Work hardening on low rails appears to be more significant, particularly within the main contact areas (centre/top and field) of the contact band, where increases of over 100 points (HB) were measured. The greater work hardening on the Up Track low rail is indicative of higher contact stresses and cyclic strain on this rail.

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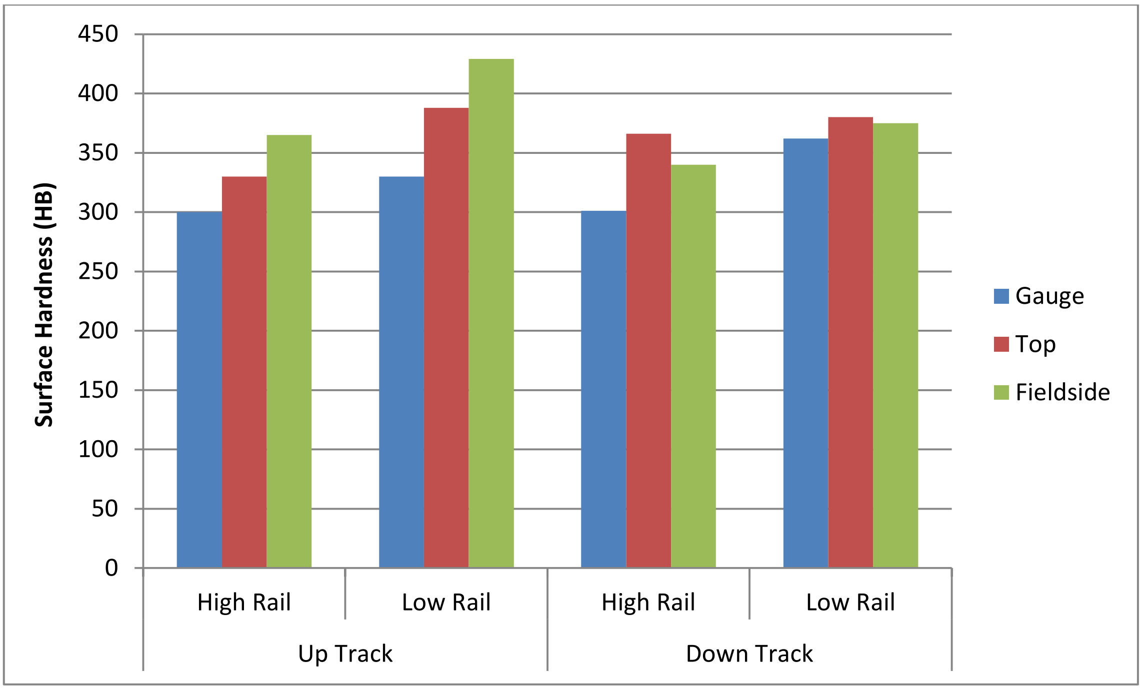

FIGURE 45: SURFACE HARDNESS OF MEASURED RAILS (1398.7 M, UP/DN TRACK, NMFO)

4.3.3 RAIL SURFACE FRICTION

Rail surface friction measurements were taken over the NMFO during the track inspection. Average surface friction results are summarised in Table 11, while full results are provided in Appendix F.

TABLE 11 : SUMMARY OF TRIBOMETER RESULTS

Curve Start (m)	Up Track (Towards Southern Cross)			Down Track (Towards Spion Kop)		
	Low/Top	High/Gauge	High/Top	Low/Top	High/Gauge	High/Top
1371	0.55	0.26	0.39	0.47	0.45	0.46
1525		0.32	0.37		0.32	
1723		0.22			0.24	

At the time of the measurement, there was no evidence of fresh lubricant on the rail gauge face, although a residual graphite film was clearly evident. In this condition, friction levels on the gauge face averaged 0.24, decreasing to ~0.20 in places where there was still residual tackiness (e.g. in the curve under the Dynon Road overpass). Gauge face friction levels increased to ~0.35 for a smooth gauge face surface with negligible residual graphite, and ~ 0.45 on a dry rough surface.

Top-of-rail friction levels averaged 0.45 for dry rail, with a slightly lower value (0.4) reported for the high rail on which the gauge face was lubricated, and up to 0.55 for the low rail in same location.

The NMFO was again inspected during the day on Monday February 15, and rail profiles taken at a number of positions nominated by V/Line personnel. Lubrication levels at this time appeared to be better than those summarized above, with evidence of a substantial grease film on the gauge face of the high rail. Friction levels at this time were not recorded, but were estimated to fall in the range 0.15-0.20.

It should be noted that the friction values recorded by the Push Tribometer are generally considered to be slightly higher than the friction levels that could be experienced under full-scale wheel/rail contact. This is in part due to the much smaller contact area obtained with the Tribometer measurement wheel, and also that the measurements are performed at a much lower speed than under normal service conditions. The reported friction levels can, however, be used to estimate the expected wear behaviour, based on the relationship between lubricant film thickness, friction coefficient and wear type shown in Figure 46.

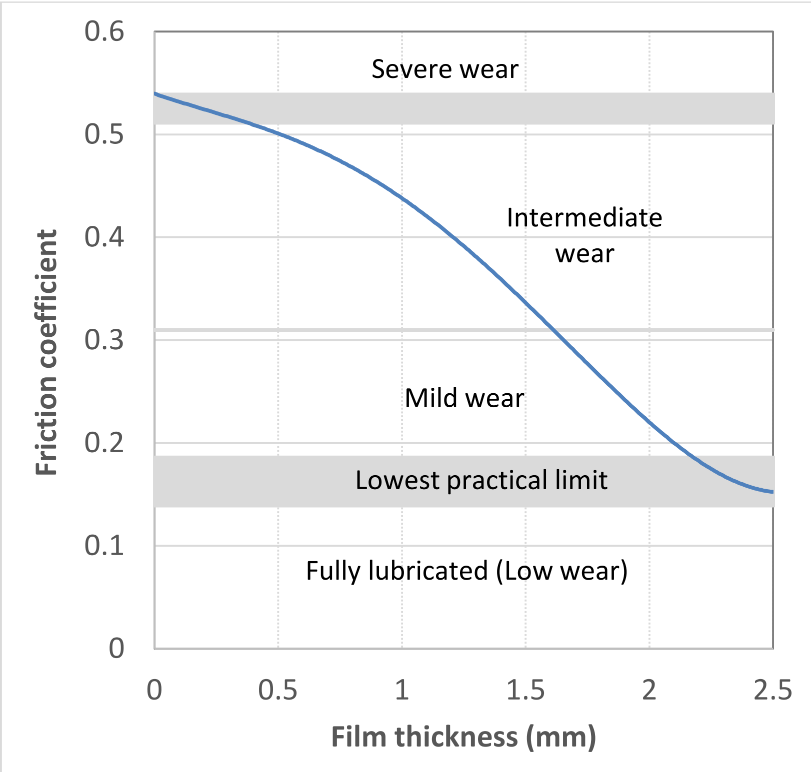

FIGURE 46: GENERAL RELATIONSHIP BETWEEN LUBRICANT FILM THICKNESS, FRICTION COEFFICIENT AND WEAR BEHAVIOUR FOR WHEEL-RAIL CONTACT, BASED ON THE RESULTS OF MCEWEN AND HARVEY [24].

5 SIMULATION

5.1 OVERVIEW OF MODELS

The issue of wheel flange wear is dominantly a wheel rail interface issue with the primary influences being the steering behavior of wheelsets, contact geometry and environmental condition encountered at the wheel and rail interface.

The primary vehicle design factors that influence wheelset steering in a 2 axle rigid bogie configuration (as used in both VLocity and Sprinter rolling stock) are the wheelbase and primary suspension longitudinal stiffness. Other factors, such as primary and secondary suspension lateral and rotational stiffness also have an effect on steering performance, however under severe curving conditions their contribution is less significant than the prevailing primary suspension stiffness.

For this assessment two basic vehicle models were created to assess the combined effect of wheelbase and primary suspension longitudinal stiffness variation between Sprinter and VLocity rolling stock designs. The models were developed using Universal Mechanism simulation software. An image of one of the models traversing the simulated North Melbourne Fly Over is shown in Figure 47.

Information obtained from Bombardier [8, 11] indicated that, while variance in wheelset spacing between the two rolling stock types was only 0.15 m (2.6 m for VLocity and 2.45 m for Sprinter), the trailing link (traction rod) used for longitudinal restraint of the VLocity wheelsets was at least 4 times stiffer than the axlebox bush used to perform the same task in the Sprinter design (VLocity > $3x10^7$ N/m, Sprinter = 7 $x10^6$ N/m).

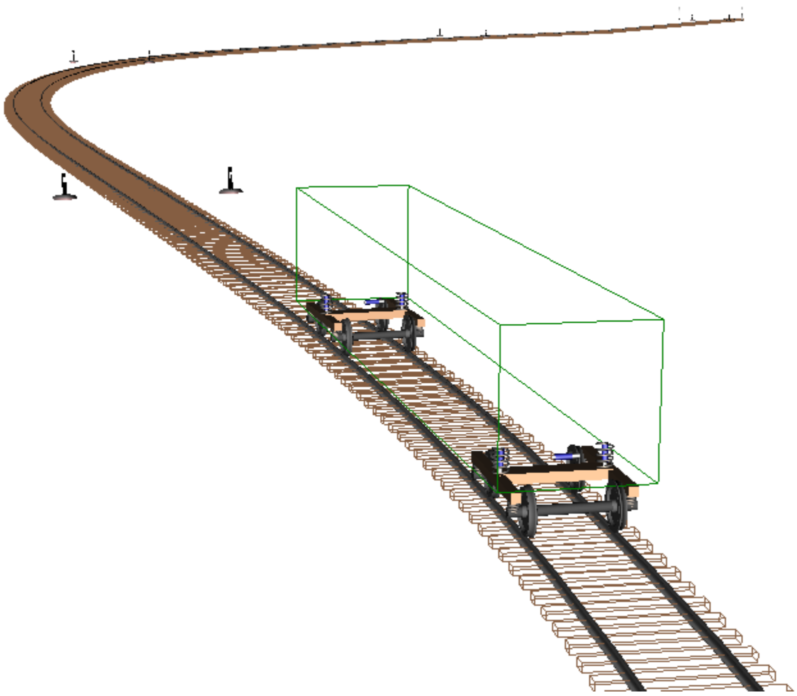

FIGURE 47: UNIVERSAL MECHANISIM MODEL TRAVERSING NORTH MELBOURNE FLYOVER (NMFO)

5.2 Simulated Track Conditions

A matrix of tests was created using 11 curve radii from 180 m to 2000 m to simulate the curving performance of both models in the RRL corridor from Southern Cross Station. Initial configuration was in the "current" condition as understood by IRT, taking into account the 25 km/h speed restriction currently (January 2016) enforced and 40mm of applied cant common to many of the tighter radius curves (<600 m radius). Gauge widening of 3 mm was also used in curves below 400 m radius, as prescribed in the RRL track design drawings [25, 26].

In addition, the specific macrogeometry present at the NMFO was modeled including horizontal alignment, vertical alignment and profile evolution (though the reverse curve).

Track and operational parameters have significant bearing on wheel wear with flange wear occurring almost exclusively on tighter radius curves. Parameters identified for investigation using simulation included:

- Rail friction modification including greasing of high rail flange and top of rail friction modifier (TOFRM) application on the low rail;
- VLocity and Sprinter rolling stock primary suspension parameters; and
- Modified superelevation and speed through the NMFO.

5.3 Simulation Output

Model output parameters of most interest are those that have greatest implication for wheel and rail wear and curving performance. These parameters include:

- Specific Energy, often referred to as Wear Energy or T-gamma and abbreviated in this report as Tγ (unit = N);
- Wheel angle of attack (AOA), the angular difference between the longitudinal reference frame of the wheel and that of the rail (unit = milliradians);
- Corrugation Index (CI), an index of the relative likelihood of rail corrugation development, based on the contact stress and creep force orientation; and
- Lateral on Vertical force ratio (L/V), which is used (in conjunction with friction and contact angle) to assess derailment risk.

Specific Energy (Tγ); is a measure of the energy expended at the wheel rail contact. This data is used as an indication of expected wear under the simulated conditions. In the absence of empirical measurements, it is not possible to directly link Tγ results to wheel or rail metal removal rates, as this also requires consideration of any changes in the primary wear mechanism(s) associated with the transition to full flange contact, including the associated increase in contact area [24].

Instead, Tγ is presented in normalized terms with the largest reported value in a given comparison assigned the value of 1 and all other results being a percentage thereof. Presentation in this manner allows the most direct means of comparison between

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simulation cases. For example where Case 1 result = 1 and Case 2 result = 0.75, Case 2 represents a 25% decrease from Case 1.

Previous research [24] suggests that direct comparison of wear energy in this manner is a conservative approach, particularly where lubrication is used, as this can greatly affect the type of energy dissipation occurring in the contact patch (viscous rather than shear friction) with even less material loss the likely outcome.

Wheel angle of attack (AOA) is a strong contributing factor to Tγ results, particularly in sharper curves, and is directly related to the longitudinal primary suspension stiffness and the available steering forces designed into the wheelsets.

Corrugation Index (CI) is a measure used to estimate corrugation growth using Tγ, contact stress and creep force orientation. Reduction in CI through changes to any of these three mechanisms is a good indicator of reduced corrugation development and growth, and is particularly pertinent to the low rails. CI is also normalized using the same method described for Tγ.

Both Tγ and CI values are highest for the leading axle of the leading bogie on a wagon (in the direction of travel) as this axle is subjected to the greatest steering forces and angle of attack, with the third axle (leading axle of the second bogie) having slightly reduced angles of attack due to the favourable action of secondary suspension.

In practice, for V/Line operations, wheel wear is expected to be balanced through bi-directional operation, without taking into consideration any left hand vs right hand bias in the distribution of curved track. As trains are not turned between Up and Down journeys the 1st axle in one direction (highest wear) becomes the 4th (lowest wear) when run in the opposite and similarly for 3rd – 2nd axle. For assessment of relative performance through simulation the most adverse conditions are most important and therefore all values assessed are calculated from contact on the leading (1st) axle of the model which would be the axle with wheels 1 and 8 when following V/Line naming conventions on VLocity and Sprinter cars.

Simulated wear energy results (Tγ) for curves below 500 m radius are shown in Figure 48, These results show that flange contact on the high rail (so-called high rail flange) is significantly higher than at the tread of either wheel (high or low rail tread contact). However, so as not to completely neglect changes that may occur to reported values on the tread, total axle (wheelset) Tγ is calculated and used to compare simulation cases, which incorporates all three contact points.

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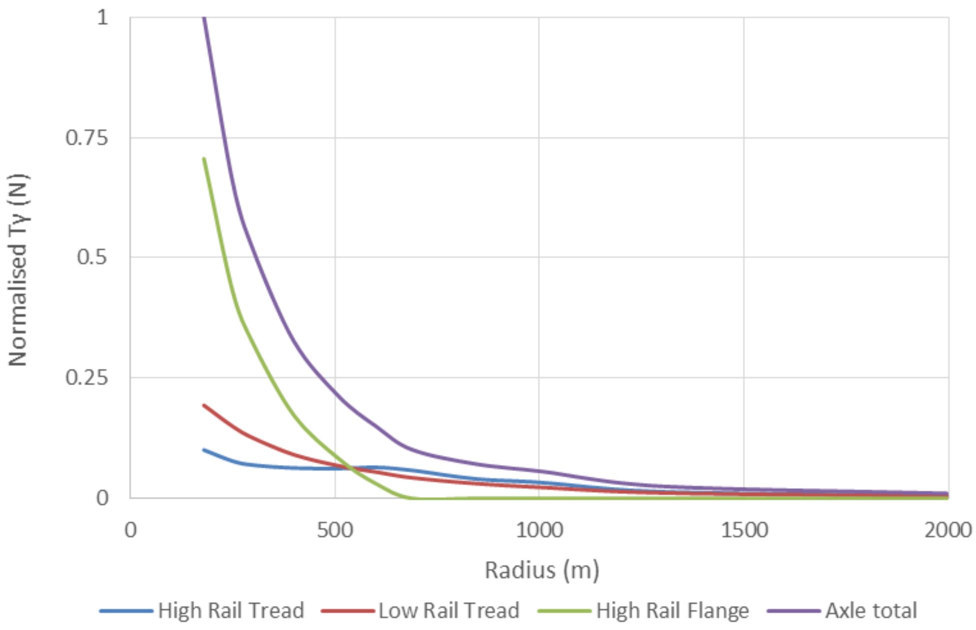

FIGURE 48: COMPARITIVE CONTRIBUTION OF TREAD, FLANGE ANDTOTAL AXLE WEAR ENERGY (Tγ)

5.4 WEAR RESULTS

5.4.1 EXISTING (AS BUILT RRL)

The so called "existing" case most closely reflects IRT's understanding of the operating conditions of the RRL section in in early 2016. As such, the test matrix used for simulation is constructed with the following parameters;

- No lubricant used; rail friction coefficient (μ) = 0.5 for all contacts;
- 40 mm cant applied to curves below 500 m radius, 20 mm applied at 600 m radius and no cant at higher radii;
- 3 mm gauge widening in curves less than 400 m radius, and;
- 25 km/h vehicle speed for all cases; based on speed log data provided by V/Line, this is understood to represent a lower bound actual speed prior to January 2016 (maximum 40 km/h), and the maximum allowable speed from January 2016 following the application of a speed restriction.

Using these parameters, a comparison between VLocity and Sprinter wagon types was conducted by varying the primary suspension longitudinal stiffness and wheelbase parameters to represent each wagon type (values given in Section 5.1 above).

Figures 49 and 50 show the predicted AOA and wear energy (Tγ) results, respectively, for various curve radii. Both sets of results show AOA and wear for the Sprinter configuration is approximately 22% lower than the VLocity, highlighting a clear relationship between primary longitudinal suspension stiffness, wheelset steering and associated wear.

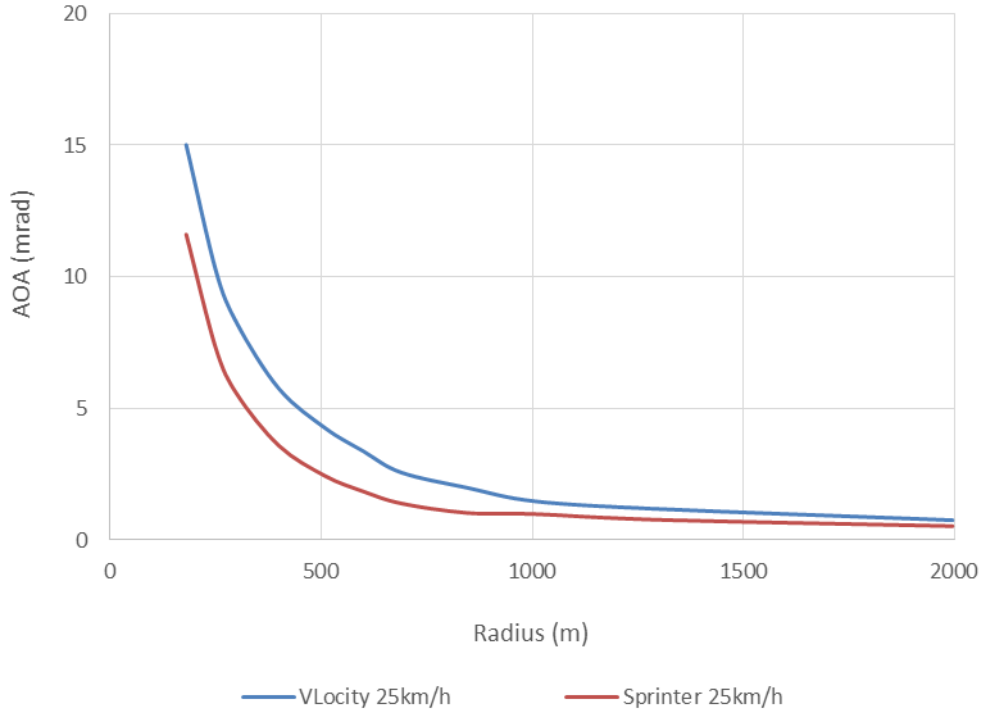

FIGURE 49: PREDICTED AOA FOR VLOCITY AND SPRINTER VEHICLES

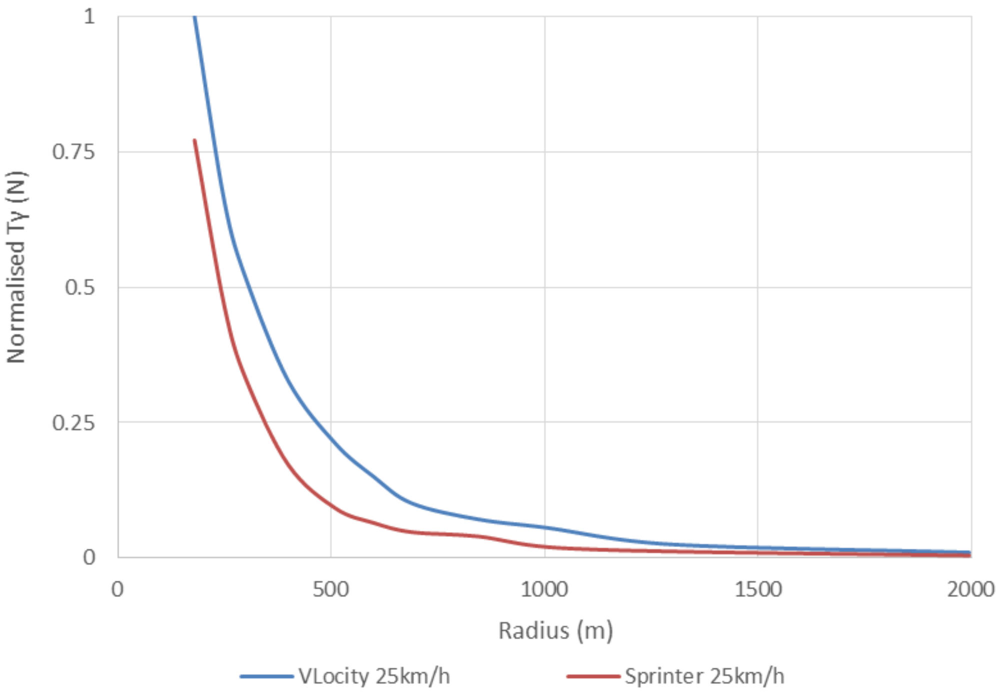

FIGURE 50: RELATIVE TOTAL AXLE Tγ FOR VLOCITY AND SPRINTER VEHICLES

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5.4.2 Gauge Face Lubrication

The application of grease to the gauge face/corner of the high rail in tight curves is a common method for controlling wheel flange and rail side wear. It is primarily effective through modification (reduction) of the available friction coefficient between the wheel and rail. To simulate its effects, two additional cases were used with friction on the high rail gauge face being modified to simulate both a partially lubricated rail and a fully lubricated rail.

Friction coefficients on the gauge corner for each case were as follows;

- Existing (dry): $\mu = 0.5$,
- Partially lubricated: $\mu = 0.25$,
- Fully lubricated: $\mu = 0.15$,
- In all cases, friction coefficient of all other rail contact (top of high rail and low rail) was unchanged: i.e. $\mu = 0.5$ and,

Simulation results in Figure 51 show a substantial reduction in wear (Tγ) due to the use of lubricant for all curves below 600 m radius, and with increasing effectiveness as curve radius tightens. However, the most significant benefits can be found in curves of 400 m radius and below. At a radius of 180 m for example, simulated Tγ is 58.2% and 34.4% of unlubricated values for partial and fully lubricated conditions, respectively. Hence, the benefits of flange/gauge face lubrication are clearly demonstrated.

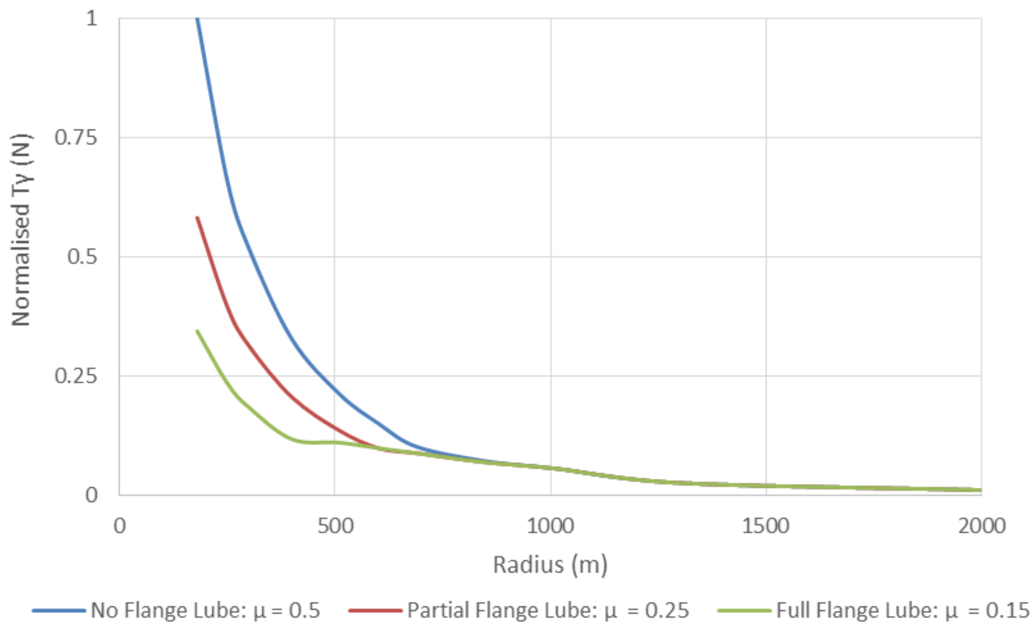

Figure 51: Relative Tγ for Vlocity Model with Varying Flange/Gauge Face Friction

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5.4.3 Modified Superelevation & Speed (NMFO)

In addition to the more generalized application of grease, specific changes to the alignment and traverse speed over the NMFO have been discussed between V/Line and IRT [3]. To support the discussion, a simulation case was developed to reproduce both the horizontal and vertical alignments of the flyover. Two test cases were then applied, being:

1. Proposed changes of:
    a. Increased speed v = 30 km/h, and
    b. Reduced track superelevation h = 0 mm.
2. The existing “low speed” situation:
    a. v = 15 km/h, and
    b. Design superelevation h = 40 mm.

It should be noted that the figure of 15km/h reflects what was considered to be a lower-bound speed after the speed restriction was implemented in January 2016, for example for a train on approach to a signal. No speed log data for this period was available.

To remove further variables, for both cases, friction coefficient mimicked those used in the Partially Lubricated state from Section 5.4.2 above (μ = 0.5 on rail head and μ = 0.25 on gauge face). This represents similar friction values to those that were measured during the IRT track inspection at this location.

Changes in superelevation and speed primarily effect loads acting at the wheel/rail interface, taking into consideration both gravitational and centripetal forces developed during curving. Operating at speeds above or below the ‘balanced’ speed for a given curve radius and applied superelevation results in an effective superelevation deficiency or excess and thus unbalance in loading on the rails.

The effective superelevation deficiency/excess for the two above cases is plotted in Figure 52. From this, it can be seen that case two, with no applied rail cant and higher operating speed, will transition the curves at a more desirable “deficient” level than the current situation (Case 1) which would be in excess.

In addition, L/V results, reported in Figure 53 indicate that, for the wheels with highest risk of derailment (being 1R in the 1st curve and 1L in the 2nd in the down direction of travel) derailment risk is slightly decreased.

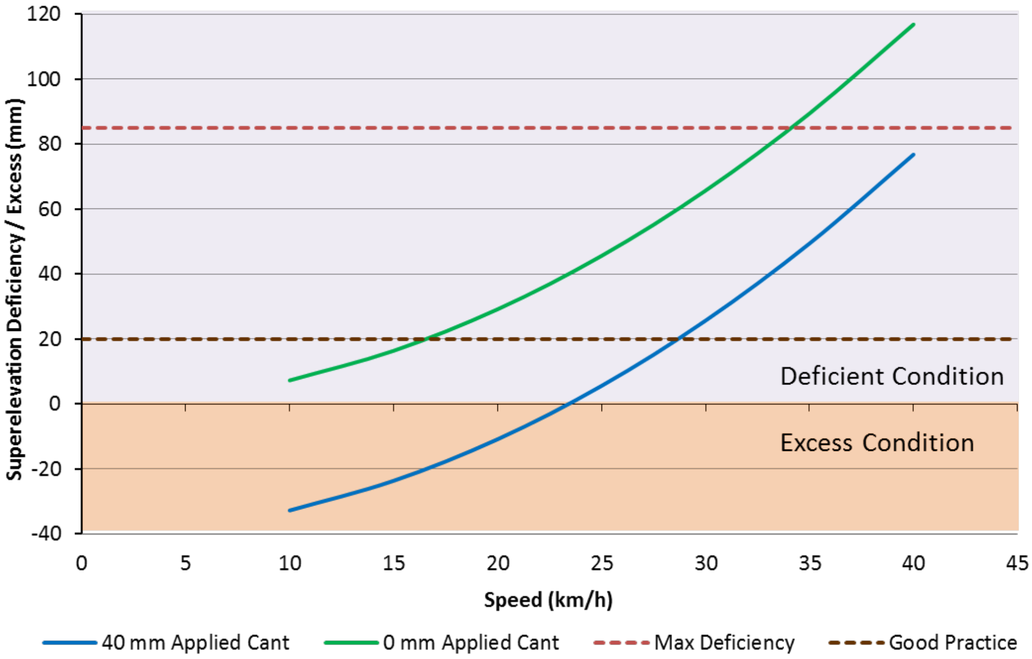

FIGURE 52: SUPERELEVATION DEFICIENCY/EXCESS VS. SPEED

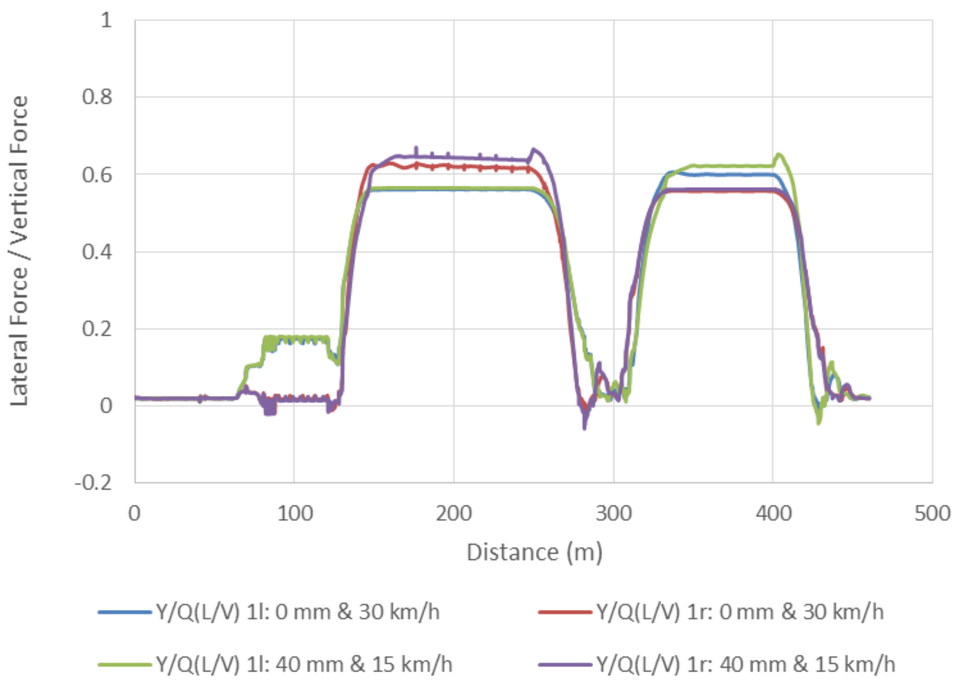

FIGURE 53: SIMULATED L/V RATIO COMPARISON OVER THE NORTH MELBOURNE FLYOVER

5.4.4 EFFECT OF TOP-OF-RAIL FRICTION MODIFIERS

Use of Top of Rail Friction Modifiers (TORFM), particularly to control noise in low speed curves, has been previously studied by IRT [27] for use at the NMFO. By decreasing available traction on the low rail, use of TORFM can also have some effect on wheelset steering and subsequently, wear energy (Tγ).

To quantify this effect, a simulation was conducted to compare the existing state (described in Section 5.4.1) to the full flange lube state (from Section 5.4.2) with the additional modification of limiting available friction on the low rail to $\mu = 0.35$.

Results for both the Low Rail Tγ (Figure 54) and Total Tγ (Figure 55) show improvements in wear energy of 32% and 67% respectively.

While the latter represents only a 1% improvement in wear over the full flange lubrication case (Figure 51) at a radius of 180m, the CI results presented in Figure 56 show a significant decrease in the predicted corrugation growth of 37% at 180m radius. This reduction would be expected to significantly reduce the growth rate of corrugations observed on some low rails within sharp radius curves on the V/Line network.

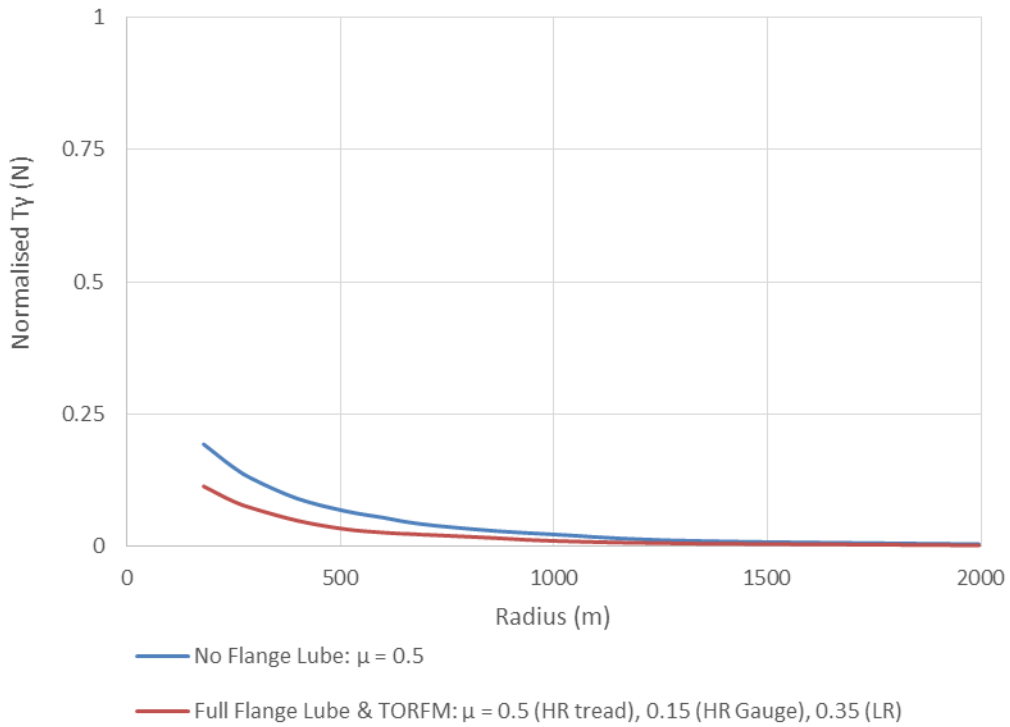

FIGURE 54: RELATIVE LOW RAIL Tγ FOR VLOCITY MODEL WITH REDUCED FRICTION ON THE LOW RAIL DUE TO APPLICATION OF TOR FRICTION MODIFIER

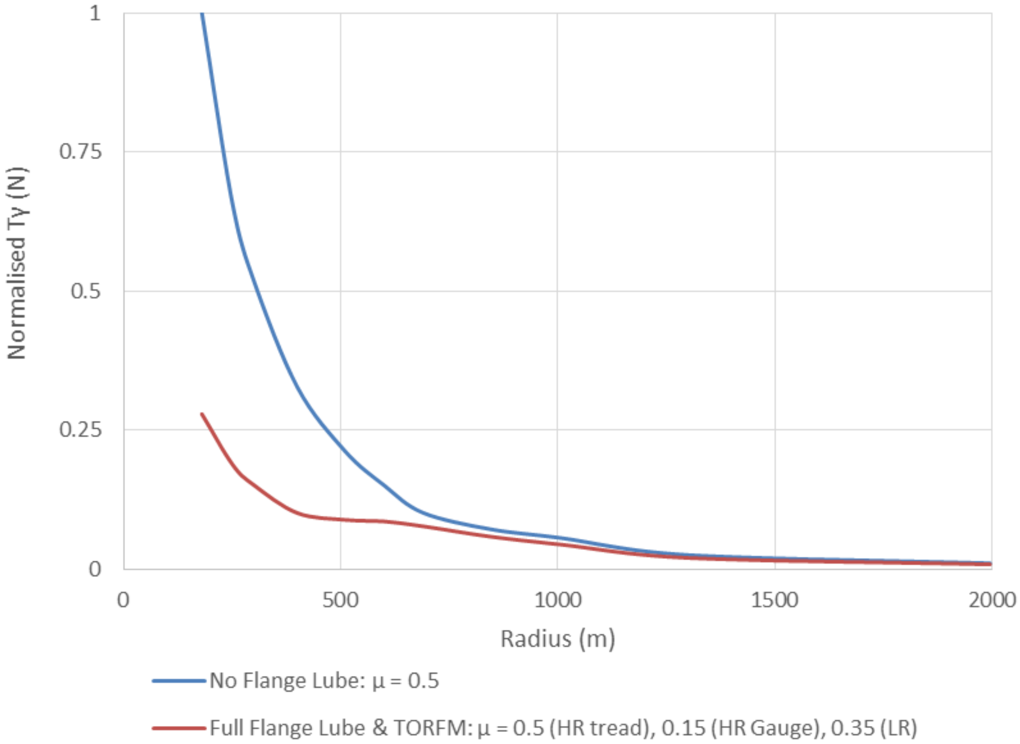

Figure 55: Relative Total Tγ for Vlocity Model with Varying Friction on the Wheel Flange due to Application of Grease Lubricant to the High Rail Gauge Face and TOR Friction Modifier Applied to the Low Rail

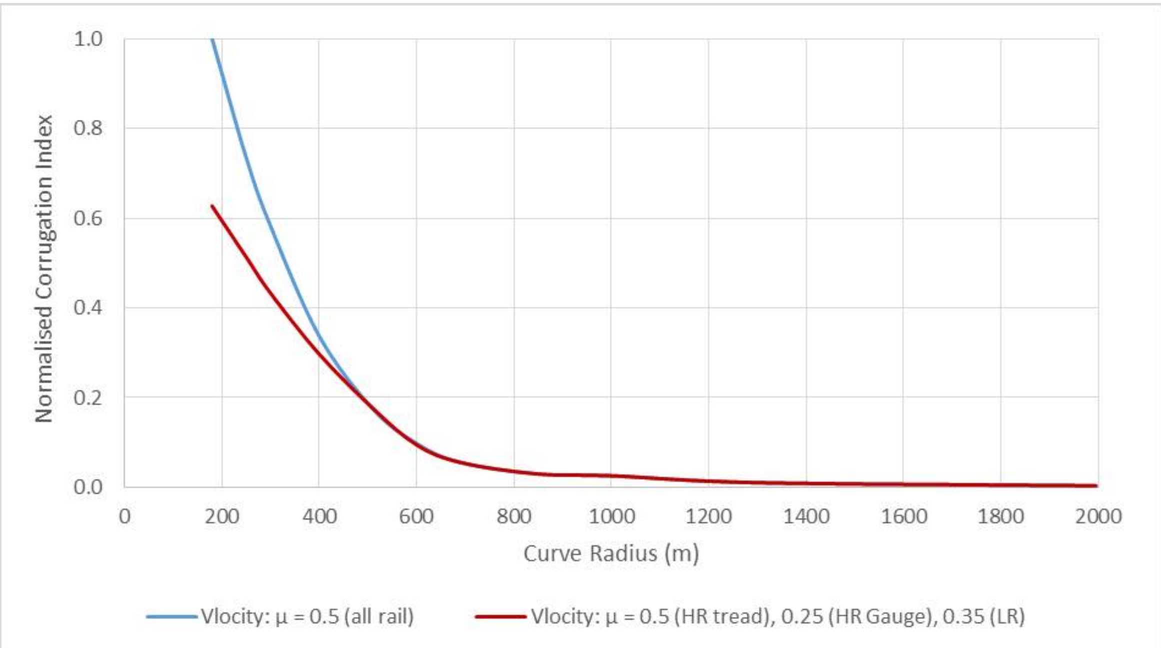

Figure 56: Normalised Corrugation Index Comparison for Low Rail

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5.4.5 PROPORTIONAL CHANGE BETWEEN TREAD & FLANGE ENERGY CONTRIBUTION

As discussed above, wear energy results have been presented on an axle basis, with the contributions of high rail tread, high rail flange and low rail tread for a common axis summed together to form a total value.

For the case in Figure 48, the pre-existing unlubricated condition (μ = 0.5), contributions to the total axle wear at the tightest radius of 180 m are 70.6%, 10.1% and 19.3% for High Rail Flange, High Rail Tread and Low Rail Tread respectively.

In practice, due to traversing both left and right curves, flange energy is distributed some times to the left wheel and sometimes to the right. On the other hand, dissipation of energy in the tread will always occur as either a high or low rail tread. In effect, this means that the ratio of energy dissipated in the flange to tread area of the wheels for this case is close to a 70 : 30 split in favor of the flange.

Figure 57 presents these proportions for the case where lubricant has been applied to both the gauge corner of the high rail (grease: μ = 0.15) and to the top of the low rail (TOR Friction Modifier: μ = 0.35). Figure 55 in Section 5.4.4 above showed that, in total, this case reports a Tγ 67% lower than the unlubricated condition but significantly, from Figure 57, it is shown that the ratio of flange to tread dissipation has changed to now be 35 : 65 with more energy being dissipated in the tread.

This should not be taken to imply that tread wear would subsequently be greater than flange wear. Consideration must be given to the much greater surface area that the energy is consumed by in the tread in relation to the flange. Subsequently, flange wear may still be greater, but at a much lower level than is currently the case.

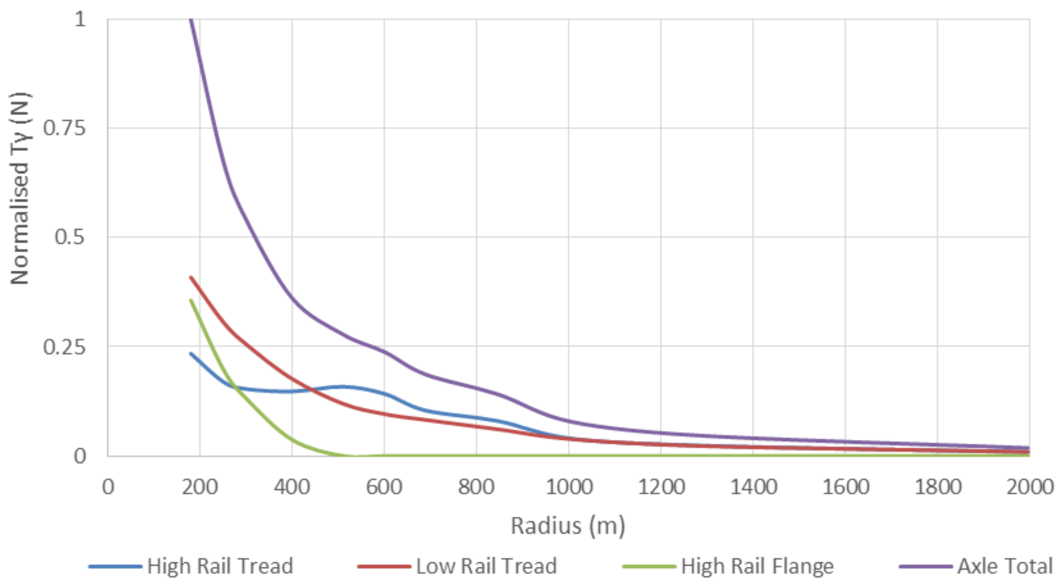

FIGURE 57: COMPARATIVE CONTRIBUTION OF HIGH RAIL TREAD, HIGH RAIL FLANGE AND LOW RAIL TREAD TO TOTAL Tγ WHERE LUBRICANT APPLIED TO BOTH HIGH AND LOW RAIL

6 DISCUSSION

6.1 Overview of Rail & Wheel Wear

The degradation of wheels and rails through wear and/or fatigue is often the primary driver behind the maintenance and replacement requirements for these critical components. The requirements and costs associated with these processes are closely linked to the operating conditions, which are a direct reflection of the track and rolling stock designs, the ongoing maintenance procedures and the way in which these are managed.

This section aims to provide an overview of key influential parameters pertaining to wheel and rail wear.

Wear behaviour in wheel-rail contact generally falls into one of three "wear modes" that characterize damage mechanisms associated and severity [28, 29, 30].

- Type 1:
  - Low wear rate
  - Moderate contact stresses
  - Low creepage
  - Oxidative and mild metallic wear processes
  - Relatively smooth surfaces, small/microscopic wear debris
- Type 2:
  - Moderate wear rate
  - Intermediate contact stresses
  - Intermediate creepage
  - Generation of surface and subsurface shear cracks
  - Involves (but not purely) a metallic wear process produced by cyclic plastic deformation and shear at the near-surface region
  - Characterised by metallic debris and rougher surface topography and plastic deformation
- Type 3:
  - Severe wear rate (adhesive wear)
  - High contact stress
  - High creepage
  - Purely metallic wear process produced by a mixture of plastic deformation and shear, plus localised adhesion and fracture of surface materials
  - Presence of larger wear particles, scoring, pitting (rough surface)

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Based on the wear data obtained by McEwen and Harvey [24] using a test rig which simulated full-scale wheel/rail contact conditions, wear rates would be expected to increase by 3-5 times when transitioning from Type 1 to Type 2 wear modes, and between Type 2 and Type 3 wear modes, or up to 15 times between Type 1 and Type 3 wear modes. In each of the above cases, the extent or severity of wear is proportional to the energy dissipated at the wheel-rail interface. As noted previously, this is a function of the tangential force and sliding distance (creep), where the tangential force is also a function of the normal force and friction within the wheel/rail contact.

$$\text{Wear} \propto T.\gamma \qquad (1)$$

Where:

γ = Creepage

T = Tangential force = μ.N

μ = Coefficient of friction

N = Normal force

It is also important to note that material characteristics, in particular hardness, are also a critical factor.

Figure 58 shows the primary factors and associated contributors that are responsible for wheel and rail degradation due to wear and rolling contact fatigue (RCF). In order to limit wheel and rail damage (wear & RCF) it is important to ensure that the three primary factors are dealt with appropriately through either design or control processes.

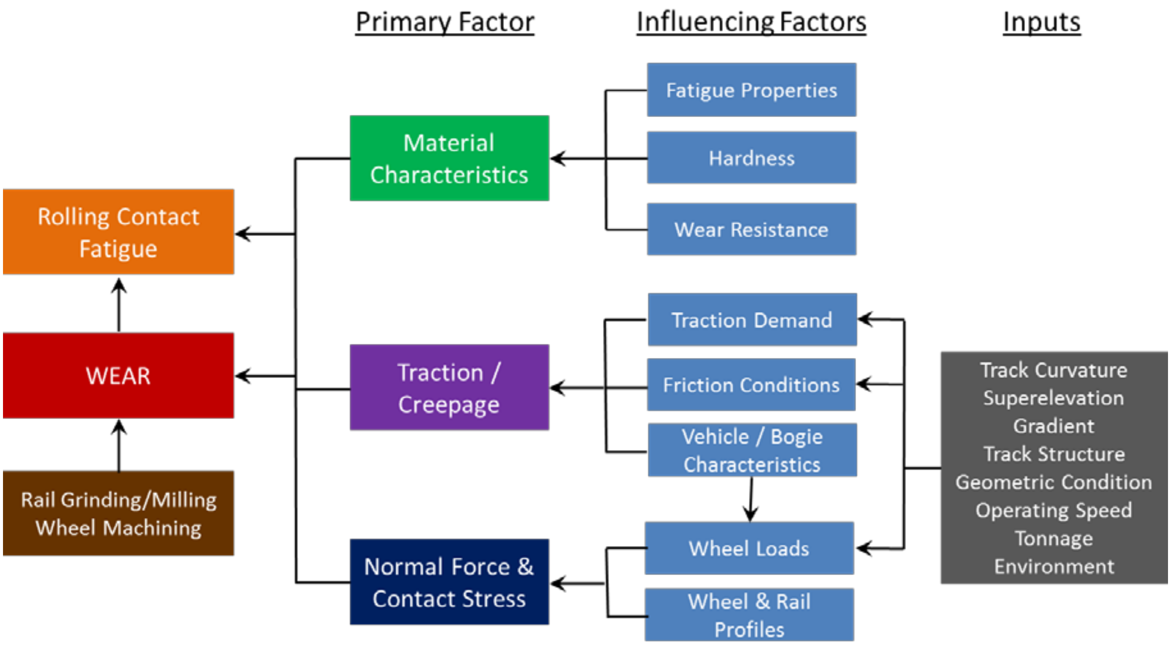

FIGURE 58: WHEEL AND RAIL DEGRADATION PROCESS
(MODIFIED FROM [32])

6.2 Rail & Wheel Wear at V/Line

6.2.1 Description of Wear

The primary wear mode of concern in the current situation is Type 3 wear resulting from unlubricated contact between the wheel flange and the rail gauge face. On the wheel flange, this results in heavily-scored surfaces such as those illustrated in Figure 59 and 60.

Figure 59: Worn VLocity Wheel Prior to Machining

Figure 60: Close Up of the Worn Flange Surface of a VLocity Wheel

6.2.2 Material Characteristics

The current wheel material grade (BS5892 grade R8T) is a hypo-eutectoid (0.56% max) carbon grade with relatively low specified rim hardness (255-286 HB) compared to the range of wheel grades that are available. This wheel material grade was considered by V/Line to have provided acceptable service lives, which is generally reflected in the VLocity wheel wear rates prior to mid-2015. Similarly the rail material grade used by V/Line (i.e. standard carbon) is also lower in hardness than other grades that are available, but is likewise considered by V/Line to have provided acceptable service performance.

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The lower carbon and rim hardness of the current wheel grade would be offset by improved resistance to thermal loading, although this should not be a major concern in the VLocity trains which are disc braked.

Wear rates in wheel and rail materials decrease with increasing material hardness or strength, as illustrated in Figures 61 and 62. However, as is also shown in Figure 62, the relationship between wear rate and material hardness is also influenced by the friction or lubrication conditions at the wheel-rail interface. In particular, implementing or improving the effectiveness of lubrication of the wheel flange/rail gauge face contact region has a greater overall effect than increasing material hardness, as also reported by McEwen and Harvey [24]. Hence effective lubrication is the most effective short-term approach to addressing the wheel wear issue, and it will be necessary to continue this approach long term in the tight curves (R<300 m).

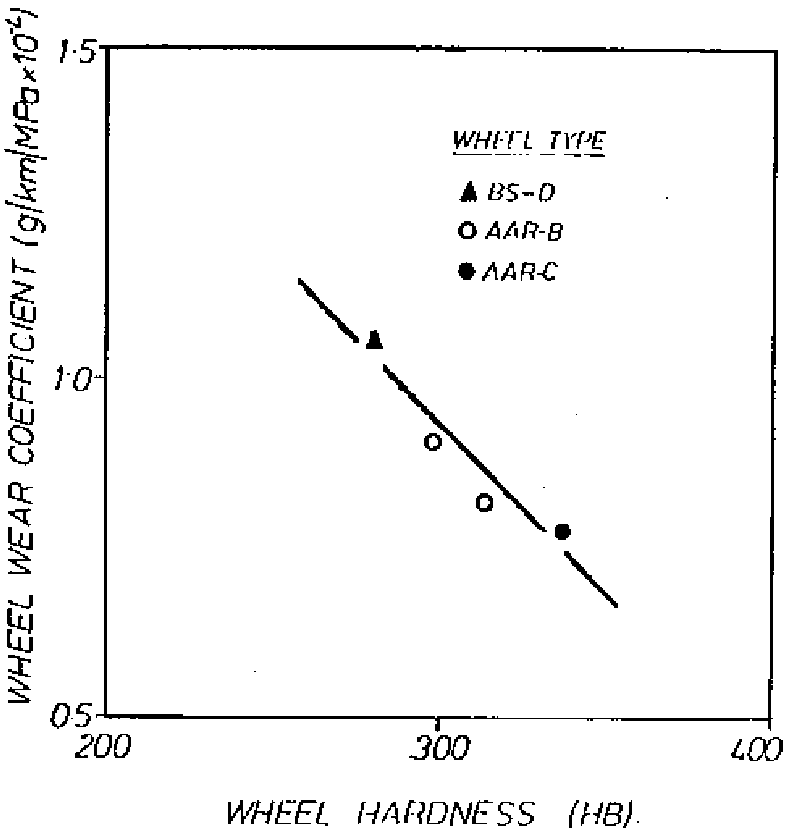

FIGURE 61: GENERAL RELATIONSHIP BETWEEN MATERIAL HARDNESS AND WEAR RATES FOR WHEEL MATERIALS [32]

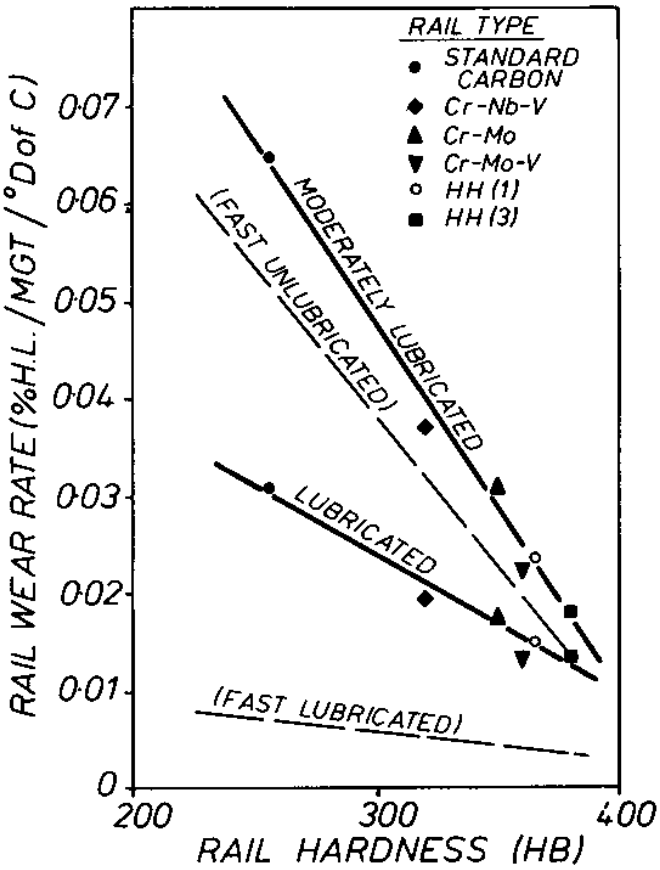

FIGURE 62 GENERAL RELATIONSHIP BETWEEN MATERIAL HARDNESS AND WEAR RATES FOR RAIL MATERIALS FOR VARYING LUBRICATION CONDITIONS [33]

In addition to lubrication of the tight curves, replacement of the existing material grades (for both wheels and rails) would be expected to provide a reduction in wear rates through two related factors:

- For any particular combination of wheel and rail profiles, wear rates will reduce in line with the relationships illustrated in Figure 61 and 62.
- The rate at which wheel and rail profiles themselves change with increasing amount of wear would also reduce. Based on the simulation results, this would also provide a significant improvement in wear rates as the optimum profile combination would be retained longer.

6.2.3 TRACTION AND CREEPAGE

As noted in Section 6.1, wear is highly influenced by the tangential force (creep force) and sliding distance (creep) occurring within the wheel-rail contact. Traction and creepage effects directly relate to the magnitude of creep forces and slip acting at the wheel/rail interface. The level of traction and creepage is highly influenced by the traction demand from the vehicle, friction conditions and vehicle bogie design characteristics.

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Traction demand is essentially related to the power and adhesion required to move the load (train) – i.e. the heavier the train, or steeper the gradient, the greater the traction demand. Traction is limited by the amount of adhesion that can be obtained from the wheel/rail contact through the limiting (coulomb) friction; hence the higher the friction the higher the adhesion available to the driven wheelsets.

In an un-lubricated condition, tribometer measurements from V/Line track show relatively high levels of friction (around 0.5). Consequently, the available adhesion limit is also high and greater tractive forces can be generated at the wheel/rail interface.

While third-body elements, such as lubricants and contaminants, can significantly change the friction/adhesion characteristics, it should be noted that speed is also an important consideration. As shown in Figure 63, available friction/adhesion decreases with increasing speed. For example, a measured (Tribometer) friction of around 0.5 reduces down to around 0.4 at 40 km/h, which is a reduction of around 20%. It should also be noted, however, that traction demand also usually decreases with speed.

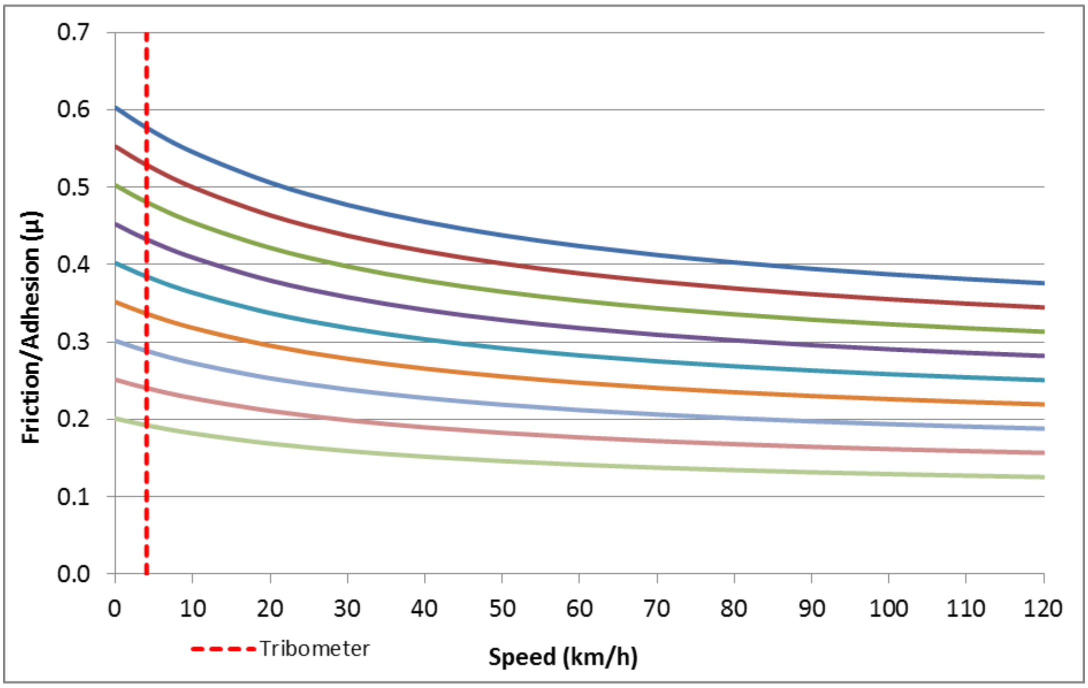

FIGURE 63: FRICTION VS. SPEED [34]

Bogie design and steering characteristics significantly influence the extent of creepage and slip within the wheel/rail contact. Specifically, design characteristics such as longitudinal stiffness from primary suspension, yaw stiffness and wheelset spacing greatly influence the steering capability.

A bogie design that allows wheelsets to be able to move (steer) into the more radial position is desirable as it allows the wheelset move closer to a pure rolling condition where creepage is low. Subsequently a softer primary suspension, particularly in the longitudinal direction, is desirable as it is the main component resisting such radial steering. Conversely, a stiffer suspension limits the radial movement of the wheelset,

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thus resulting in high angles of attack (variation from the radial position) and consequently higher creepage/slip (Figure 64).

As noted previously, the VLocity bogie design has a longitudinal stiffness of around 4 times that of a Sprinter, as well as a slightly longer wheel base which also affects curving ability. These effects can be seen in the simulated angle of attack results provided in Section 5.4.

It is assumed that the higher stiffness of the VLocity bogie is due to the higher operating speed (160 km/h) compared to the Sprinter (130 km/h). In order to maintain appropriate ride quality, higher speed bogies generally need to be stiffer than those designed for lower speeds. The trade-off is that the steering/curving capability of the stiffer bogie is reduced and, consequently, actions need to be taken in order to control wear in sharp curves. As a result, high speed networks are often designed such that there are no, or very few, sharp curves on the mainline – those that do need to ensure that wear mitigation processes are in place and maintained.

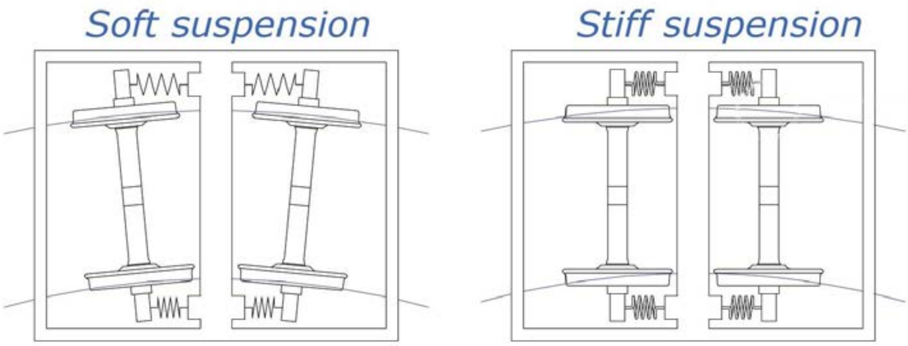

FIGURE 64: BOGIE SUSPENSIONS [35]

6.2.4 NORMAL FORCE & CONTACT STRESS

Normal force, as noted in Section 6.1, is a primary factor associated with wheel and rail wear and is directly influenced by wheel loading conditions. The magnitude of wheel loading conditions is typically a function of the following operating conditions:

- Track curvature
- Superelevation
- Track structure type
- Geometric conditions (track roughness)
- Operating speed
- Mass (self-weight and payload)
- Vehicle curving characteristics

The resulting contact stress is a disproportional function of the normal force, and is highly sensitive to the transverse profiles of the wheel and rail (contact geometry). In simplistic terms, high contact stresses repeatedly exceeding the strength of the material

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are, particularly when in combination with slip/creep, responsible for the development of rolling contact fatigue (RCF), deformation and wear.

Under loading conditions such as the NMFO, where stiff suspension vehicles (VLocity) with a relatively high vehicle mass (loaded trains) travel over very tight radius curves, both normal force and contact stress are likely to be significantly higher than most other areas of the V/Line network.

The suitability of wheel and rail profiles was not fully examined during this investigation since it was clear early on that profile compatibility in this case was of secondary concern. However, both wheel flanges and the gauge corner of high rails have rapidly adopted a common worn shape, which generally represents the lowest stress/wear condition possible when curving.

6.2.5 Main Contributors to High Wheel and Rail Wear at V/Line

Based on the inspection and analysis work undertaken for this investigation, the following key points are considered to represent the most significant contributors to the high wheel and rail wear issue, which developed at V/Line in late 2015.

i. Curve radii: The tight curves (i.e. curves with R<300 m) introduced to the mainline system as part of the RRL project are considered to be extremely sharp for broad gauge conditions. Moreover, without mitigation, such curves are unsuited to the curving behaviour of the VLocity bogies which utilise a relatively stiff suspension designed to provide increased stability at higher speeds.

ii. High friction: High friction conditions, such as those associated with the absence of any gauge face lubrication in the above curves prior to mid-January 2016, resulted in higher traction (tangential) forces and increased wear.

iii. Wheel and rail materials: The wear resistance characteristics of the material grades currently used for both wheels and rails is considered low by comparison with other grades that are available, although the wear performance had previously been considered (by V/Line) to be satisfactory. However wear performance declined with the introduction of the tight radius in the RRL.

While any one of the above could potentially cause a higher wear situation, it is the combination of these conditions that is considered to be the root cause of the wear issues that developed in late 2015.

6.2.6 Evolution of the VLocity Wheel Wear Problem

The commencement of VLocity operations on the RRL track in mid-2015 resulted in an increase in average flange wear rates from 0.27mm/month in June 2015 to 0.56mm/month on July 2015, as reported by V/Line and confirmed by the analysis of the supplied wheel wear data from Bombardier (section 4.1.1 of the current report).

From July 2015 until November 2015 average wheel flange wear rates per month remained relatively stable, despite a steady increase in patronage levels [36]. The return to more consistent wear rates (albeit at a higher level than prior to commencement of the RRL operations) indicates that wheel and rail contact conditions in these sharper curves may have stabilized during this period.

The newly-laid rail (and either ground or milled) sections in the RRL sections would be expected to have worn in during this period, with some changes to profiles and work hardening in the main contact regions. No data on the rail profiles in the sharper curves at this time was available, although rail gauge face angle date reported separately by V/Line [37] indicated that the condition of the high rails on the NMFO was relatively stable between late July 2015 and mid-October 2015, with a marked increase on the rail gauge face angle evident in late December 2015.

The wheel wear data also shows that the average flange thickness of the VLocity fleet decreased slightly between June and July 2015 (Figure 65). However this trend does not necessarily reflect the influence of the RRL operations, as not all Vlocity trains are inspected on a monthly basis. The VLocity flange thickness data does show, however, that monthly average flange thickness levels continued to decrease through till December 2015, with an increase in the range of flange thickness levels apparent in January 2016.

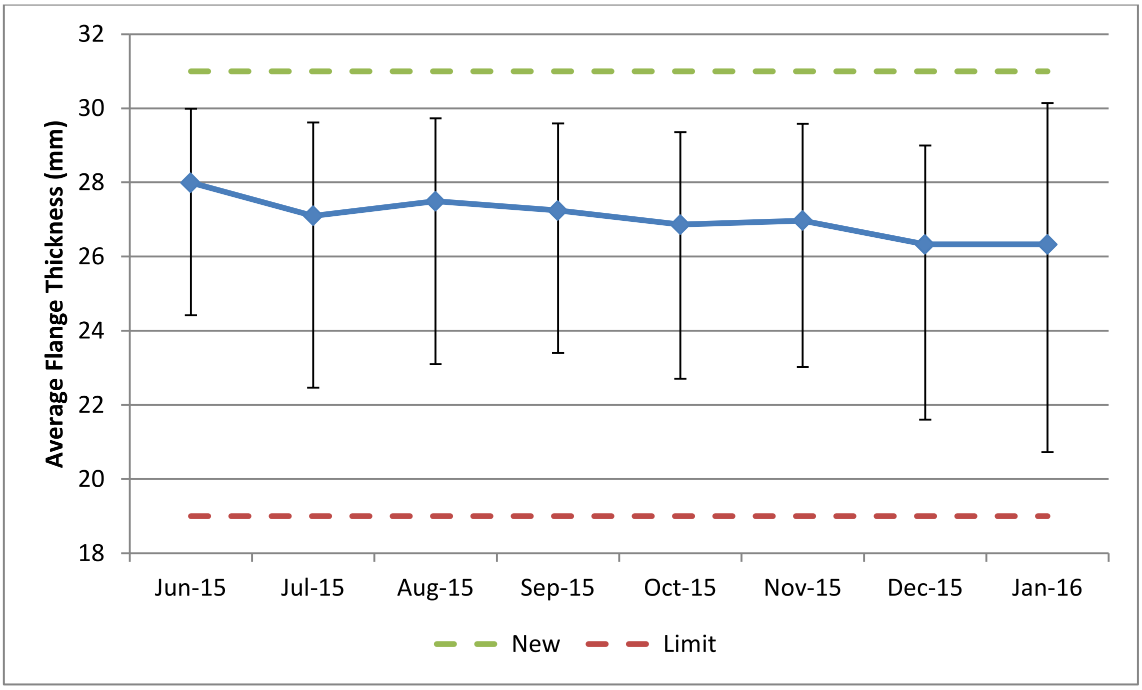

FIGURE 65: VLOCITY FLEET AVERAGE FLANGE THICKNESS BY MONTH

The change in rail profiles in the sharper curves to result in the rail condition evident during the inspection performed by IRT in mid-February, would have resulted in a marked deterioration in wheel/rail contact conditions as illustrated in Figure 66. The upper combination of new MP2 wheel profile and RPH2000 rail profile provides uni-point contact around the gauge corner, with negligible contact down the gauge face. Potentially higher contact stress levels at the gauge corner could be expected with this profile combination, but wear rates would be relatively low.

In a partly-worn condition (middle combination in Figure 66), there is more extensive contact between the wheel flange and the rail gauge face, which would have given rise to a marked increase in wear rates.

In the fully-worn condition, the contact extends to the tip of the flange and slightly lower down the rail gauge face, further increasing wear rates and also resulting in the development of arises on the wheel flange.

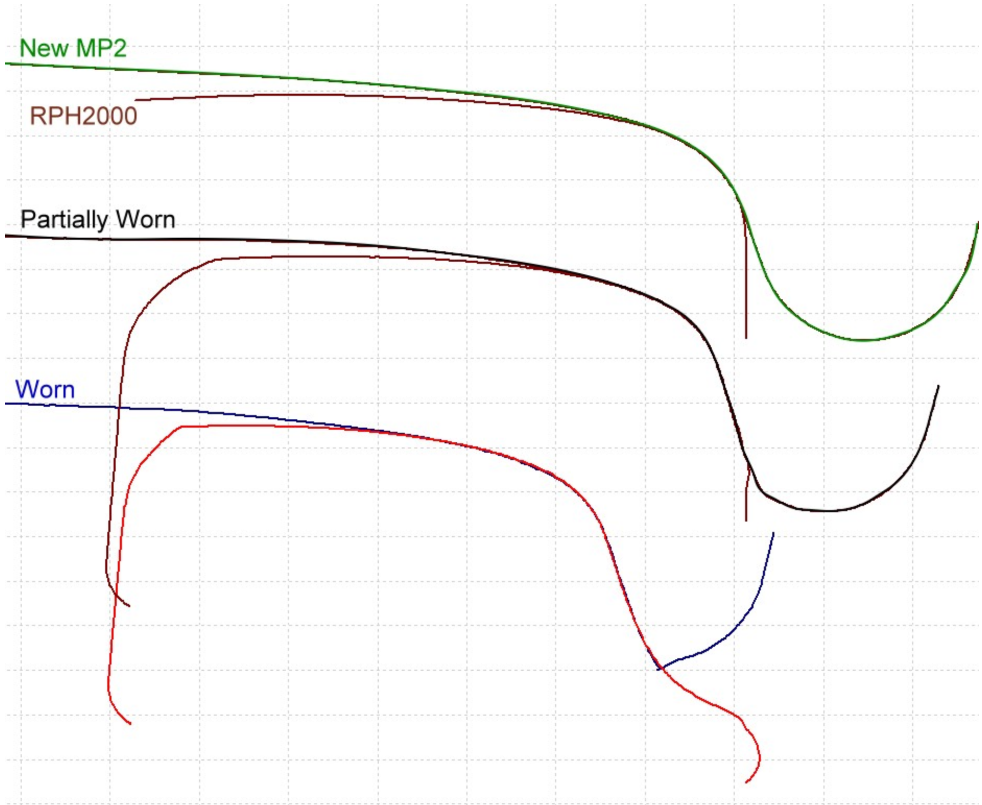

FIGURE 66 : WHEEL/RAIL PROFILE COMBINATIONS ILLUSTRATING THE TRANSITION FROM A LOW WEARING TO HIGH WEARING CONDITION

Throughout the period discussed above, no lubrication was in use in the sharper curves in the RRL. Hence both partially-worn and fully-worn conditions would result in the severe (Type 3) wear damage apparent on the wheel flanges and the lack of any significant work-hardening on the rails. Once lubrication of the sharper curves was implemented in early 2016, wear rates would be expected to decrease although the effectiveness of the lubricant would have been compromised by the high-wearing profile combination and the rough surfaces which were generated previously. Lubrication would be expected to become more effective (i.e. the lubricant would be expected to perform for a longer period) as the surface roughness levels decreased.

Based on the combination of wheel and rail profiles shown in Figure 66 above, wheel flange wear rates in the sharper curves would be expected to improve following the recent re-railing of the sharp curves in the NMFO, provided the newly-installed rails were ground or milled to the RPH2000 profile as previously recommended [3].

7 REDUCING AND CONTROLLING WEAR

Wheel and rail wear on the V/Line network can be reduced or controlled through the following mitigation measures.

- Friction management.
- Wheel and rail materials of higher hardness
- Wheel-rail interface management.
- Track re-alignment, including adjusting the cant of the tight curves to suit the typical operating speeds.
- Softening of the VLocity bogie.

The first two items above are considered to be relatively easy to justify based on the estimated reduction in wear rates that would be achieved, and also straightforward to implement and maintain. It is acknowledged, however, that the last two items would not only require a significant amount of further study and investigation, but also considerable funding to implement.

7.1 FRICTION MANAGEMENT

7.1.1 FLANGE LUBRICATION

Application of rail curve lubricants containing extreme pressure (EP) additives, such as molybdenum disulphide (MoS_2) or graphite, is by far the most effective approach to mitigating wheel wear and the one that can be implemented the most readily.

The currently-adopted strategy of applying (by hand) the graphite-bearing Rocol product in the NMFO has been shown to be effective. However the current method of application is not sustainable in the longer term and an appropriate alternative approach needs to be identified and implemented.

There are a number of important items that need to be considered when selecting and implementing effective wheel-rail lubrication for the V/Line system; these are briefly outlined below:

i. Whilst the primary requirement is to reduce wheel flange wear (and rail gauge face wear in the sharper curves), do management of friction levels on the running surface of one or both rails in these curves need to be included? For example, application of top-of-rail (TOR) friction management products has previously been to limit wheel squeal on the NMFO, and application of similar products under the current conditions would be expected to result in less corrugations in the low rail of these curves.

ii. For the reduction of wheel flange wear, what is the most suitable product? Important considerations include suitability for the intended method of application, the type of EP additive and sensitivity to environmental conditions, such as elevated ambient temperatures and rainfall. In addition, the durability of

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the lubricant film is extremely important when intermittent application (as is currently the case) is involved, while for track-mounted application methods, carrying distance is important.

iii. The intended method of application, which could be using wayside lubricators, or vehicle mounted systems, which apply lubricant either to the wheel flange or directly to the rail gauge face. In the case of vehicle-mounted application systems, a curve-sensing system must be incorporated so that lubricant is only applied in the relevant track sections. For vehicle-mounted application systems, a further option is the use of dry stick or cartridge products which incorporate the lubricant (and EP additive) in a polymer base. These products, which are installed such that they are in continuous contact with the wheel flange, are commonly-used on locomotives. For track-mounted application systems, the configuration of the wiper bars is important, as is placement of lubricators to provide the longest effective lubrication distance.

For either type of application system, correct adjustment and ongoing inspection and maintenance is necessary to ensure optimum lubricant levels are maintained, less wastage and contamination of rolling stock and track, and to ensure that the running surface of the rail is not contaminated.

iv. Simulation results in Section 5.4 show that the benefit of flange lubrication is realised in curves below 600 m radius, but more significantly in curves of 400 m radius and below.

v. Lubricant application rates may need to consider variations in surface roughness of wheels and rails, as this will influence the value of λ. For rougher surface finishes (such as that on re-profiled VLocity wheels (Figure 67)), a thicker lubricant film will be required to maintain the same effective friction during flanging. In addition, the effectiveness of the lubrication will decrease more rapidly, such that more frequent application will be necessary until such time as the surface roughness decreases. Alternatively, using lower feed rates during reprofiling this section of the profile should provide an immediate improvement in the effectiveness of lubrication on re-profiled wheels.

FIGURE 67: APPEARANCE OF REPROFILED VLOCITY WHEEL

vi. Monitoring of lubrication effectiveness. Wear would be expected to increase if the application of lubricant were to be interrupted, hence consideration should be given to implementing a monitoring system which is capable of assessing the effectiveness of the lubricant film on a continuous basis. Sensing technologies which have in the past been used for monitoring the effectiveness of wheel-rail lubrication have been based on the rise in temperature of the rail head during the passage of a train [41], or the acoustic response in either the audible range or the much-higher frequency acoustic emission levels associated with the wear damage [42].

7.1.2 TOP-OF-RAIL FRICTION MODIFIERS

As noted in Section 5.4, top-of-rail friction modifiers (TORFM) have been successfully used for the reduction of wheel squeal noise [25], which is understood to be an on-going issue on the NMFO.

In addition to noise control, the benefit of TORFM in terms of a slight reduction of wear was also demonstrated through simulation. Of potentially greater importance, however, is the expected reduction of corrugation development in the sharper curves. Simulation results show that the application of TORFM can potentially reduce corrugation development by around 37% in the sharpest curves (R180 m).

Also of interest are the combined benefits of improved rail material and the use of TORFM on corrugation development. Figure 68 shows the earlier results for the current rail material as well as the expected further benefit of utilizing head hardened rail. By using head hardened rail in conjunction with TORFM, corrugation development in the low rail is expected to be reduced by over 60% from the current level.

Concerns raised over the use of *TramSilence* (tested previously) on the NMFO are warranted since over application of this product can result in wheel slip conditions. Care must be taken to ensure the application rate of this product is consistent with the manufacturer's recommendations. Alternatively, further investigation could be undertaken into the use of other TORFM products that do not drop the available friction level as far when over applied.

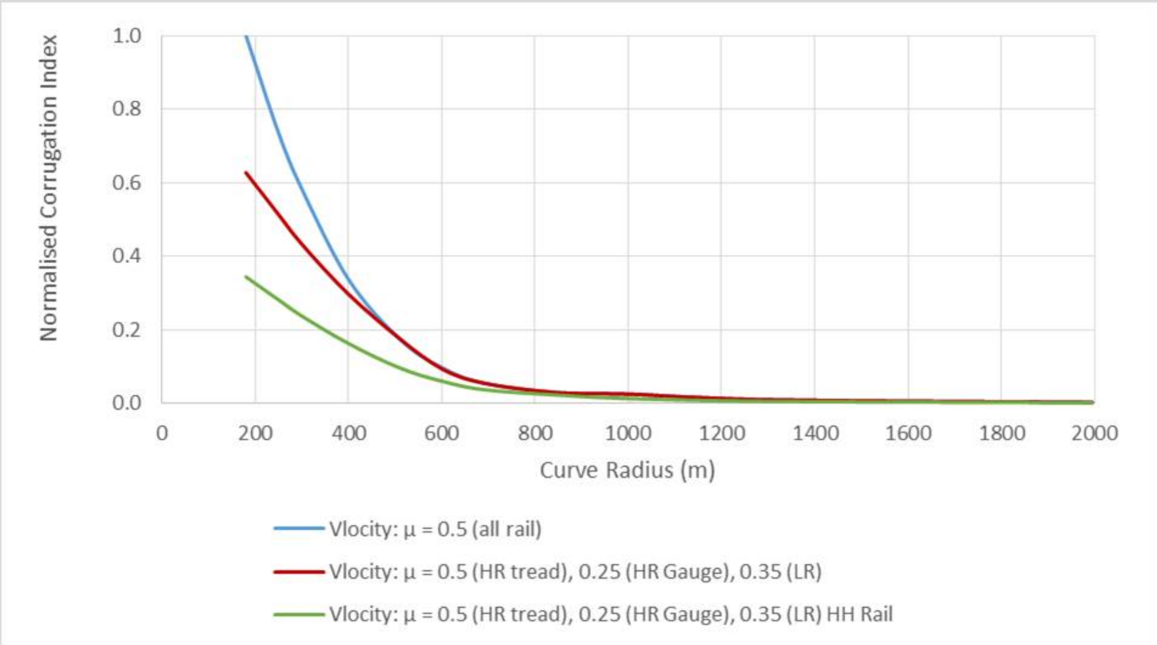

FIGURE 68: NORMALISED CORRUGATION INDEX – TORFM & HEAD HARDENED RAIL

7.2 IMPROVED WHEEL AND RAIL MATERIALS

Altering wheel material to the RS8T or R9T grades [16] is one option that can be considered; this would allow maximum carbon levels to be increased from 0.56% in the R8T grade to 0.60% for the R9 grade, and a corresponding increase in the maximum rim hardness levels from 285 HB to 311 HB. Alternatively an AAR Class B grade, with a maximum carbon level of 0.67% and rim hardness of 341 HB [38], could also be considered. The current wheel manufacturer produces a range of other wheel grades that could also be considered, although use of even higher hardness grades such as AAR Class C (0.77% maximum carbon, maximum hardness 363 HB) is not recommended.

Altering the wheel material grade represents a change to the design specification for the VLocity trains, and hence Bombardier may need to be consulted regarding any proposed changes.

Use of the Head-hardened grade (AS1085.1-2002) rail with nominal hardness and yield strength levels of 360 HB and 850 MPa, respectively, in the sharper curves (R<400 m) is an option that is strongly recommended. This should result in a ~50% reduction in rail wear rates for the same wheel-rail contact conditions. Rolling contact fatigue (RCF) damage is not expected to be an issue within the sharper curves, provided the recommended rail profile is installed as soon as possible after rerailing. The latter is particularly important in the dual gauge track sections on the NMFO, as the 50 kg/m section used in this location has a relatively sharp gauge corner detail in the as-rolled condition. Alternatively, an intermediate strength grade with nominal hardness levels of

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~320 HB would be expected to provide wear performance between the As-rolled and Head-hardened grades. A number of such grades are produced internationally; the applicable standard and grade in this case is EN 13674 Part 1 and R320Cr (320-360 HB) respectively [39].

7.3 Wheel-Rail Interface Management

Prior to implementing any change to the rail material grade, it would be prudent to examine the potential for RCF damage, particularly for curves in the 400-900m radius range. This could be carried out using the existing simulation model, but with a wider range of wheel and rail profiles.

Given the changes to the current V/Line operating environment and likely on-going need for regular rail profiling works in certain areas, it is recommended that a wheel-rail interface management review be undertaken to:

- Examine the suitability of current wheel and rail profiles and suggest revisions to help improve wheel/rail contact conditions on the V/Line network. The review should aim to ensure:
  - The control of wear and RCF (if harder materials used).
  - Limited corrugation growth (combined with TORFM).
  - Vehicle stability and ride quality are maintained.
- Develop a comprehensive network wide wheel-rail interface management plan that includes:
  - Friction management strategy.
  - Rail and wheel profiling standards and/or guidelines.
  - Implementation and monitoring plan.

7.4 Track Alignment

One of the main contributing factors pertaining to the current wear issue is the introduction of a number of very tight curves into the operating environment.

While a number of suitable control measures have already been discussed (improved materials and friction modification), the benefits of a revised track alignment cannot be omitted.

The easing of sharp curves along the RRL section would significantly reduce wear and the need for on-going control measures. It is acknowledged, however, that the cost of such an undertaking would be very high.

At the very least, however, the easing of the NMFO curves, and any other curves below 300 m radius, should be considered since this would significantly improve the longer term wear performance and efficiency of V/Line operations.

7.5 VLocity Bogie Modification

Another key contributing factor pertaining to the current wear issue is the limited ability of the VLocity vehicles to steer around the sharp curves on the RRL track. This is due to the high primary suspension stiffness of the VLocity bogies that were designed for stability and ride quality at high speeds (160 km/h). Simulation results have demonstrated the impact this has had on VLocity vehicles and why they are more susceptible to higher wheel wear in sharp curves than other vehicles, such as the Sprinter, which operate at lower speeds.

While the current wear issue does not stem from problems with the VLocity design, since these vehicles had been operating on the network for around 10 years prior to RRL with no reported wheel wear issue, further investigation could be undertaken to determine whether modifications could be made to improve curving performance without detriment to high speed stability and ride quality.

Should modification be possible, however, it is likely to be a particularly costly exercise to retrofit all VLocity vehicles. Furthermore, the need for a change in bogie design would need to be reassessed should some of the other control measures noted above be implemented. As such, the modification of bogie stiffness is not considered to be a preferred option at this stage.

8 SUMMARY

The objective of the current investigation was to determine the root cause(s) of the accelerated wheel wear on VLocity passenger rolling stock operated by V/Line that became evident in late 2015, and provide recommendations on possible remediation strategies that can be used to reduce or control the wheel wear behaviour.

The primary results obtained during the investigation are summarised as follows.

8.1 VLOCITY WHEEL WEAR DATA

i. Analysis of the wheel wear data recorded by Bombardier (and supplied via V/Line) for the period June 2015 to mid-February 2016 confirmed that the average wheel flange wear rates for the VLocity fleet increased by a factor of ~2 (from 0.27mm/month to 0.56mm/month) in July 2015 following the commencement of services on the Regional Rail Link (RRL). Thereafter, wheel flange wear rates remained relatively stable and in the range 0.44mm/month to 0.54mm/month until November 2015. The average wear rate then increased to 0.70mm/month in December 2015 and 1.32mm/month in January 2016[2].

ii. Average wheel flange wear rates over the above period were similar for motor and trailer bogies in the VLocity trains. However there was clear and consistent left vs right bias in the wear data which was first evident in the data for July 2015 and continued to January 2016. The bias in the wear data reflects the corresponding distribution of curve directions in the sharper curves, i.e. curves of less than 800 m radius in the RRL.

8.2 INSPECTION OF ROLLING STOCK AND TRACK CONDITIONS

i. Inspection of worn wheel flanges on VLocity rolling stock confirmed the occurrence of severe (adhesive or scoring) wear, consistent with dry sliding contact with the rail gauge face during curving.

ii. Inspection of the rail condition at a number of locations in the RRL and Regional Fast Rail (RFR) track sections confirmed the presence of elevated rail gauge face wear losses in the high rails in curves of radius less than ~ 250 m. In some locations corrugations were also evident on the low rail.

iii. The wheel machining process was inspected at the Downer Newport Workshops. While no significant profile anomalies were identified that would be expected to contribute to the present wear issue, however, a number of machined profiles were found to contain minor profile anomalies (note: wheelset diameter matching

[2] V/Line also advised that there was also an increase in the average distance travelled per month for the VLocity fleet, from 3,946,490 km average per month for January to June 2015 to 4,454,499 average per month between July and December 2015.

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was within tolerance). It is therefore recommended that the underfloor wheel lathe at Newport Workshops be checked and re-calibrated.

iv. The surface finish on reprofiled (machined) wheels, although typical of such operations, was relatively coarse compared to that on new (as-supplied) wheels.

8.3 Application of Rail Lubrication

i. In the curves on the North Melbourne Fly Over, in which lubrication of the high rail gauge face had been implemented in early 2016, some residual graphite film was evident during the initial IRT inspection, which was performed during non-running hours at night. At this time friction levels on the gauge face averaged 0.24, decreasing to ~0.20 in places where there was still some residual lubricant present.

ii. Gauge face friction levels increased to ~0.35 for a smooth gauge face surface with negligible residual graphite, and ~ 0.45 on a dry rough surface.

iii. During a subsequent (daylight) inspection during running hours, lubrication levels at this time appeared to be better than those assessed previously, with evidence of a substantial grease film on the gauge face of the high rail. Friction levels at this time were not recorded, but were estimated to fall in the range 0.15-0.20.

8.4 Assessment of Vehicle-Track Interaction Behaviour

i. For the VLocity rolling stock under existing conditions, flanging was predicted to occur for all curves of radius <600m, with predicted flange energy levels to increase with decreasing curve radius down to the minimum of 180m.

ii. Predicted flange energy levels for the Sprinter rolling stock under the same conditions were lower than those of the VLocity rolling stock, consistent with the differences in longitudinal stiffness of the bogies.

iii. For the VLocity rolling stock, simulation of wheel/rail contact conditions has shown that reducing the flange friction levels from 0.5 (representing the unlubricated condition) to 0.25 (poor lubrication) flange energy levels in the sharper curves reduced by approximately 40%. Further reduction of flange friction levels to 0.15 (good lubrication) reduced flange energy levels by around 65% from the unlubricated condition.

iv. Modification of superelevation on the NMFO showed a reduction in L/V and, in conjunction with flange lubrication, served to reduce the risk of flange climb.

v. For the VLocity rolling stock, application of TOR Friction Management shows an estimated 37% reduction in corrugation growth in 180 m radius curves.

8.5 Root Cause(s) of the Accelerated Wheel Wear on VLocity Trains

Based on the above results, conditions which gave rise to the marked increase on wheel flange wear rates in the VLocity fleet from December 2015 onwards were as follows:

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a). The commencement of VLocity operations on the RRL in mid-2015 resulted in an immediate increase in average flange wear rates, which reflected a combination of the sharper curves present in some sections of the RRL, high friction and the relatively high longitudinal stiffness of the VLocity bogies. In addition, V/Line advised that there was an increase in the average distance travelled per month for the VLocity fleet associated with the introduction of the RRL.

b). Average wheel flange wear rates per month remained relatively stable from July 2015 until November 2015, indicating that wheel and rail contact conditions in these sharper curves may have stabilized during this period, although the extent of rail gauge face wear in the (unlubricated) high rails in the sharper curves would have continued to increase.

c). By late December 2015 the extent of high rail gauge face wear had increased, resulting in the worn rail condition evident during the inspection of these curves in mid-February.

d). Over the above period there would have been a marked deterioration in wheel/rail contact conditions as illustrated in Figure 69.

- The upper part of this figure shows a combination of new MP2 wheel profile and RPH2000 rail profile which results in a uni-point contact around the gauge corner, with negligible contact down the gauge face. Potentially higher contact stress levels at the gauge corner could be expected with this profile combination, but wear rates would be relatively low.
- In a partly-worn condition (middle combination in Figure 69), there is more extensive contact between the wheel flange and the rail gauge face, which would have given rise to a marked increase in wear rates.
- In the fully-worn condition, the contact extend to the tip of the flange and slightly lower down the rail gauge face, further increasing wear rates and also resulting in the development of arises on the wheel flange.

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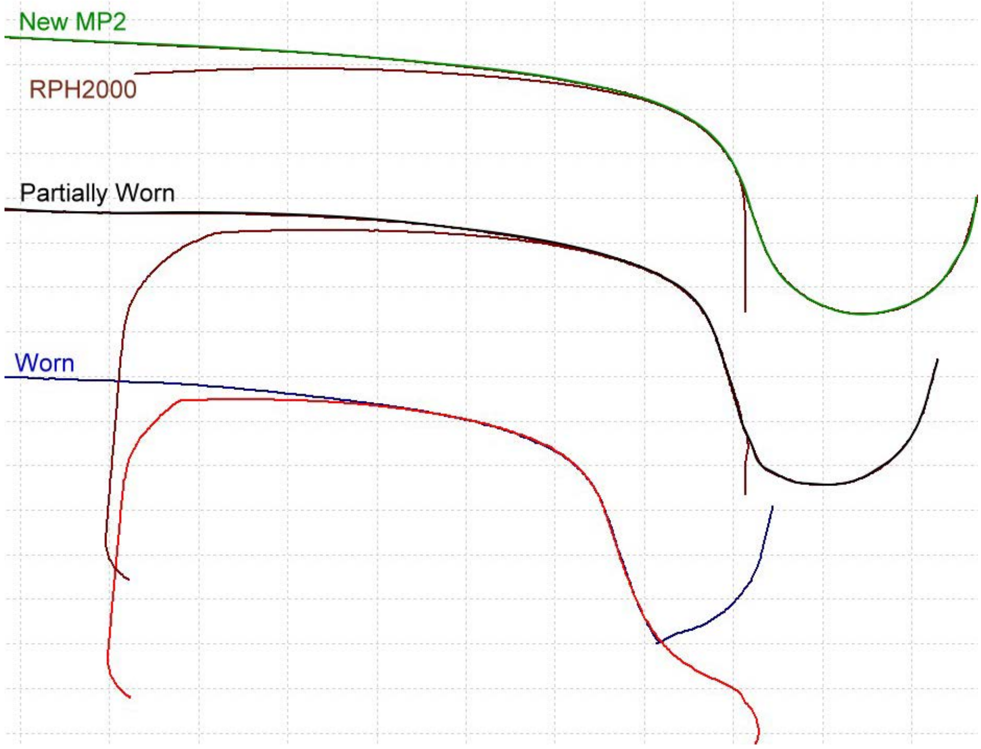

FIGURE 69: WHEEL/RAIL PROFILE COMBINATIONS ILLUSTRATING THE TRANSITION FROM A LOW WEARING TO HIGH WEARING CONDITION

e). Throughout the period discussed above, no lubrication was in use in the sharper curves in the RRL. Hence both partially-worn and fully-worn conditions would result in severe wear damage and a substantial increase in wear rates.

f). Under these adverse contact conditions, the relatively low wear resistance of current wheel and rail material was unable to combat or control the high rate of wear.

g). Once lubrication of the sharper curves was implemented in early 2016, wear rates would be expected to decrease, although the effectiveness of the lubricant would have been compromised by the high-wearing profile combination and the rough surfaces which were generated previously. Lubrication would be expected to become more effective (i.e. the lubricant would be expected to perform for a longer period) as the surface roughness levels decreased.

8.6 REDUCING AND CONTROLLING WEAR

A number of strategies can be used to reduce or control wheel and rail wear on the V/Line network; these are based on the following:

- Application of friction management products.
- Use of wheel and rail materials of higher hardness (and hence wear resistance).
- Wheel-rail interface management plan.

- Re-alignment of the track in the tight curves, including adjusting the cant of these curves to suit the typical operating speeds.
- Improving the curving behaviour of the VLocity bogie.

8.6.1 Friction Management

i. Application of rail curve lubricants containing extreme pressure (EP) additives such as molybdenum disulphide (MoS_2) or graphite is by far the most effective approach to mitigating wheel wear, and the one that can be implemented the most readily. However manual application of these products is not sustainable in the longer term, and an alternative approach needs to be identified and implemented.

ii. Simulation results show that the benefit of flange lubrication is realised in curves below 600 m radius, but more significantly in curves of 400 m radius and below.

iii. In addition to noise control, the benefit of TOR Friction Management is a reduction in corrugation development of around 37% in the sharpest curves (R180 m).

iv. The combined benefits of improved rail material and the use of TOR Friction Management on corrugation development was also examined. Simulation results show that by using head hardened rail in conjunction with TOR Friction Management, corrugation development in the low rail could be expected to reduce by around 60% from the current level.

v. Identification of the most appropriate friction management strategy needs to take into consideration the following:

   - Are management of friction levels on the running surface of one or both rails in these curves required?
   - What are the most suitable product(s)?
   - The intended method of application, which could be using track-mounted lubricators, or vehicle mounted systems which apply lubricant either to the wheel flange or directly to the rail gauge face.
   - For either type of application system, correct adjustment and ongoing inspection and maintenance is necessary to ensure that optimum lubricant levels are maintained, with less wastage and contamination of rolling stock and track, and to ensure that the running surface of the rail is not contaminated.
   - The range of curve radii in which lubrication should be applied.
   - Establishing the correct lubricant application rates, taking into consideration variations in surface roughness of wheels and rails.
   - Monitoring of lubrication effectiveness.

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vi. In conjunction with implementation of an ongoing friction management strategy, reducing the surface roughness on the as-machined VLocity wheels to match that on the as-supplied (new) wheels should increase the effectiveness of any lubricant which is applied to the gauge face of the high rail in the sharper curves.

8.6.2 Wheel and Rail Materials

i. Although the wear performance of wheel and rail materials currently used by V/Line has previously been considered satisfactory, as reflected in the VLocity wheel wear rates prior to introduction of the RRL services in mid-2015. However the use of material grades which provide increased wear resistance should be considered.

ii. Wear rates in wheel and rail materials decrease with increasing material hardness or strength. Hence replacement of the existing material grades (for both wheels and rails) would be expected to provide a reduction in wear rates through two related factors:

   a. For any particular combination of wheel and rail profiles, wear rates will reduce in line with the increase in material hardness

   b. The optimum profile combination would be retained for a longer service period.

8.6.3 Wheel-Rail Interface Management Plan

Given the changes to the current V/Line operating environment and likely on-going need for regular rail profiling works in certain areas, it is recommended that a wheel-rail interface management review be undertaken to:

- Examine the suitability of current wheel and rail profiles and if appropriate, identify revisions to help improve wheel/rail contact conditions on the V/Line network.
- Develop a comprehensive network wide wheel-rail interface management plan.

8.6.4 Track Alignment

One of the main contributing factors pertaining to the current wear issue is the introduction of a number of very tight curves into the operating environment.

The easing of sharp curves along the RRL section would significantly reduce wear and the need for on-going control measures. It is acknowledged, however, that the cost of such an undertaking would be very high.

At the very least, however, the easing of the NMFO curves, and any other curves below 300 m radius, should be considered since this would significantly improve the longer term wear performance and efficiency of the V/Line operation.

8.6.5 VLOCITY BOGIE MODIFICATION

Another key contributing factor pertaining to the current wear issue is the limited ability of the VLocity vehicles to steer around the sharp curves on the RRL track. This is due to the high primary suspension stiffness of the VLocity bogies that were designed for stability and ride quality at high speeds.

While the current wear issue does not stem from problems with the VLocity design, further investigation could be undertaken to determine whether modifications could be made to improve curving performance without detriment to high speed stability and ride quality.

Should modification be possible, however, it is likely to be a costly exercise and the need for a change in bogie design would need to be reassessed following the implementation of other control measures noted above. Whilst still an option, the modification of bogie stiffness is not the preferred option at this stage.

9 RECOMMENDATIONS

Of the various options outlined in Section 8 above to reduce wheel (and rail) wear rates, the following are recommended in order to provide a long-term improvement.

9.1 Friction Management

i. Implementation of a more suitable method of applying lubrication to high rails in the sharper curves, as the current method of manual application is not sustainable in the longer term.

ii. The surface roughness on the as-machined VLocity wheels should be reduced (ideally to the same level as present on the as-supplied new wheels) to increase the effectiveness of any lubricant which is applied to the gauge face of the high rail in the sharper curves.

iii. Investigate the benefits and potential risks of using a combination of friction management methods which include application of curve grease to the gauge face of the high rail and a top-of-rail friction modifier (TORFM) to the low rail in the sharper curves.

9.2 Improved Wheel and Rail Materials

i. Replacement of the existing material grades for both wheels and rails to higher (and more wear-resistant) grades should be investigated and the most appropriate grades implemented.

   For wheels, use of the RS8T or R9T grades in the above specification can be considered; this would provide a moderate increase in rim hardness levels to a maximum of 311 HB. Alternatively an AAR Class B grade, with a maximum rim hardness of 341 HB can be considered.

ii. Altering the wheel material grade represents a change to the design specification for the VLocity trains, and hence Bombardier may need to be involved in any proposed changes.

iii. For rails, the options which are considered suitable are the Head hardened grade (nominal hardness 380 HB), or an intermediate strength (~320 HB) grade, noting that the latter may require the use of imported rails.

iv. An assessment of the expected wear versus rolling contact fatigue behaviour of the alternative rail grades should be performed prior to installation of other grades.

9.3 Wheel-Rail Interface Strategy

Initiate a review of wheel-rail interface management on the V/Line network to:

a) Examine the suitability of current wheel and rail profiles and (where required) identify revisions to help improve wheel/rail contact conditions.

b) Develop a comprehensive network wide wheel-rail interface management plan.

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9.4 Revise Track Alignment

Investigate the feasibility of easing the sharp curves along the RRL section, in particular the NMFO and any other sharp curves below 300 m radius, which would significantly reduce wear and the need for on-going control measures.

9.5 Modify VLocity Bogie Design

While not a preferred option, there is scope to investigate the feasibility of altering the primary suspension characteristics of the VLocity in order to improve curving performance. However, the need for a change in bogie design should be reassessed following the implementation of some of the other control measures noted above.

10 REFERENCES

1. D. Welsby, S. Younes & M. Kwong (2016), VLocity Wheel Measurements for V/Line Pty Ltd. Monash University Institute of Railway Technology Report No: Monash/RT/2016/1132, January.
2. P. Mutton, D. Welsby, S. Younes & M. Kwong (2016), VLocity Wheel Wear Investigation for V/Line Pty Ltd, 2nd Interim Report. Monash University Institute of Railway Technology Report No: Monash/RT/2016/1135, January.
3. D. Welsby, P. Mutton & S. Younes (2016), Review of Changes to Superelevation on the North Melbourne Flyover. Monash University Institute of Railway Technology Report No: Monash/RT/2016/1139, February.
4. D. Welsby, P. Mutton & S. Younes (2016), Impact of Friction on Potential Flange Climb Risk. Monash University Institute of Railway Technology Report No: Monash/RT/2016/1145, February.
5. V/Line Annual Report 2014-2015, V/Line Corporation. https://corporate.vline.com.au/getattachment/cc310c6b-b9a2-4d13-bfdb-83de0c6f60ba/Annual-Report-2014-15. (accessed 22nd February 2016).
6. VLocity, Vicsig Passenger http://vicsig.net/index.php?page=passenger&section=rollingstock&subs=railmotors&rmtype=VLocity (accessed 22nd February 2016).
7. VLocity 160 DMU datasheet, Bombardier Transportation.
8. VLocity P4-8a Bogie Assembly Drawing: 3EER400002-1001 (Power Bogie) & Requirement specification for Primary Traction Rod: 3EER400002-1287 (Traction Rod), Bombardier Transportation. (Supplied on request by Bombardier 21st January 2016).
9. Sprinter, Vicsig Passenger http://vicsig.net/index.php?page=passenger&section=rollingstock&subs=railmotors&rmtype=Sprinter, (accessed 22nd February 2016).
10. Sprinter Facts and Figures, A. Goninan & Co. Limited.
11. Sprinter Bogie General Arrangement Drawing: B50661 & Bogie Pivot Bearing Detail Drawing: D11862, A. Goninan & Co. Limited. (Supplied on request by Bombardier 20th January 2016).
12. N Class, Vicsig Locomotives http://vicsig.net/index.php?page=locomotives&class=N&orgstate=V&type=Diesel-Electric, (accessed 22nd February 2016).
13. ‘N’ Class datasheet, Clyde Engineering.
14. N Cars, Vicsig Passenger http://vicsig.net/index.php?page=passenger&section=rollingstock&subs=railmotors&rmtype=Sprinter, (accessed 22nd February 2016).

15. VLocity Wheel Drawing: 3EER400002-0470, Bombardier Transportation. (Supplied on request by Bombardier 18th January 2016).

16. British Standard BS 5892-3: 1992+A2:2009, Railway rolling stock materials – Part 3: Specification for Monobloc wheels for traction and trailing stock, British Standards Institute, 2009.

17. Wheel Product Data Sheet: RVR13A-200. Comsteel. (Supplied on request by V/Line on 4th February 2016).

18. Portable Tribometer Product Sheet, LB Foster Salient Systems. http://www.lbfoster-salientsystems.com/pdf/Tribometer_Product_sheet_screen.pdf (accessed 28th February 2016).

19. VLocity Wheel Specifications, Bombardier Transportation, 2007.

20. Inspection and Assessment of Rail – External Document: NIPR 2703, V/Line. (Supplied by on request by V/Line 20th January 2016).

21. Department of Transport and Regional Services, Code of Practice for the Defined Interstate Rail Network, Commonwealth of Australia, Canberra, 2003.

22. Grassie, S.L. (2004), Wheel/Rail Interaction and Rail Grinding Strategy for Regional Fast Rail Project, (revised Draft), March.

23. Epp, K. (2005), Tight Gauge Compensation for Regional Fast Rail Project, Monash University Institute of Railway Technology Report No: Monash/RT/2005/192, May.

24. McEwen I. J. and Harvey R. F (1986), Wheel/Rail wear & Lubrication – Laboratory studies and their relevance to field situations. Proceedings of the International Symposium of Contact Mechanics and Wear of Rail/Wheel Systems.

25. Regional Rail Link Detailed Track Plan Drawings: SSS_C0862 to C0864, VicTrack. (Supplied on request by V/Line 20th January 2016).

26. Regional Rail Link Longitudinal Section Drawings: SSS_0869 to SSS_0875 & SPJ_C0071 to SPJ_0088, VicTrack. (Supplied on request by V/Line 5th February 2016).

27. S. Thomas, D. Welsby & S. Younes (2014), Measurement of Rail Friction Following Application of “Tramsilence” Product on the North Melbourne Flyover. Monash University Institute of Railway Technology Report No: Monash/RT/2014/908, February.

28. Bolton P. J. and Clayton P. (1984), Rolling-sliding wear damage in rail and tyre steels, Wear Volume 93, Issue 2, pages 145-165.

29. Danks D. and Clayton P. (1987), Comparison of the wear process for eutectoid rail steels: Field and laboratory tests, Wear 120, Issue 2, Pages 233-250.

30. Mutton P. J. (1985), The influence of microstructure on the wear behaviour of rail and wheel materials, M.App.Sc. thesis, University of Melbourne.

31. Magel, E. (2011), Rolling Contact Fatigue A Comprehensive Review, Federal Railroad Administration, Washington DC.

32. Mutton P. J. and Epp C. J. (1983), Factors influencing rail and wheel wear, Proc. Railway Engineering Symposium, IEAust, Melbourne.

33. Mutton P. J., Boelen R. and Marich S. (1986), Requirements for wheel and rail materials, Proc. 6th Int. Rail Track Conf., Rail Track Association, Melbourne.

34. Verbeek, H. (1973), Present knowledge of adhesion and its utilization, Rail International, June.

35. Jönsson, P. (2007), Dynamic performance of freight wagons and their influence on cost for track deterioration, Presentation at Elmia Nordic Rail Conference, Jönköping, Sweden; Oct. 9-11.

36. Liddle G. (2016), Presentation to the Victorian Government Standing Committee on the economy and infrastructure, 9 February 2016, http://www.parliament.vic.gov.au/images/stories/committees/SCEI/Infrastructure/Vline_Metro_PTV_presentation_9_Feb_216.pdf (accessed 7th March 2016).

37. Email to D. Welsby regarding V/Line track measurements & data, V/Line, 20th January 2016.

38. Manual of Standards and Recommended Practices, Section G - Wheels and Axles, Specifications M-107M-208 (2010), Association of American Railroads

39. European Standard EN1 13674-1, Railway applications – Track – Rail – Part 1: Vignole railway rails 46 kg/m and above.

APPENDIX A

SUMMARY OF MEASUREMENTS

TABLE A1: LIST OF INSPECTED ROLLING STOCK

Car No.	Set No.	Date Inspected	Location	Stock	Manufacturer	Date In Service
1118	VL18	16/01/2016	Newport Workshops	VLocity DMU	Bombardier Transportation	22/10/2005
1218	VL18	16/01/2016	Newport Workshops	VLocity DMU	Bombardier Transportation	22/10/2005
1142	VL42	17/01/2016	Newport Workshops	VLocity DMU	Bombardier Transportation	23/06/2010
1342	VL42	17/01/2016	Newport Workshops	VLocity DMU	Bombardier Transportation	23/06/2010
1242	VL42	17/01/2016	Newport Workshops	VLocity DMU	Bombardier Transportation	23/06/2010
1124	VL24	19/01/2015	Newport Workshops	VLocity DMU	Bombardier Transportation	25/02/2006
1324	VL24	19/01/2015	Newport Workshops	VLocity DMU	Bombardier Transportation	25/02/2006
1157	VL57	19/01/2015	West Melbourne Depot	VLocity DMU	Bombardier Transportation	04/05/2015
1357	VL57	19/01/2015	West Melbourne Depot	VLocity DMU	Bombardier Transportation	04/05/2015
1257	VL57	19/01/2015	West Melbourne Depot	VLocity DMU	Bombardier Transportation	04/05/2015
ACN54	N18	19/01/2015	West Melbourne Depot	N Type Coach	Victorian Railways	09/09/1984
BRN52	N18	19/01/2015	West Melbourne Depot	N Type Coach	Victorian Railways	09/09/1983
BN1	N18	19/01/2015	West Melbourne Depot	N Type Coach	Victorian Railways	16/09/1981
N452	-	19/01/2015	West Melbourne Depot	N Class Locomotive	Clyde Engineering	10/10/1985
N459	-	21/01/2015	West Melbourne Depot	N Class Locomotive	Clyde Engineering	15/04/1986
7008	-	21/01/2015	West Melbourne Depot	Sprinter DMU	A Goninan & Co.	20/07/1994

TABLE A2: LIST OF INSPECTED TRACK LOCATIONS

Measurement Point (m)	Track	Line	Location	Curve Radius (m)	Applied Cant (mm)	Curve Length (m)	Measured Gauge (mm)	Curve Speed (km/h)	Date Inspected
1352.2	Up	SCS (Flyover) – Spion kop	North Melbourne	180	40	139	1608	40	05/02/2016
1362	Up	SCS (Flyover) – Spion kop	North Melbourne	180	40	139	1620	40	05/02/2016
1398.7	Up	SCS (Flyover) – Spion kop	North Melbourne	180	40	139	1622	40	05/02/2016
1398.7	Down	SCS (Flyover) – Spion kop	North Melbourne	180	40	139	1614	40	05/02/2016
1577.2	Up	SCS (Flyover) – Spion kop	North Melbourne	181	40	122	1616	40	05/02/2016
1577.2	Down	SCS (Flyover) – Spion kop	North Melbourne	185	40	125	1614	40	05/02/2016
1769.7	Up	SCS (Flyover) – Spion kop	North Melbourne	180.1	40	112	1615	40	05/02/2016
1769.7	Down	SCS (Flyover) – Spion kop	North Melbourne	180.1	40	110	1614	40	05/02/2016
1909	Up	SCS (Flyover) – Spion kop	North Melbourne	400	30	147	1616	35	05/02/2016
1909	Down	SCS (Flyover) – Spion kop	North Melbourne	180.5	40	144	1618	40	05/02/2016
2180	Up	SCS (Flyover) – Spion kop	North Melbourne	396	30	174	1606	40	05/02/2016
2180	Down	SCS (Flyover) – Spion kop	North Melbourne	400	30	175	1607	40	05/02/2016
2350	Up	SCS (Flyover) – Spion kop	North Melbourne	380	40	86	1609	40	05/02/2016
2350	Down	SCS (Flyover) – Spion kop	North Melbourne	400	40	94	1610	40	05/02/2016
5000	Up	SCS (Plat. 5-16) – Sunshine	Footscray	1104	30	321	1600	80	05/02/2016
5000	Down	SCS (Plat. 5-16) – Sunshine	Footscray	1100	30	327	1604	80	05/02/2016
5200	Up	SCS (Plat. 5-16) – Sunshine	Footscray	522	80	150	1606	80	05/02/2016
5200	Down	SCS (Plat. 5-16) – Sunshine	Footscray	518	80	150	1606	80	05/02/2016
5500	Up	SCS (Plat. 5-16) – Sunshine	Footscray	840	0	155	1605	70	05/02/2016
5500	Down	SCS (Plat. 5-16) – Sunshine	Footscray	844	0	155	1606	70	05/02/2016
5757	Up	SCS (Plat. 5-16) – Sunshine	Footscray	510	80	177	1605	80	05/02/2016
5757	Down	SCS (Plat. 5-16) – Sunshine	Footscray	514	80	177	1609	80	05/02/2016
11700	Up	SCS (Plat. 5-16) – Sunshine	Sunshine	650	80	263	1605	130	05/02/2016

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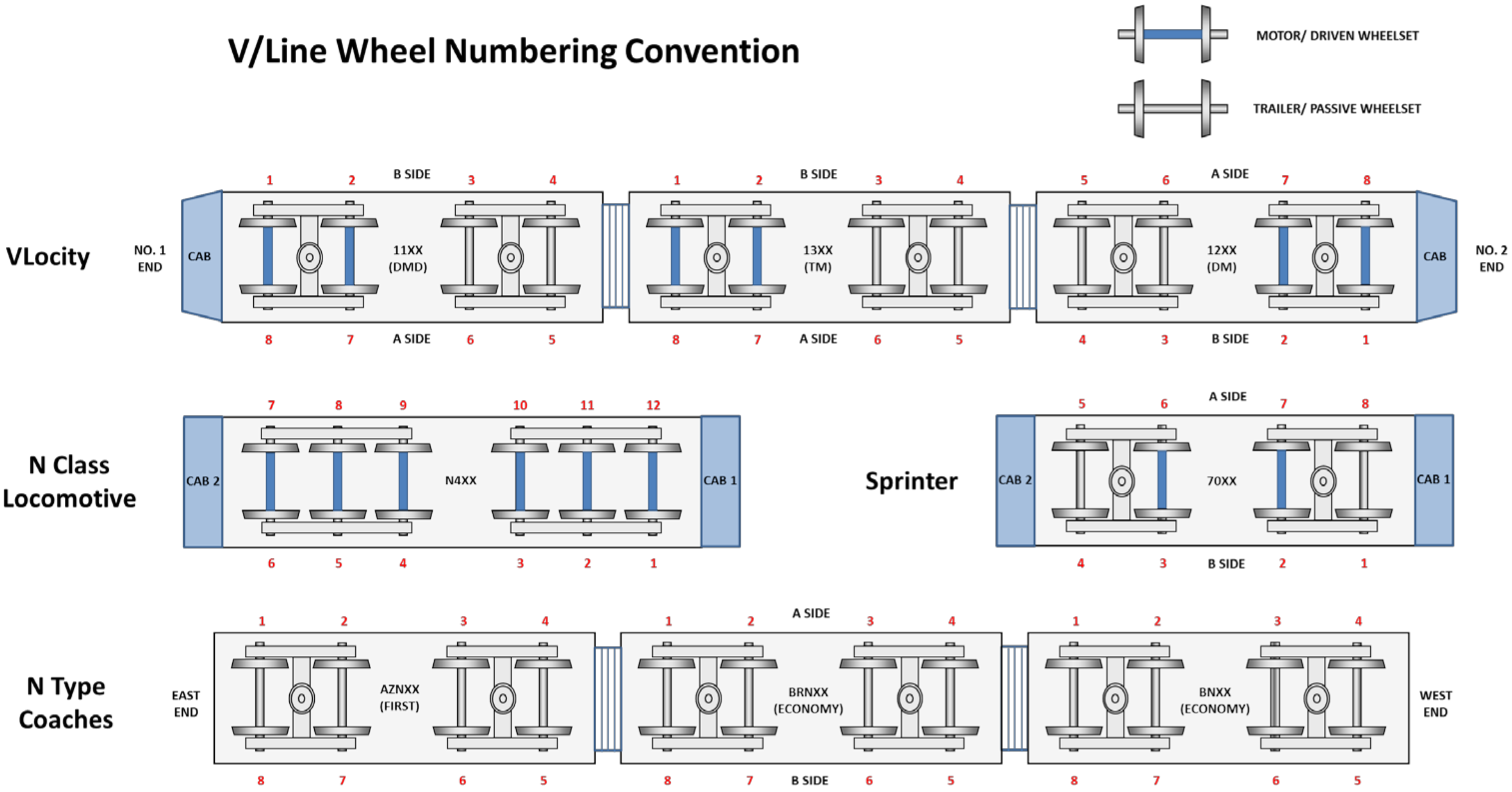
Measurement Point (m)	Track	Line	Location	Curve Radius (m)	Applied Cant (mm)	Curve Length (m)	Measured Gauge (mm)	Curve Speed (km/h)	Date Inspected
11700	Down	SCS (Plat. 5-16) – Sunshine	Sunshine	625	80	249	1607	130	05/02/2016
12500	South	Sunshine – Ballarat	Sunshine	250	40	238	1614	40	05/02/2016
12500	North	Sunshine – Ballarat	Sunshine	254	40	238	1616	40	05/02/2016
19650	Up	Deer Park – Manor Junction	Deer Park West	455	40	327	1608	65	06/02/2016
19650	Down	Deer Park – Manor Junction	Deer Park West	455	40	60	1608	65	06/02/2016
20350	Up	Deer Park – Manor Junction	Deer Park West	1304	70	1491	1603	115	06/02/2016
20350	Down	Deer Park – Manor Junction	Deer Park West	1300	70	1655	1602	115	06/02/2016
36900	Up	Deer Park – Manor Junction	Wyndham Vale	2000	90	2508	1602	160	06/02/2016
36900	Down	Deer Park – Manor Junction	Wyndham Vale	1995	90	2502	1604	160	06/02/2016
46000	Up	Deer Park – Manor Junction	Manor	2000	90	2104	1605	160	06/02/2016
46000	Down	Deer Park – Manor Junction	Manor	2004	90	2108	1602	160	06/02/2016
56300	Single	Sunshine – Ballarat	Bacchus Marsh	664.43	140	159	1607	115	06/02/2016
57000	Single	Sunshine – Ballarat	Bacchus Marsh	680.7	140	148	1608	115	06/02/2016
58300	Single	Sunshine – Ballarat	Bacchus Marsh	700	140	200	1607	115	06/02/2016

Appendix B

Wheel Identification Convention

V/Line Wheel Numbering Convention



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APPENDIX C

WHEEL WEAR RESULTS

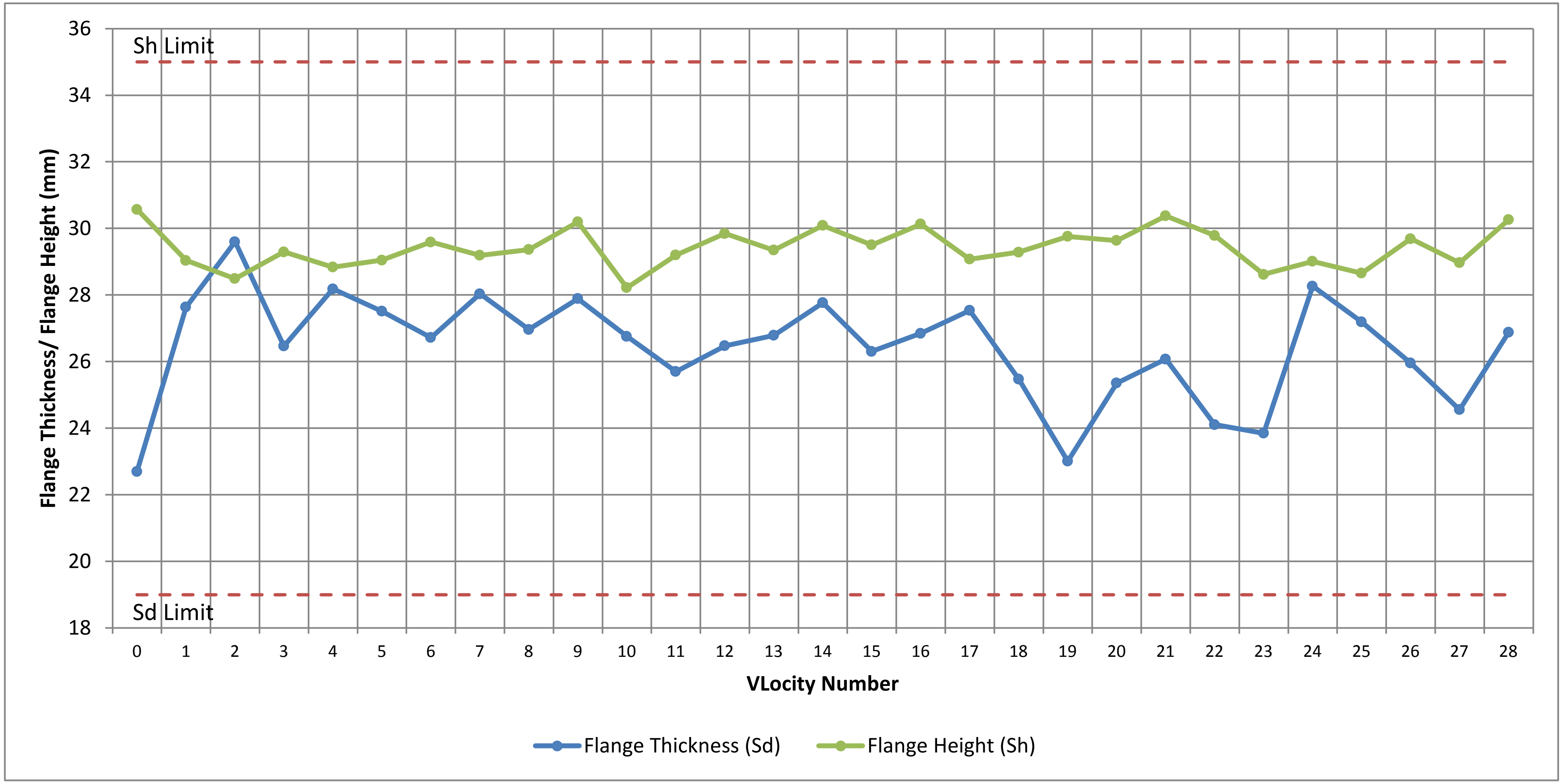

FIGURE C1: VLOCITYFLEET (VL0-VL28) AVERAGE FLANGE THICKNESS AND FLANGE HEIGHT (AS OF LAST INSPECTION, BEFORE 31ST JANUARY 2016)

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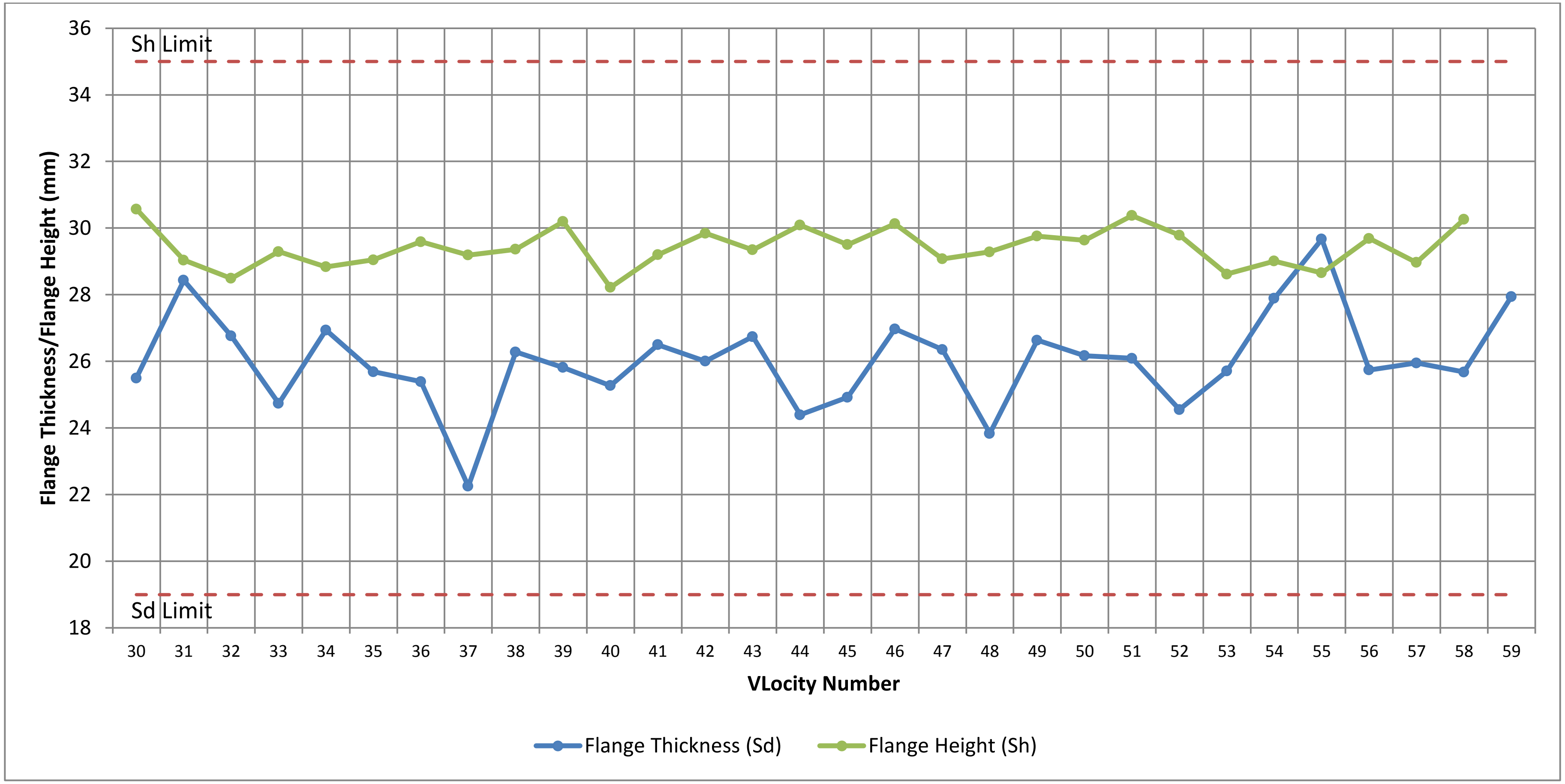

FIGURE C2: VLOCITY FLEET (VL30-VL59) AVERAGE FLANGE THICKNESS AND FLANGE HEIGHT (AS OF LAST INSPECTION, BEFORE 31ST JANUARY 2016)

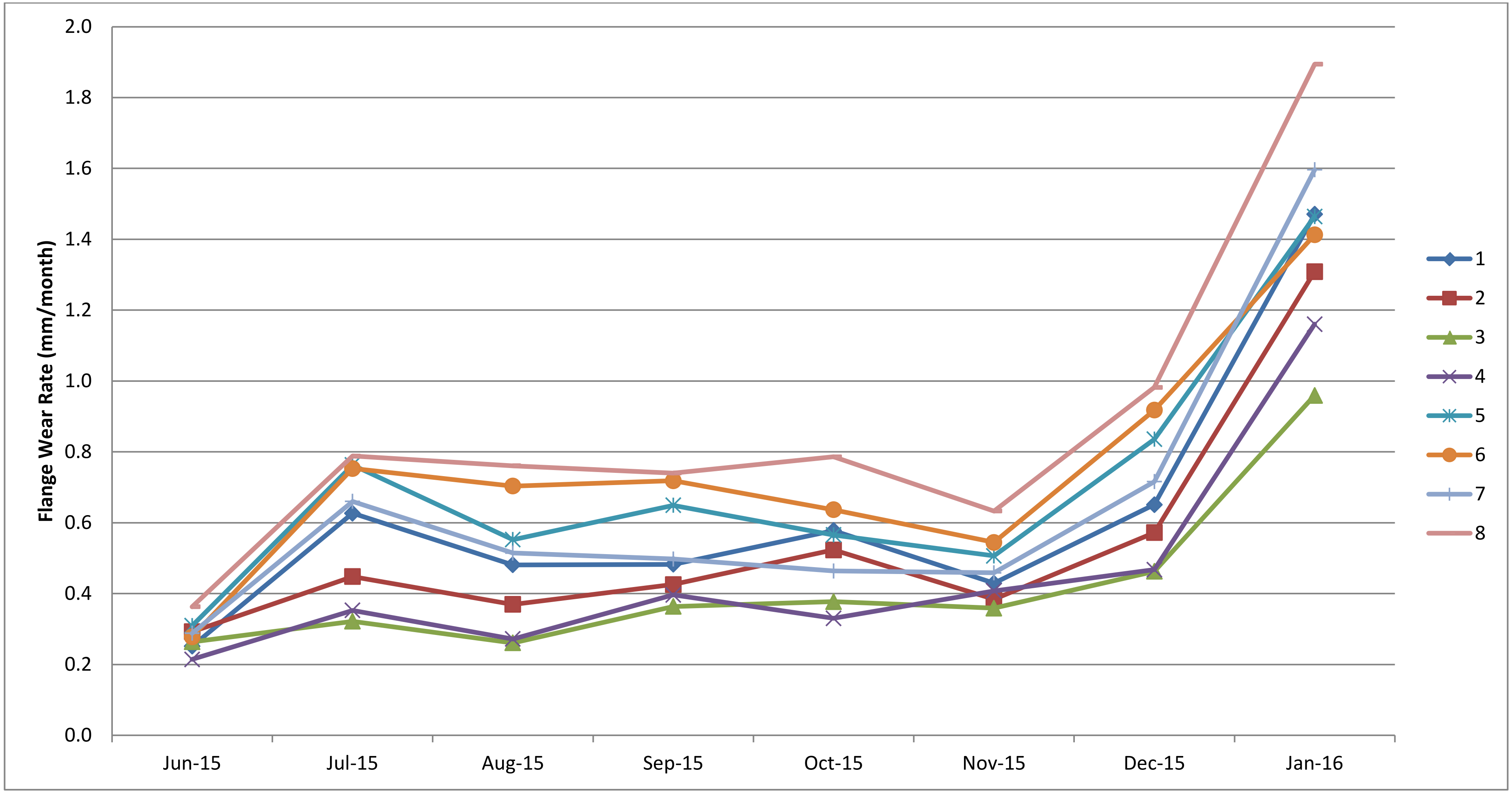

FIGURE C3: FLANGE WEAR RATE MEASUREMENTS FOR ALL WHEELS – 11XX SERIES CAR

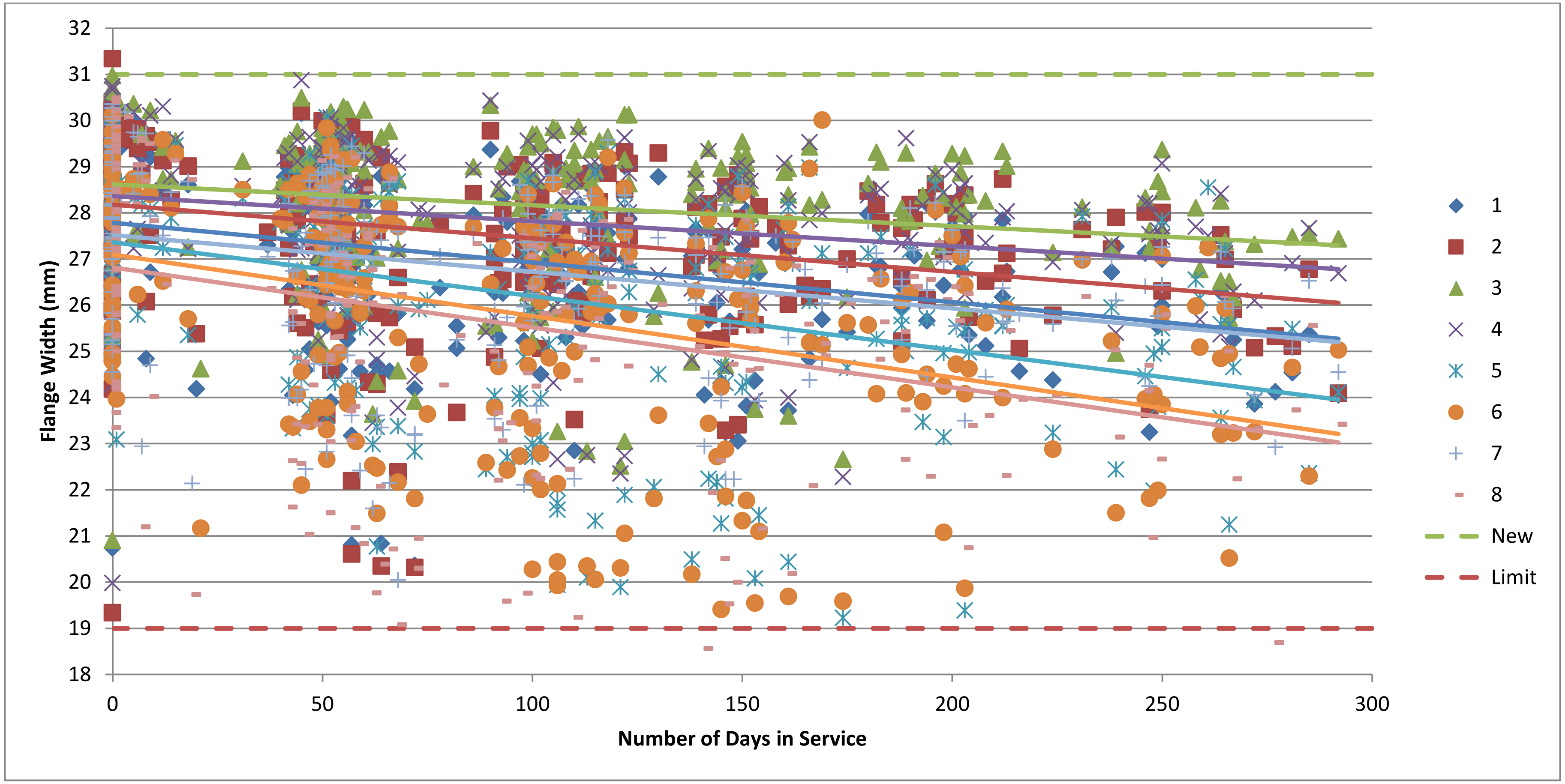

FIGURE C4: FLANGE WIDTH MEASUREMENTS (SD) FOR ALL WHEELS – 11XX SERIES CAR

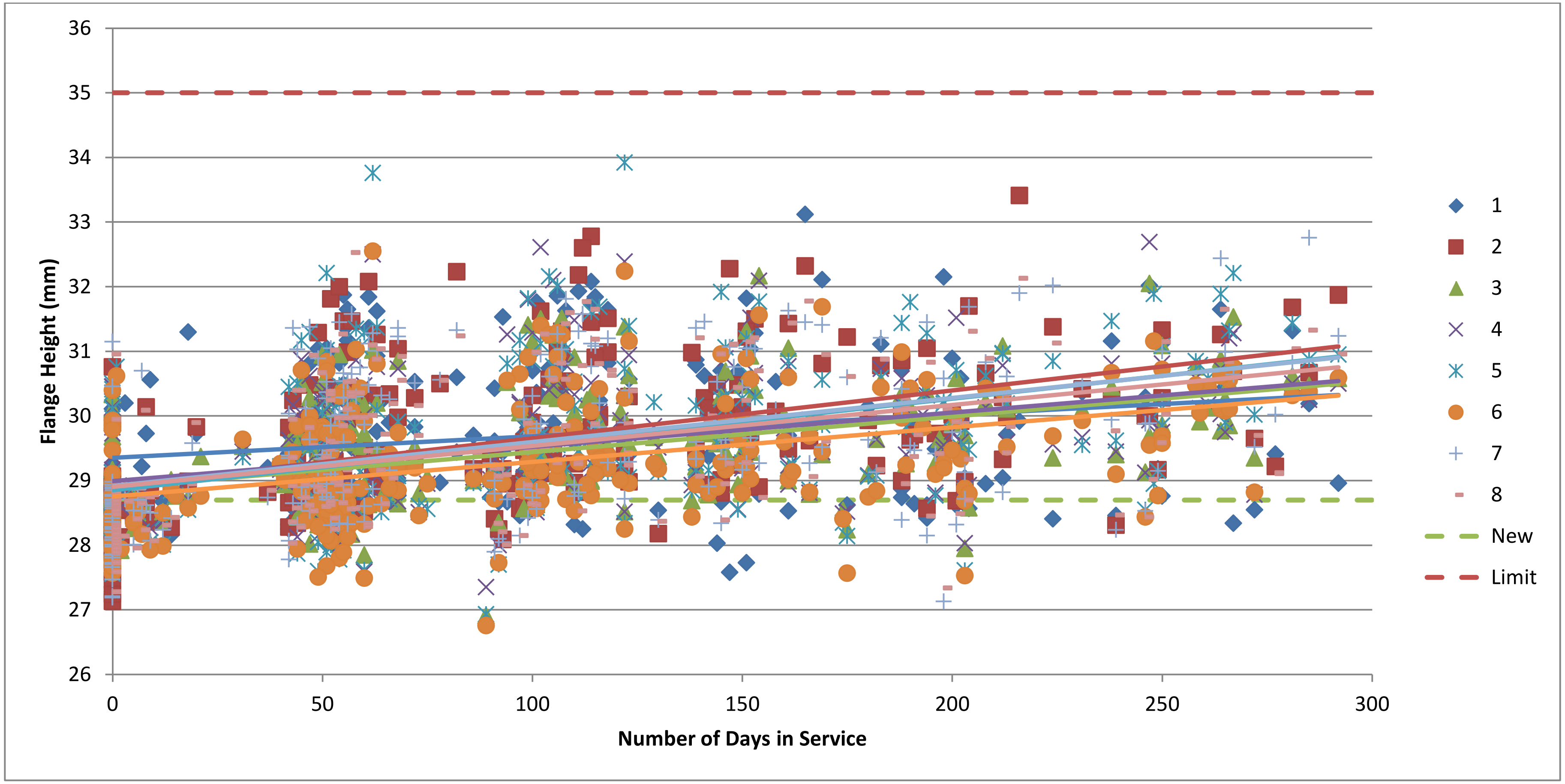

FIGURE C5: FLANGE HEIGHT MEASUREMENTS (SH) FOR ALL WHEELS – 11XX SERIES CAR

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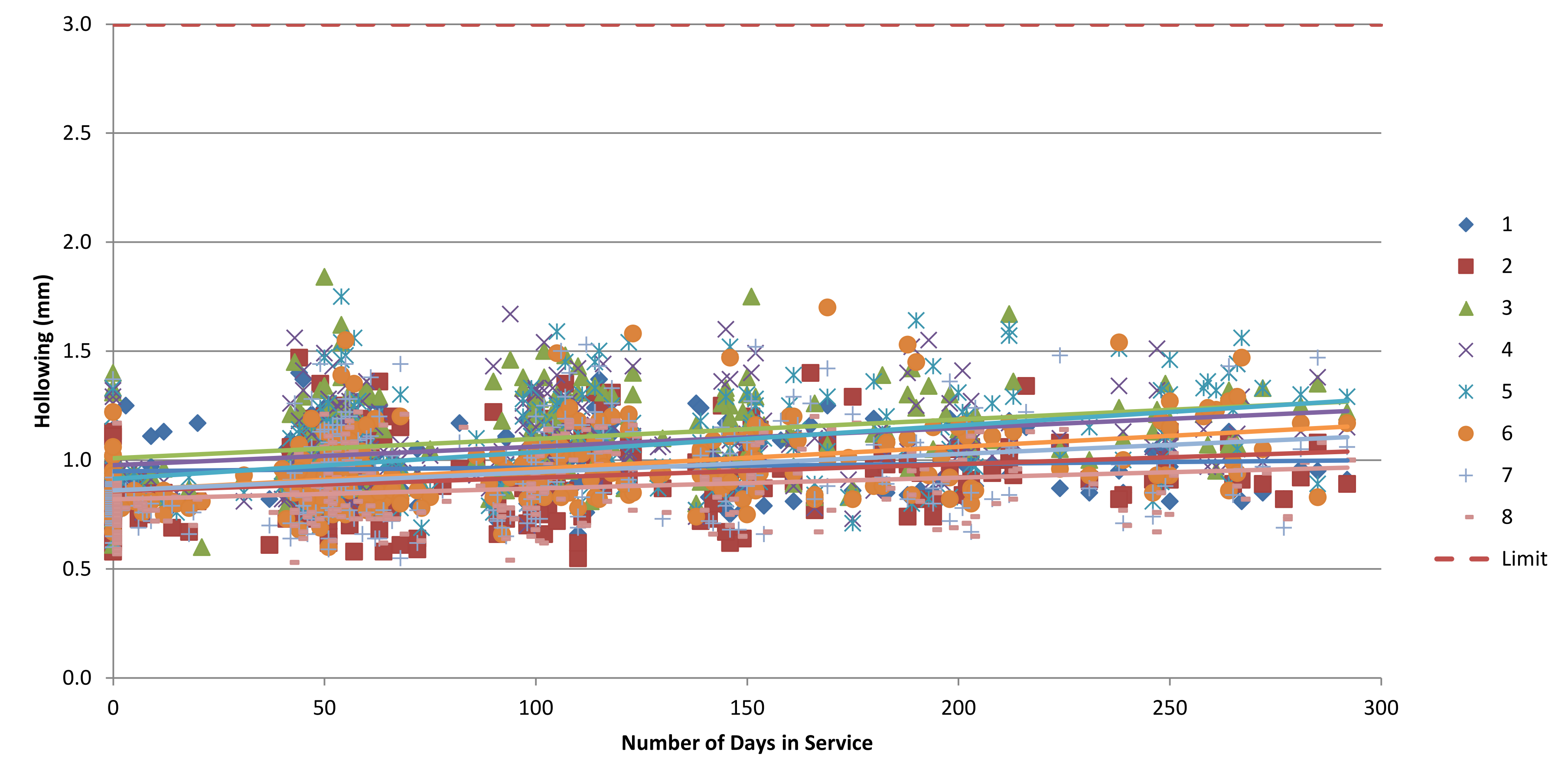

FIGURE C6: WHEEL HOLLOWING MEASUREMENTS FOR ALL WHEELS – 11XX SERIES CAR

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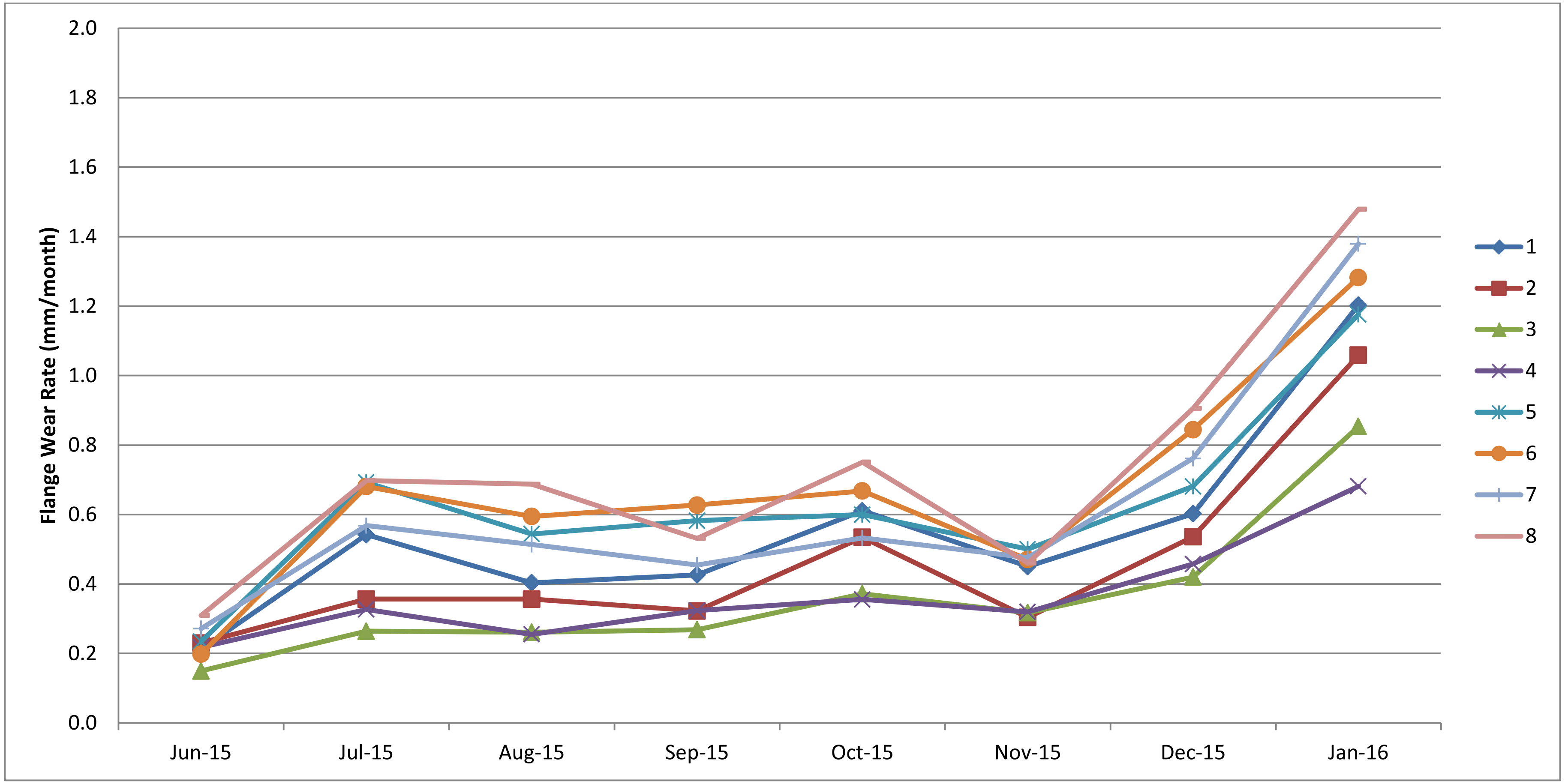

FIGURE C7: FLANGE WEAR RATE MEASUREMENTS FOR ALL WHEELS – 13XX SERIES CAR

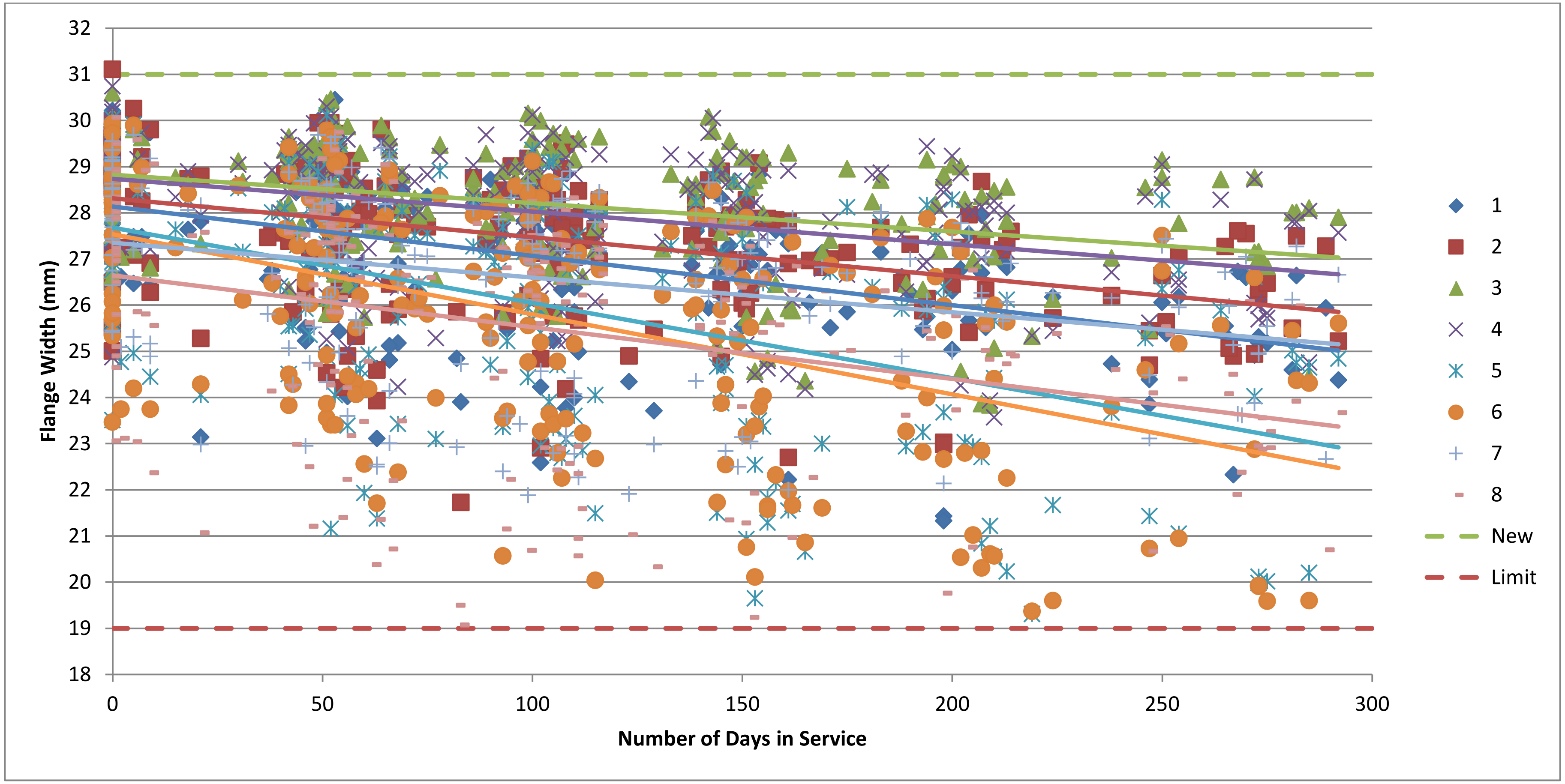

FIGURE C8: FLANGE WIDTH MEASUREMENTS (SD) FOR ALL WHEELS – 13XX SERIES CAR

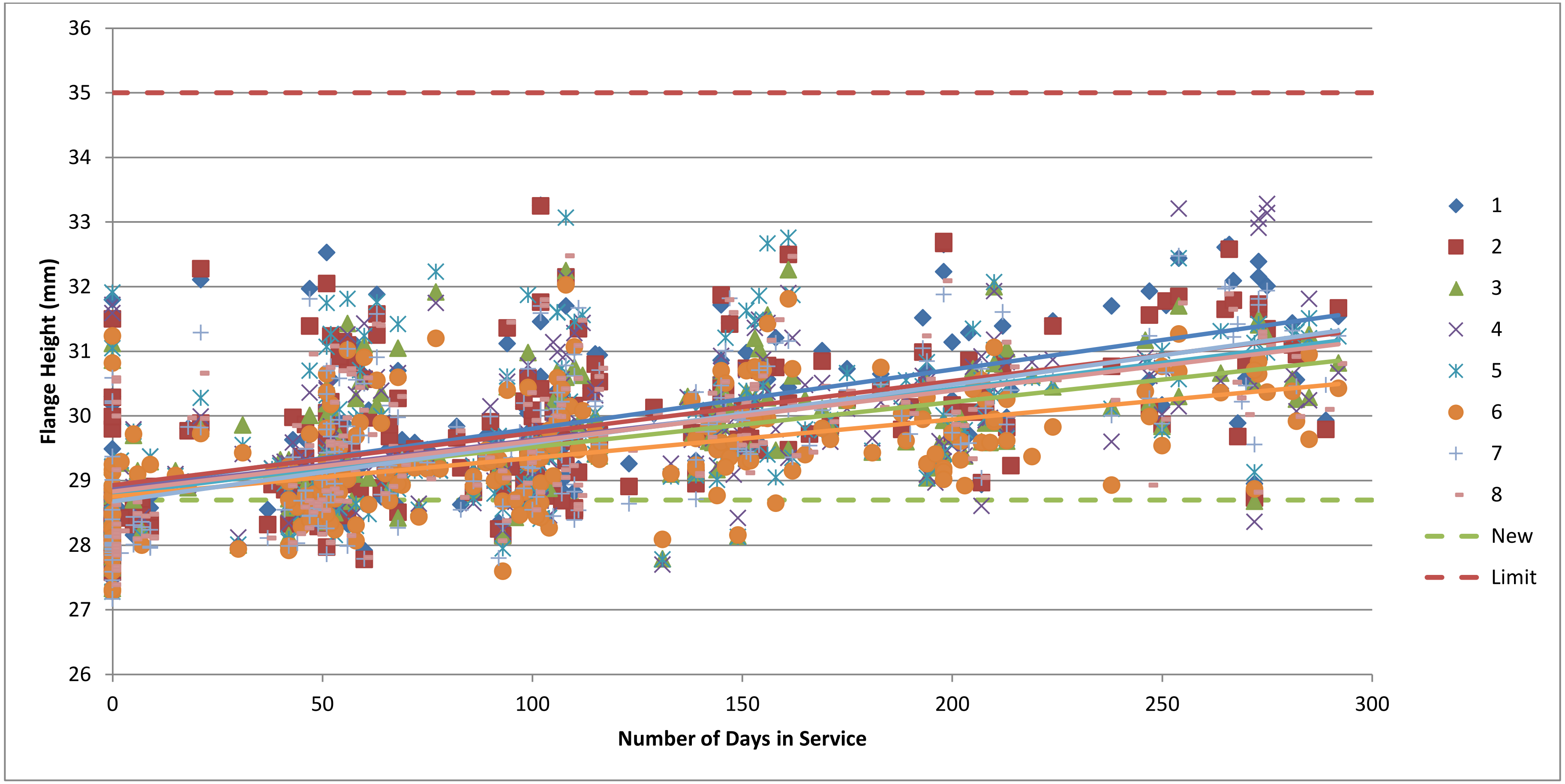

FIGURE C9: FLANGE HEIGHT MEASUREMENTS (SH) FOR ALL WHEELS – 13XX SERIES CAR

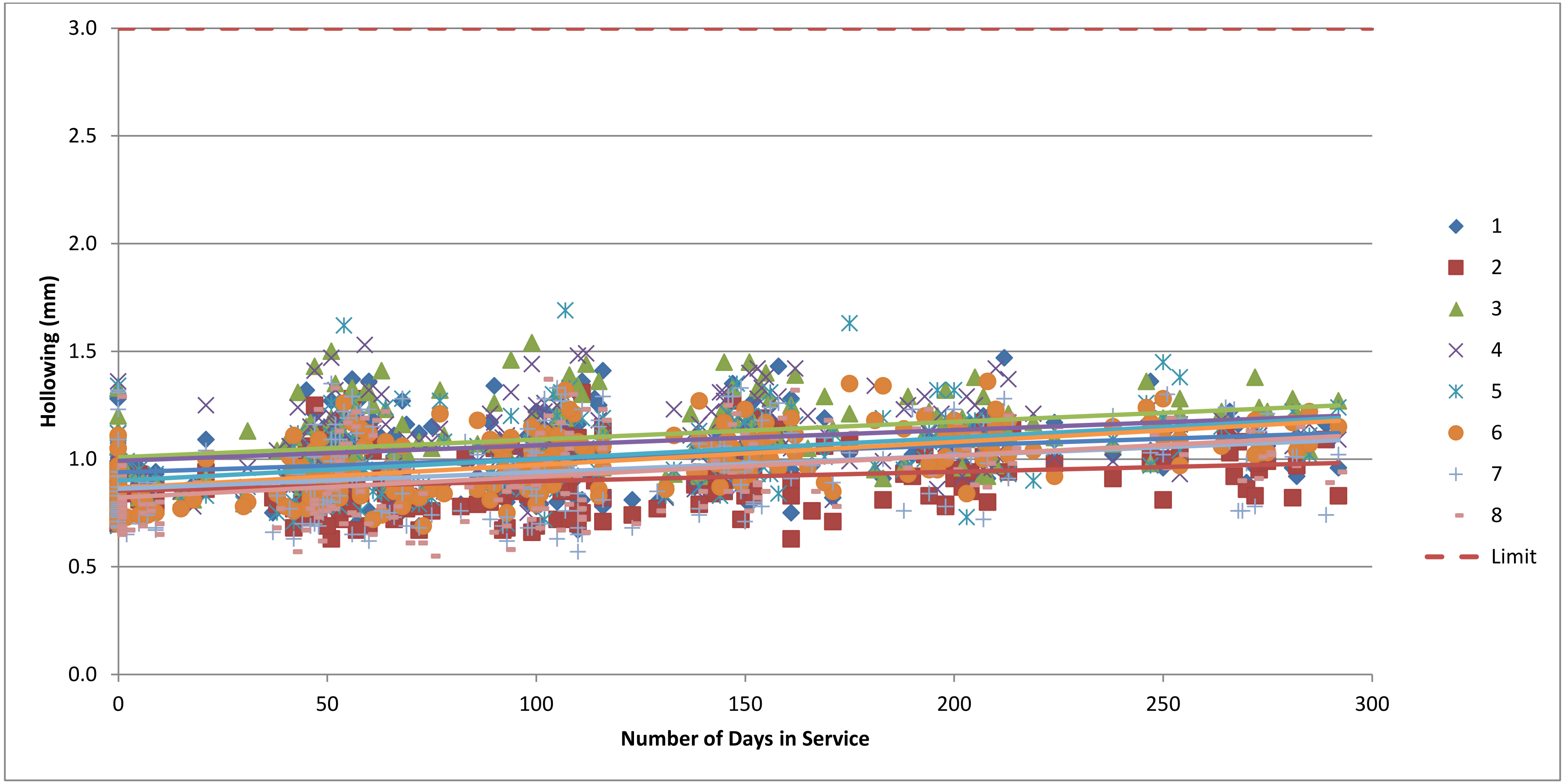

FIGURE C10: WHEEL HOLLOWING MEASUREMENTS FOR ALL WHEELS – 13XX SERIES CAR

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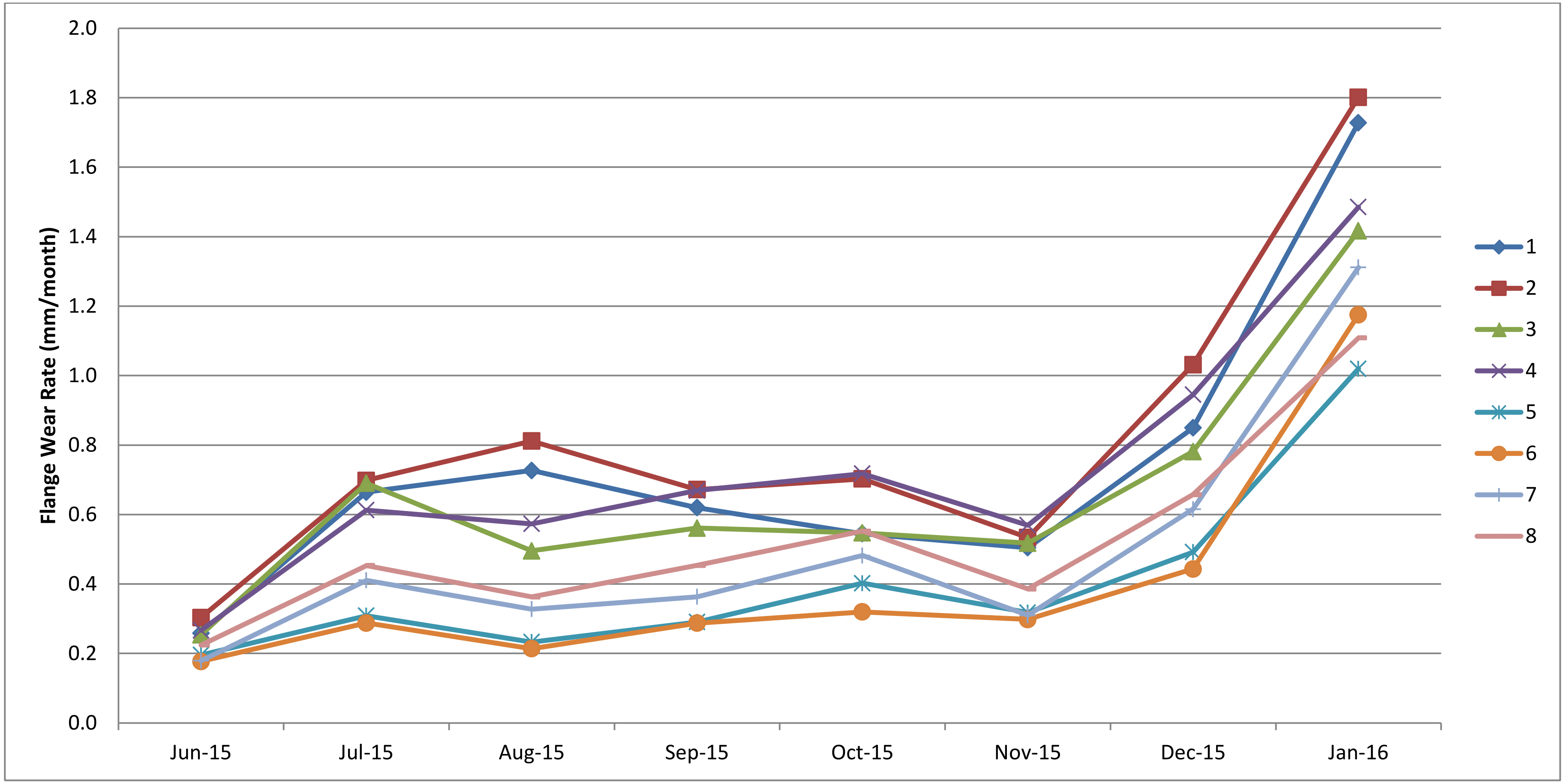

FIGURE C11: FLANGE WEAR RATE MEASUREMENTS FOR ALL WHEELS – 12XX SERIES CAR

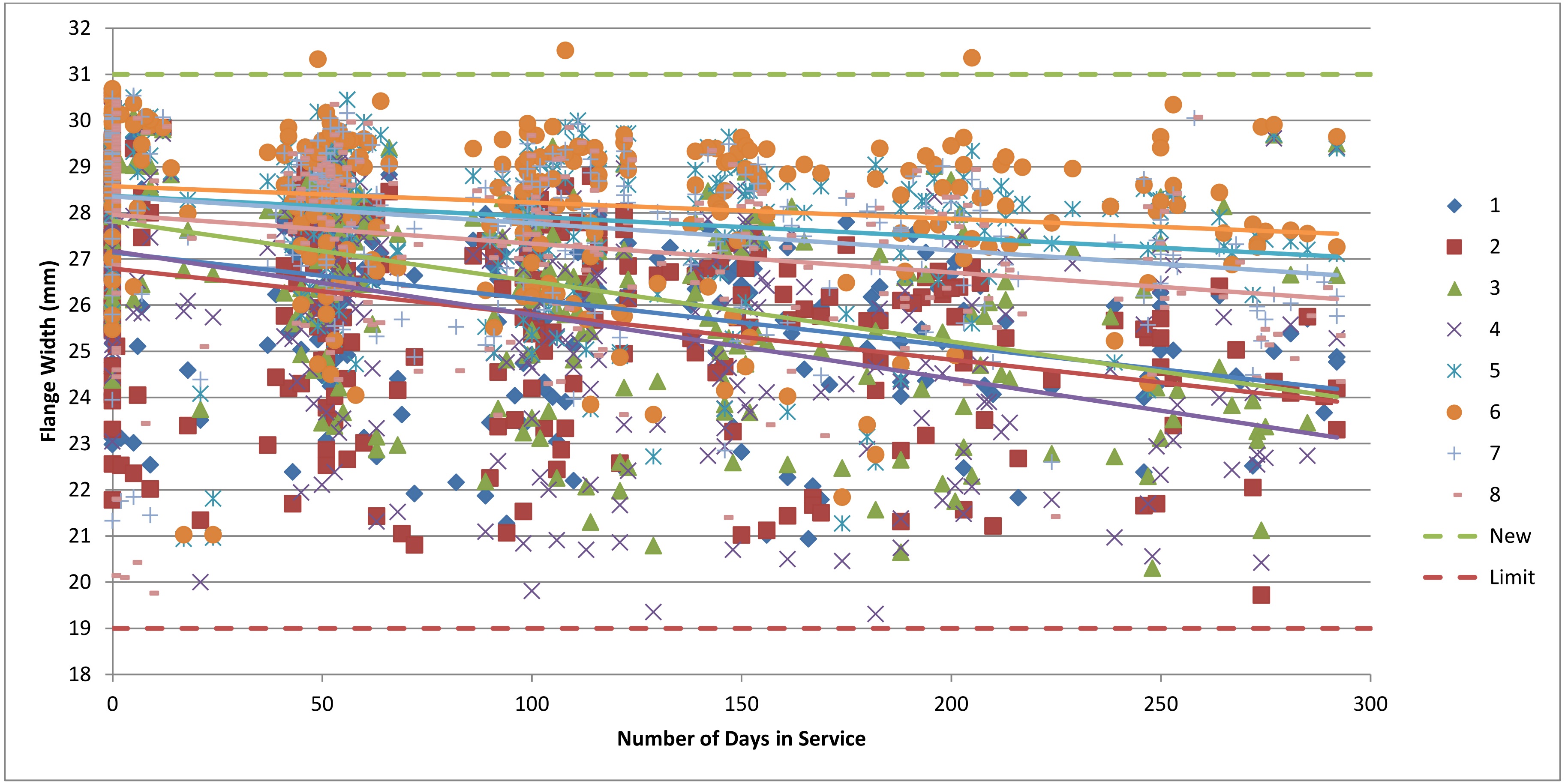

FIGURE C12: FLANGE WIDTH MEASUREMENTS (SD) FOR ALL WHEELS – 12XX SERIES CAR

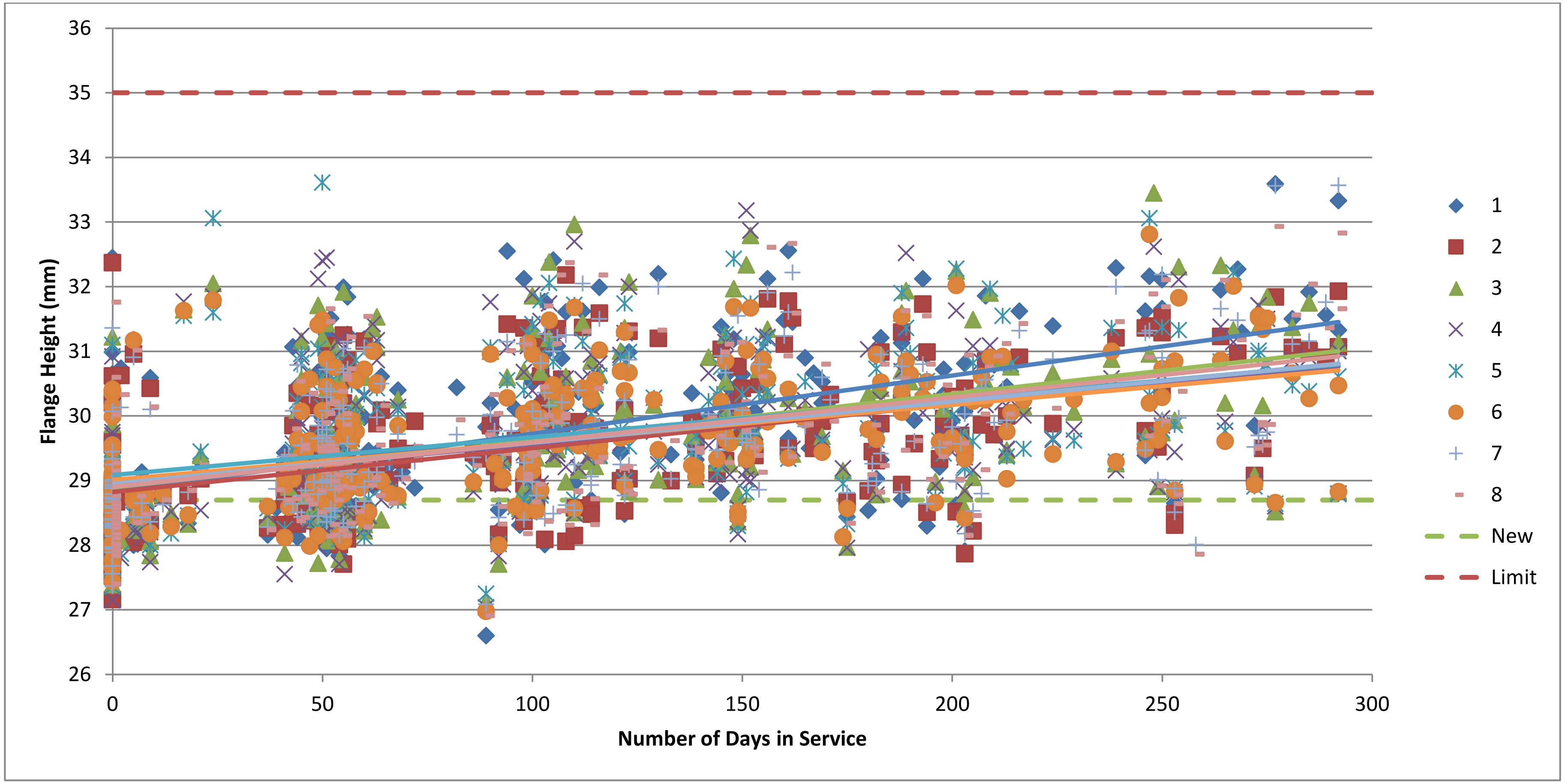

FIGURE C13: FLANGE HEIGHT MEASUREMENTS (SH) FOR ALL WHEELS – 12XX SERIES CAR

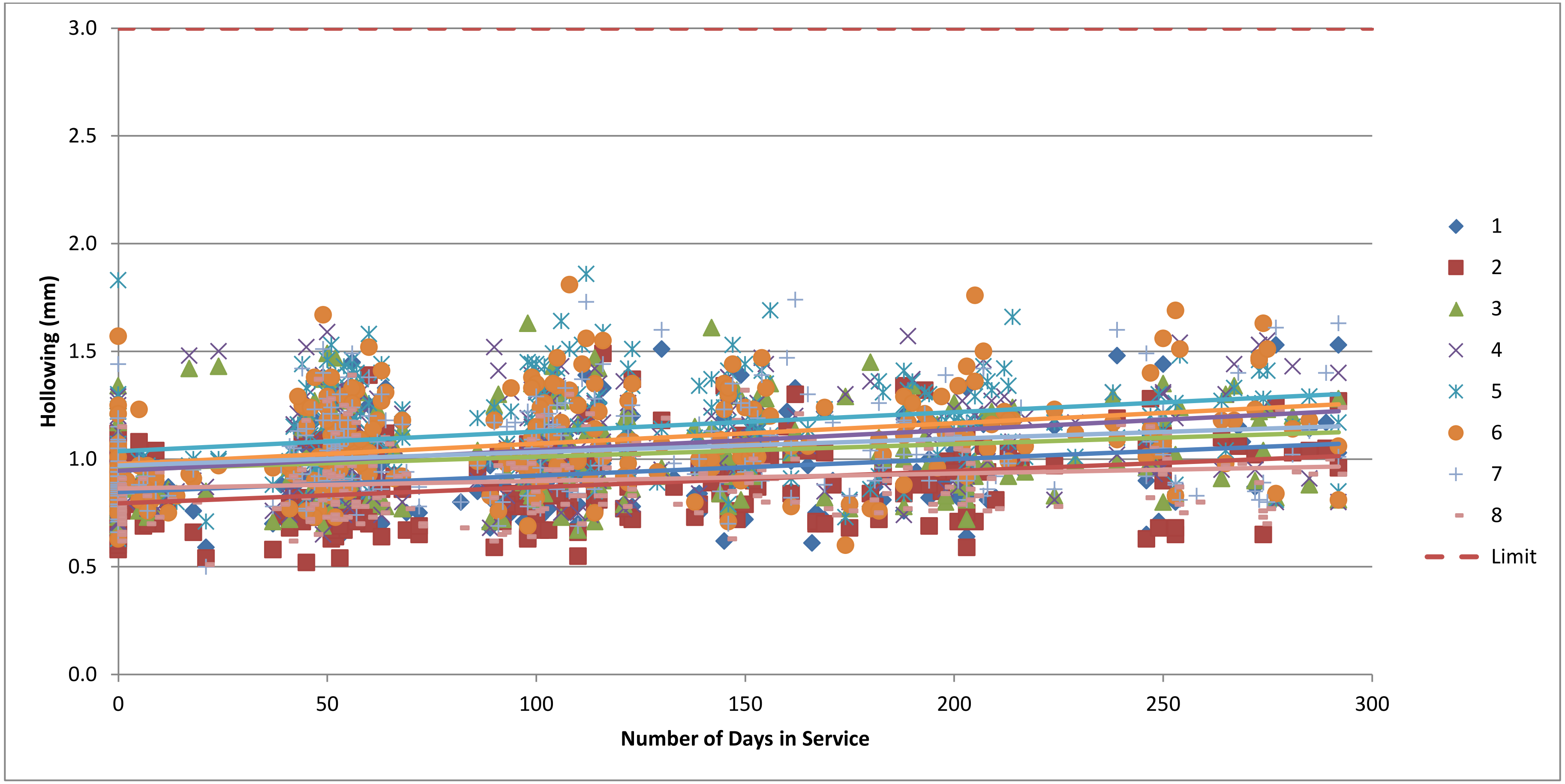

FIGURE C14: WHEEL HOLLOWING MEASUREMENTS FOR ALL WHEELS – 12XX SERIES CAR

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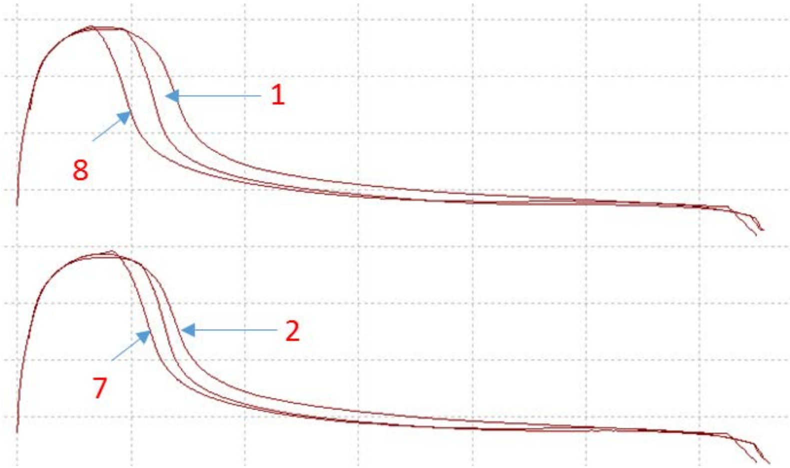
Appendix D

Wheel Inspection Results

<table>
<tr><th colspan="2">CAR NUMBER: 1118</th><th colspan="2">STOCK: VLOCITY DMU</th><th>DATE INSPECTED: 16/01/2016</th></tr>
<tr><td colspan="3" rowspan="2"></td><td>NO IMAGE</td><td>NO IMAGE</td></tr>
<tr><td>NO IMAGE</td><td>NO IMAGE</td></tr>
<tr><td colspan="3">PROFILE OVERLAY (PRE-MACHINING)</td><td colspan="2">SURFACE CONDITION (PRE-MACHINING)</td></tr>
</table>

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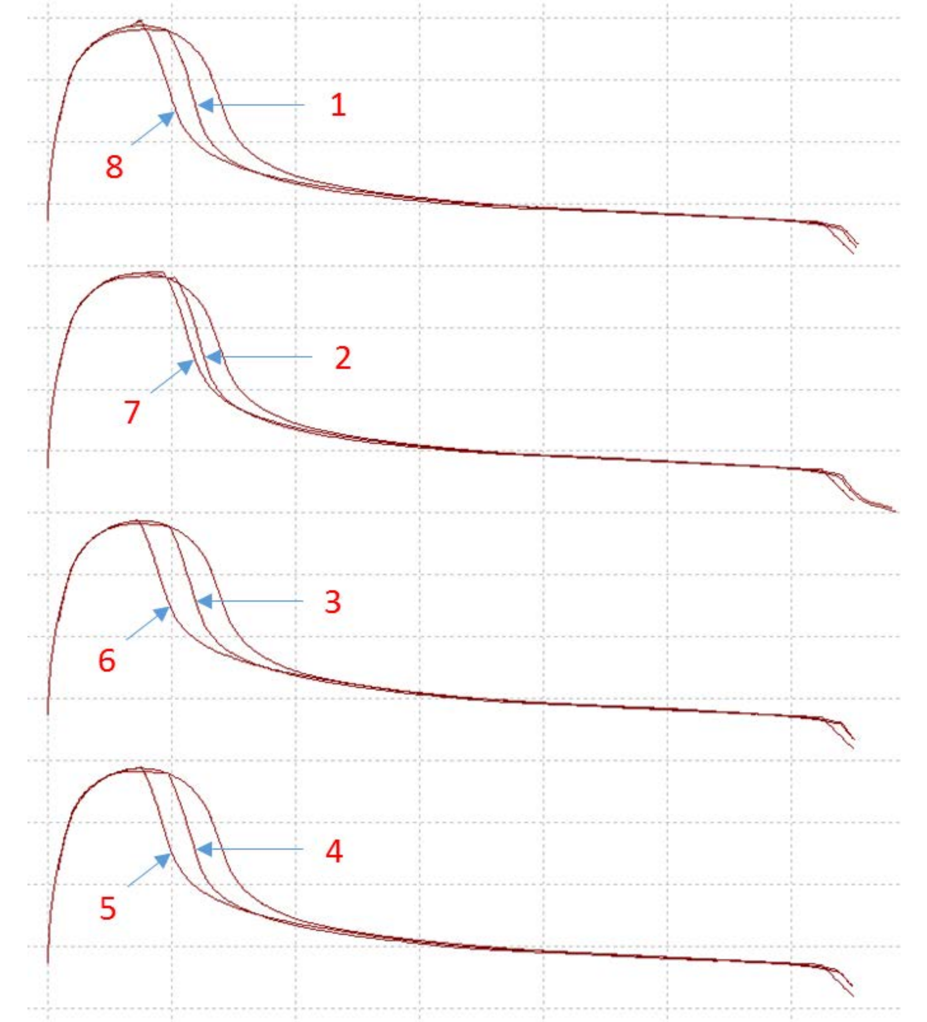
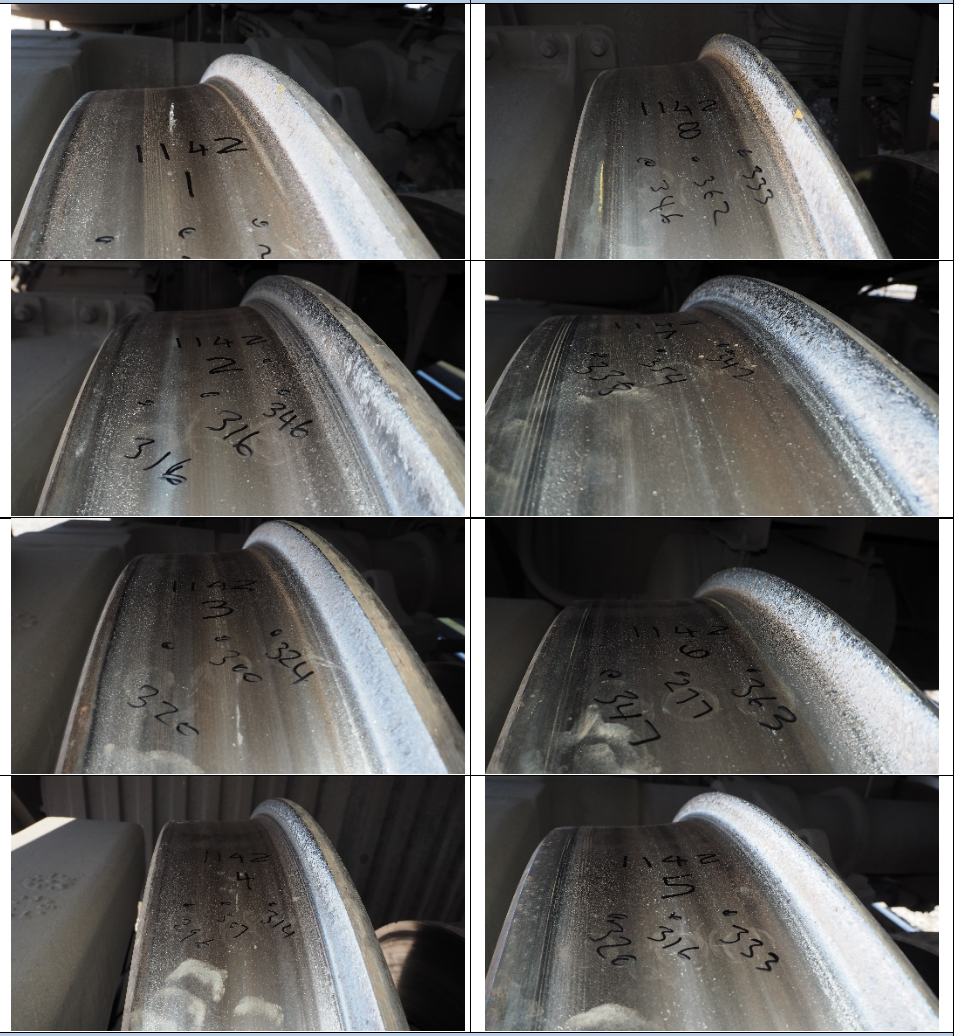
CAR NUMBER: 1142	STOCK: VLOCITY DMU	DATE INSPECTED: 16/01/2016

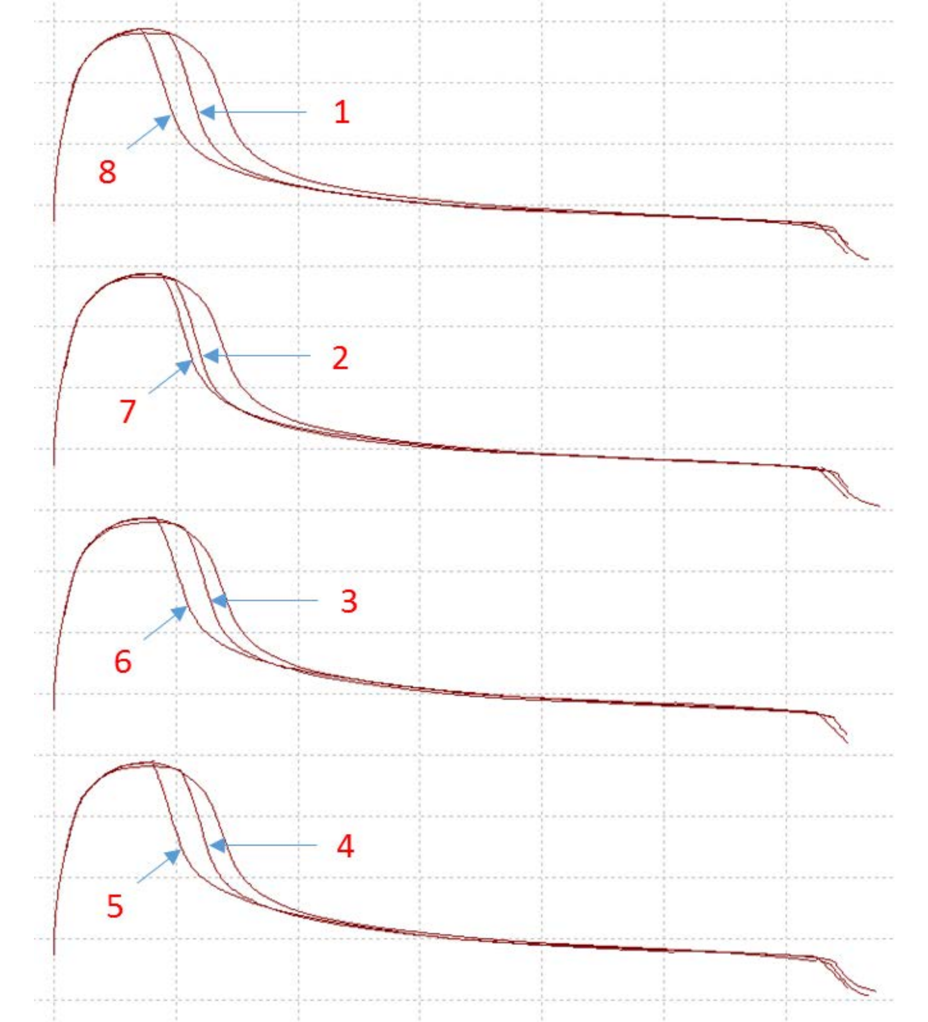




PROFILE OVERLAY (PRE-MACHINING)	SURFACE CONDITION (PRE-MACHINING)

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

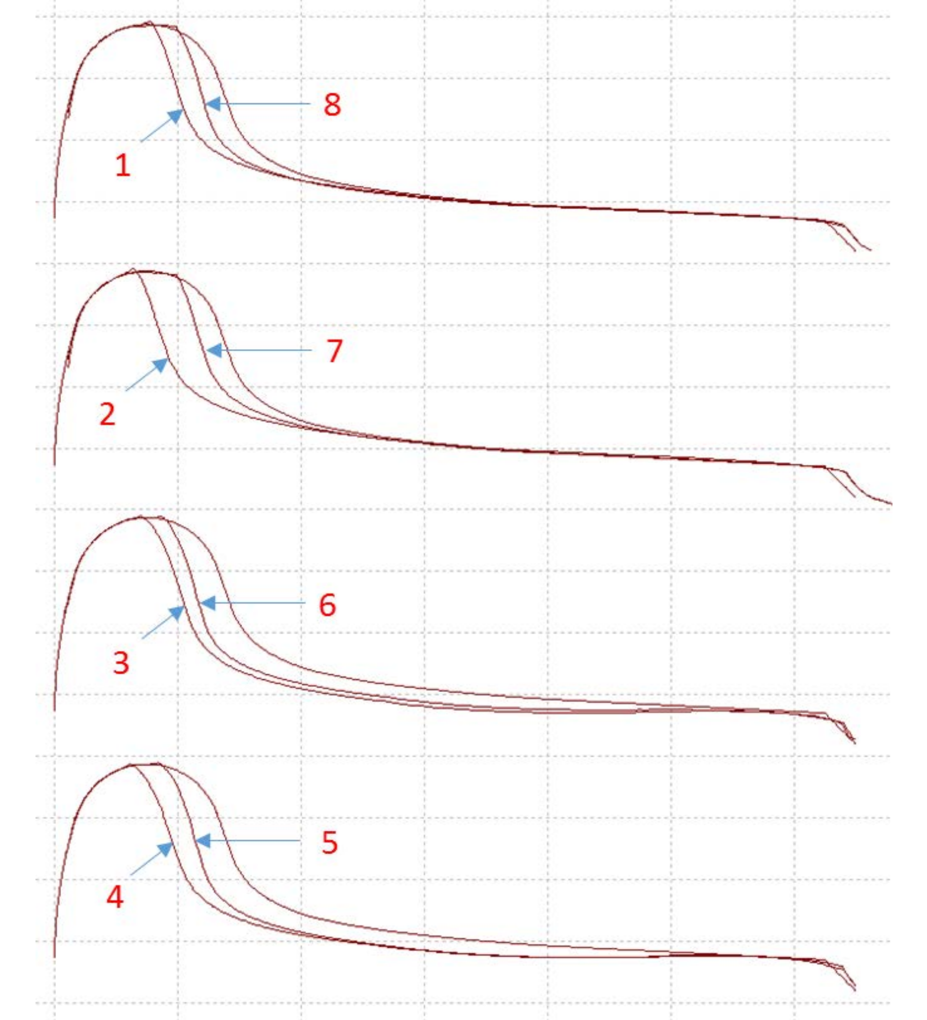
Car Number: 1342	**Stock: VLocity DMU**	**Date Inspected: 16/01/2016**

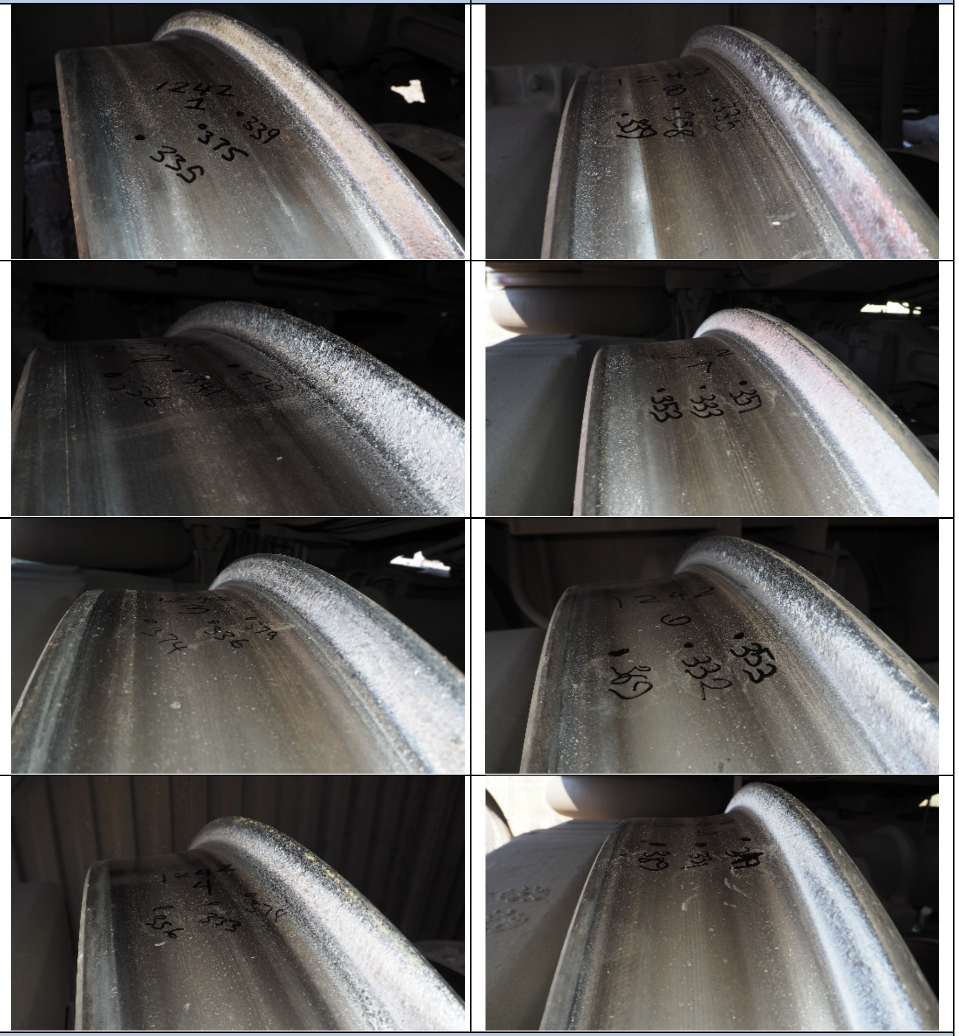


Profile Overlay (Pre-Machining)	**Surface Condition (Pre-Machining)**

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

Car Number: 1242	Stock: VLocity DMU	Date Inspected: 16/01/2016

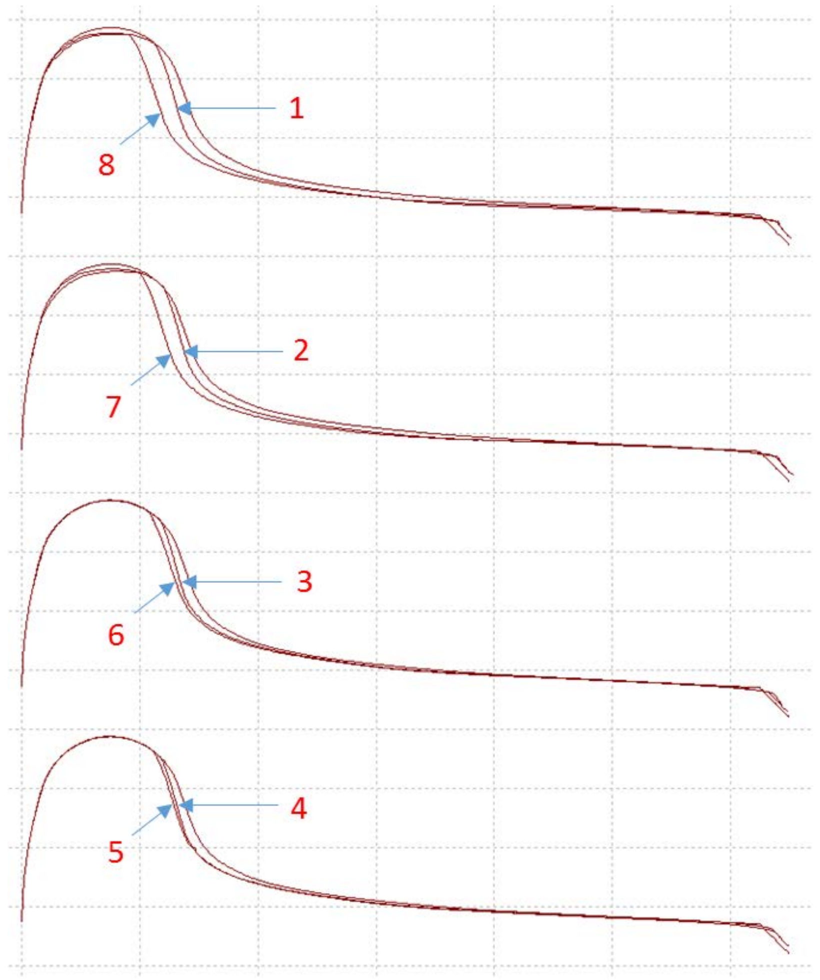


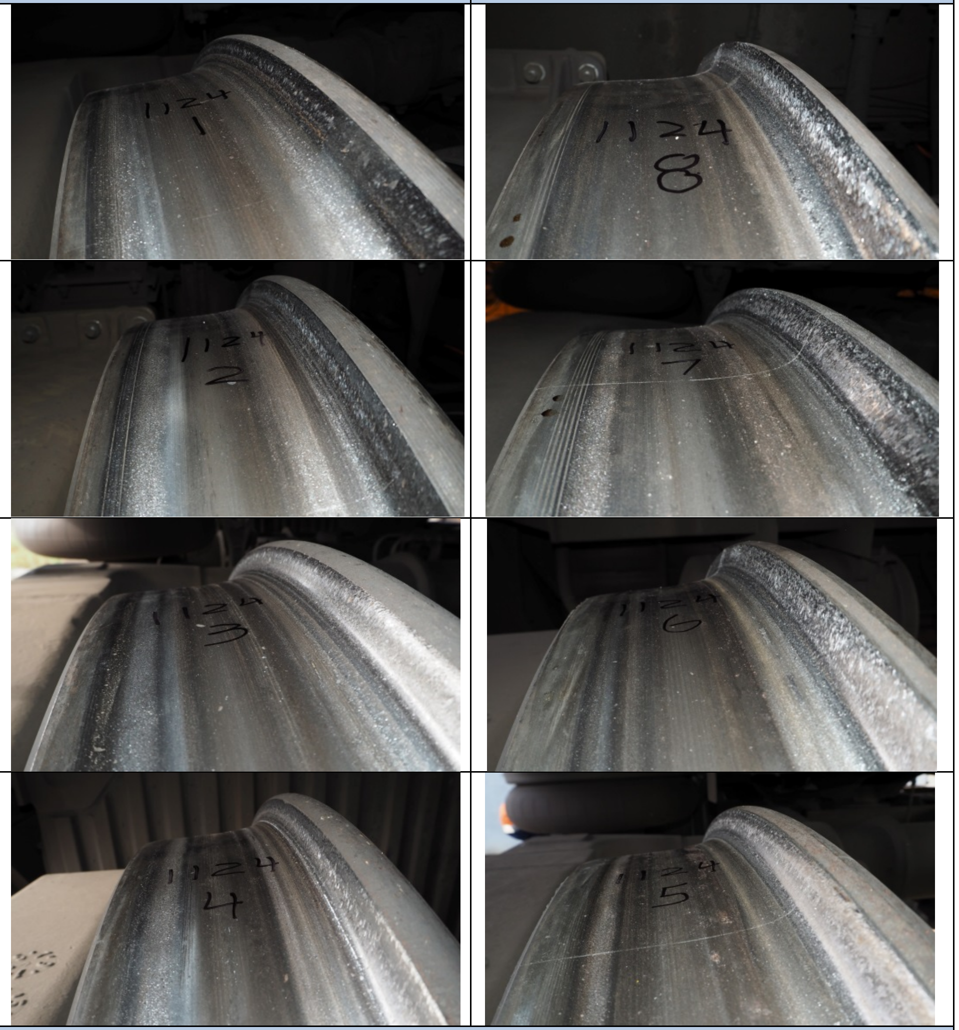


Profile Overlay (Pre-Machining)	Surface Condition (Pre-Machining)

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

Car Number: 1124	**Stock: VLocity DMU**	**Date Inspected: 19/01/2016**

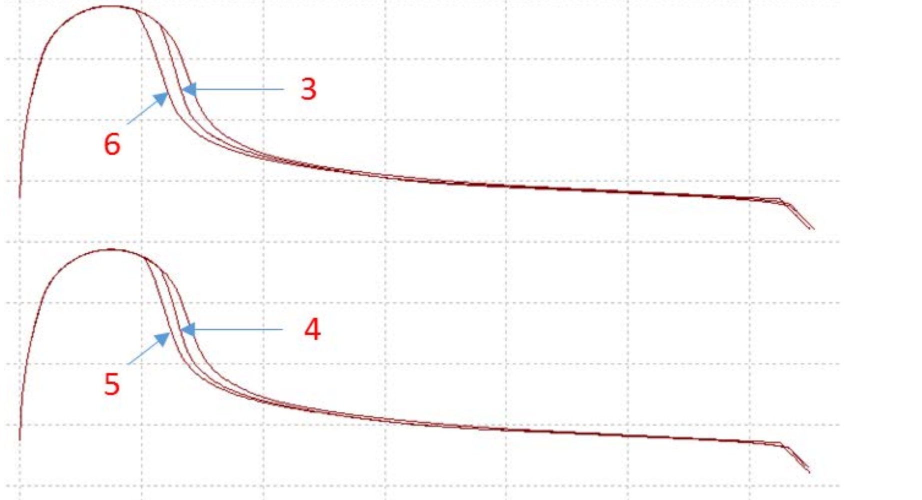




Profile Overlay (Pre-Machining)	**Surface Condition (Pre-Machining)**

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

CAR NUMBER: 1324	STOCK: VLOCITY DMU	DATE INSPECTED: 19/01/2016

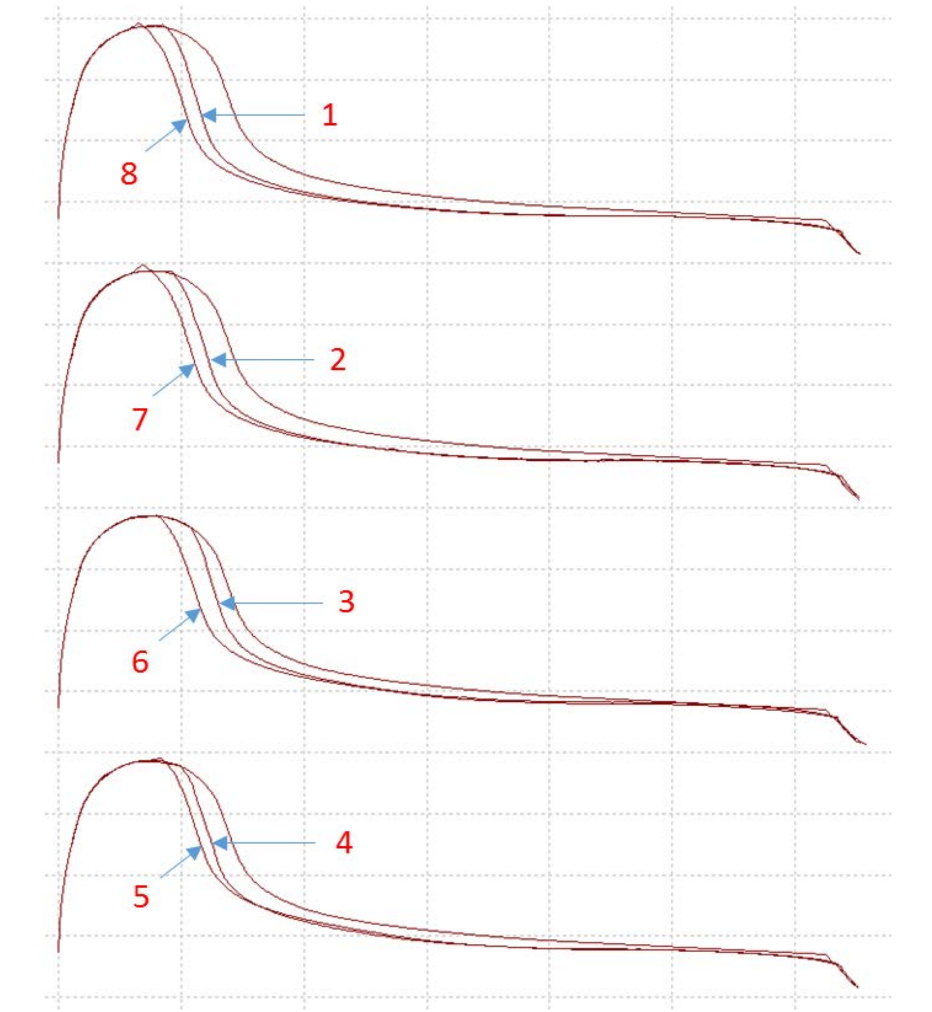


PROFILE OVERLAY (PRE-MACHINING)

SURFACE CONDITION (PRE-MACHINING)

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

Car Number: 1157	Stock: VLocity DMU	Date Inspected: 19/01/2016

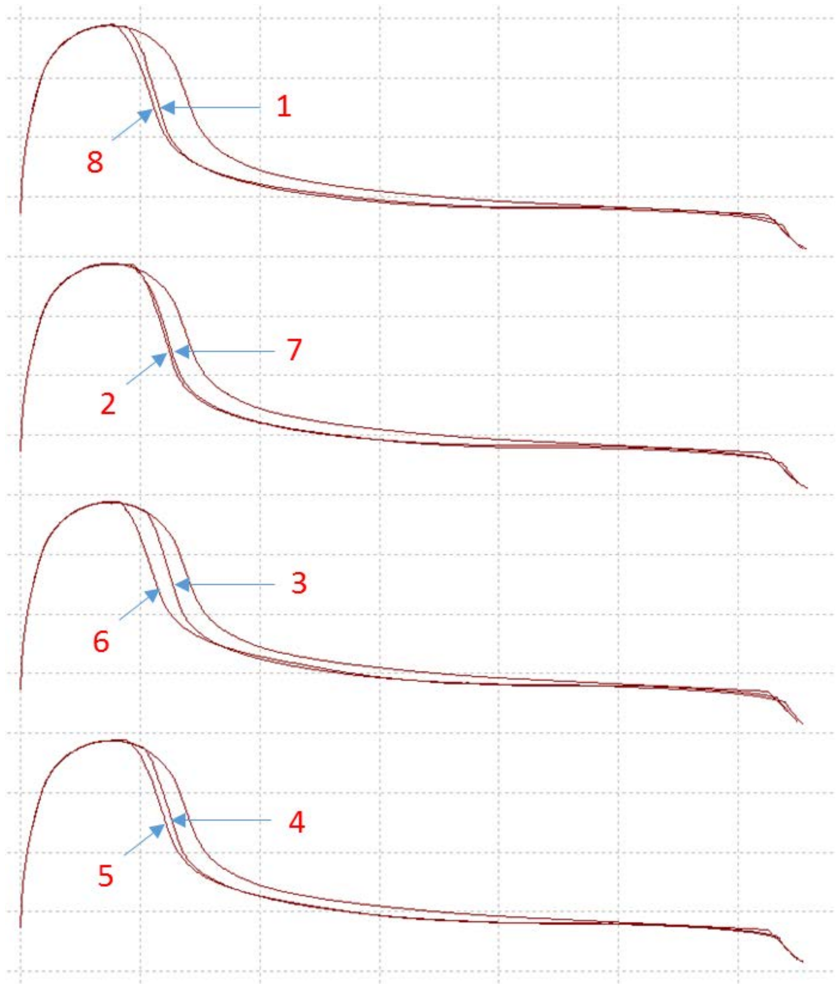


Profile Overlay (On Inspection)

Surface Condition (On Inspection)

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

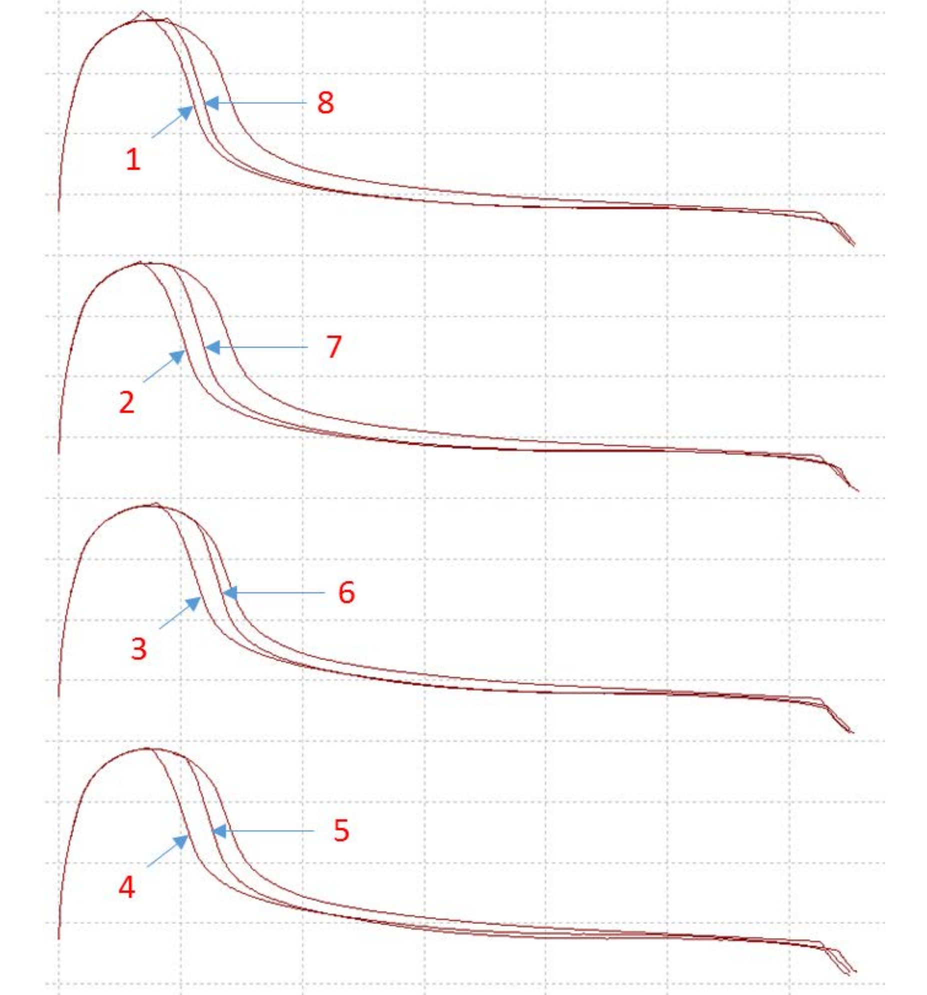
CAR NUMBER: 1357	STOCK: VLOCITY DMU	DATE INSPECTED: 19/01/2016

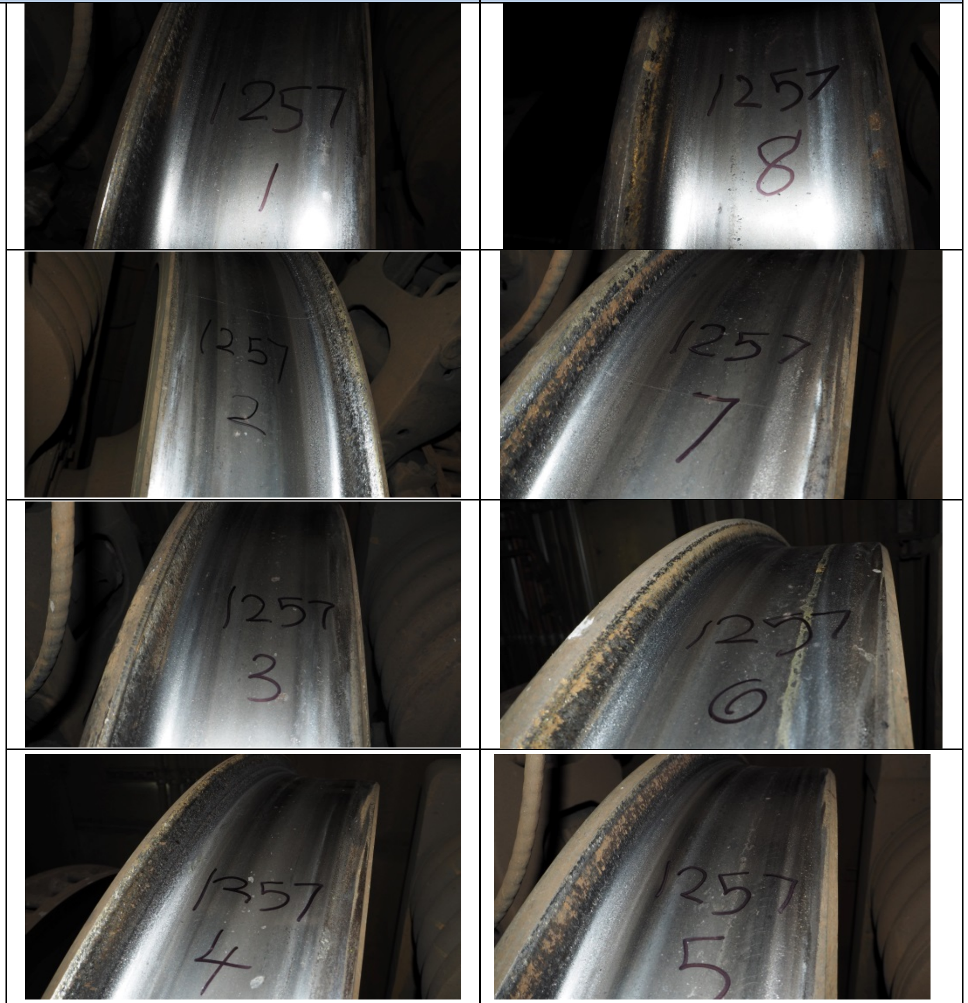


PROFILE OVERLAY (ON INSPECTION)	SURFACE CONDITION (ON INSPECTION)

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

CAR NUMBER: 1257	STOCK: VLOCITY DMU	DATE INSPECTED: 19/01/2016

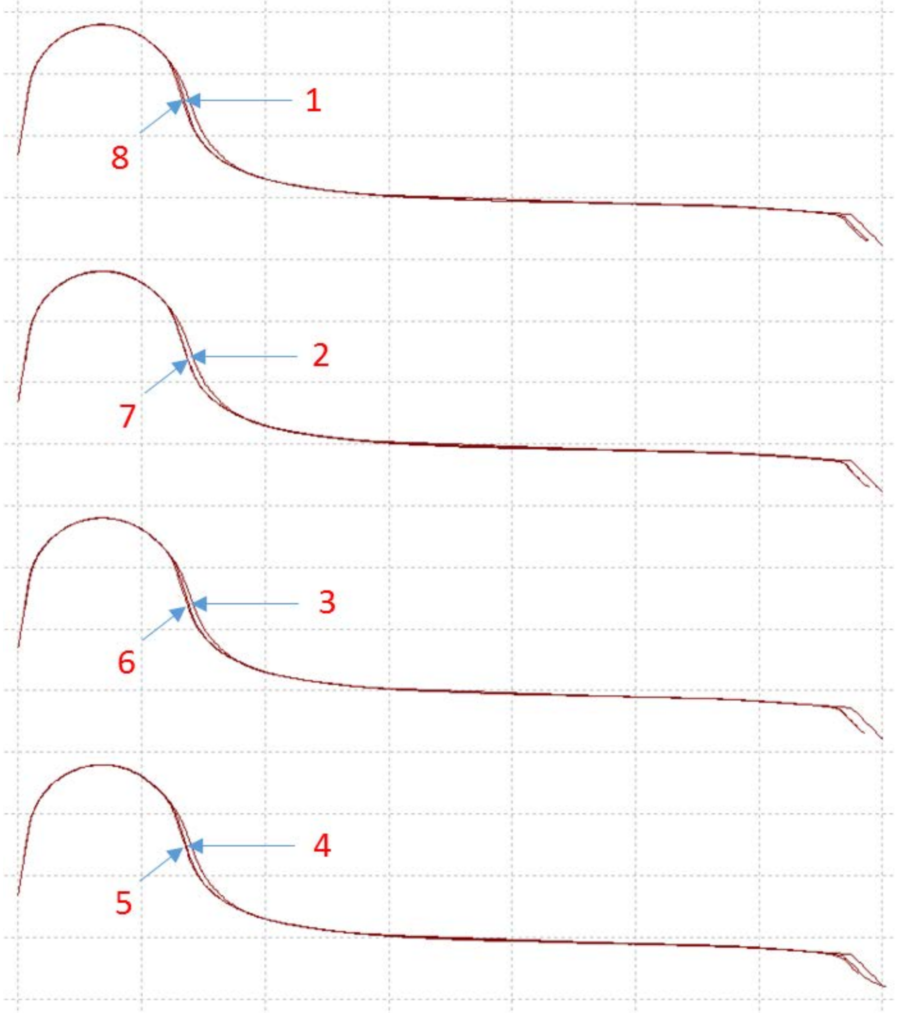


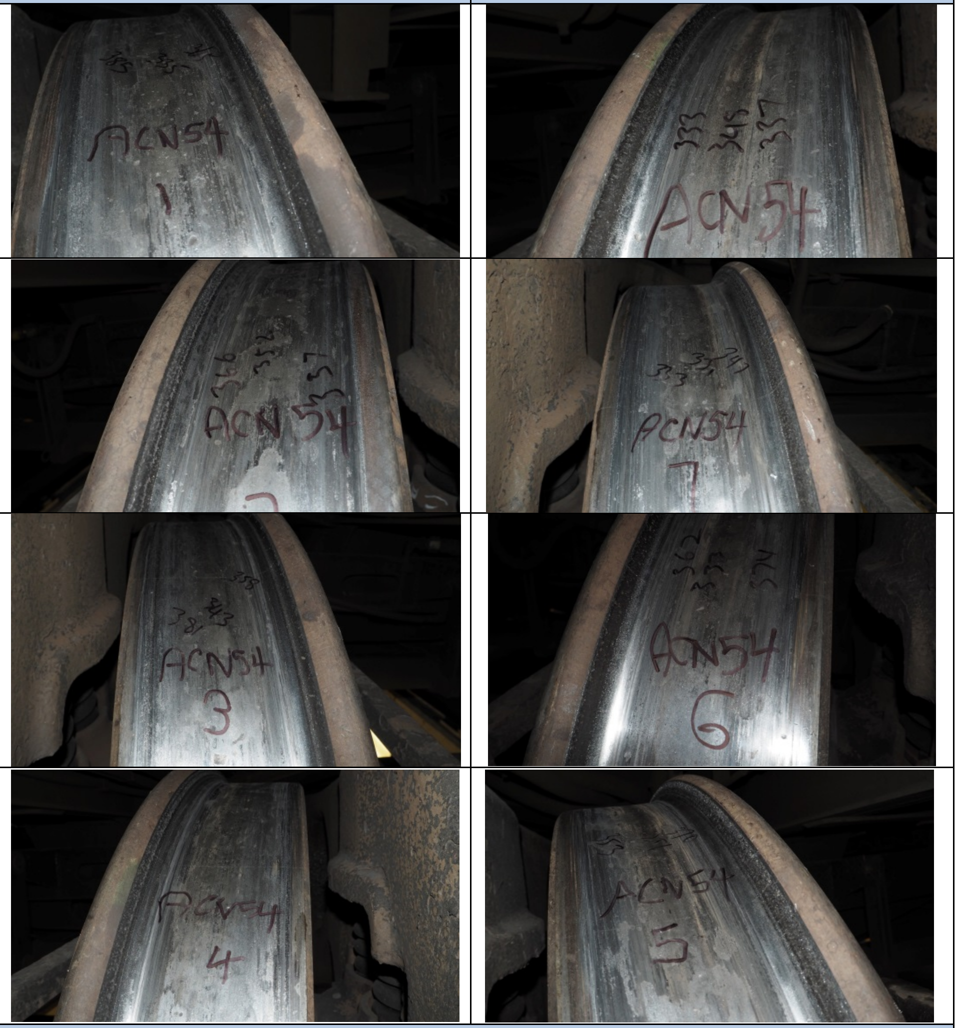


PROFILE OVERLAY (ON INSPECTION)	SURFACE CONDITION (ON INSPECTION)

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

CAR NUMBER: ACN54	STOCK: N TYPE COACH	DATE INSPECTED: 19/01/2016





PROFILE OVERLAY (ON INSPECTION)	SURFACE CONDITION (ON INSPECTION)

Institute of Railway Technology
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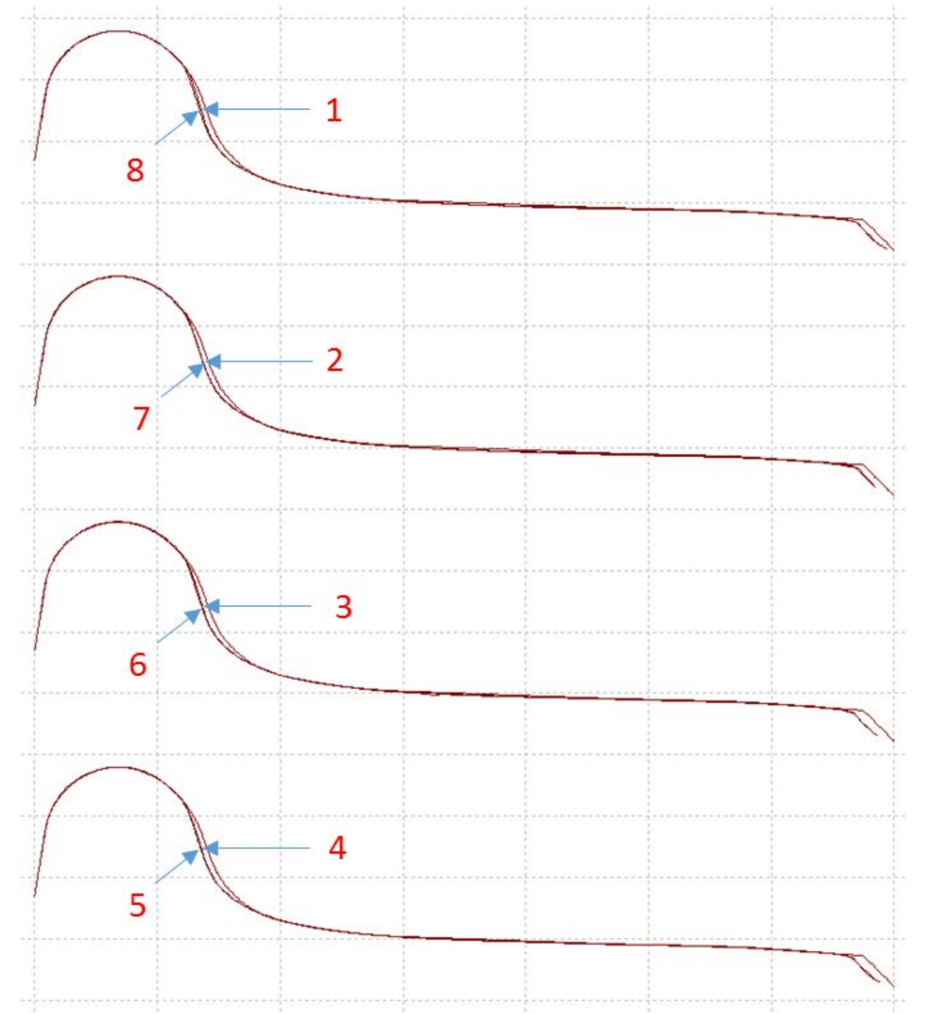
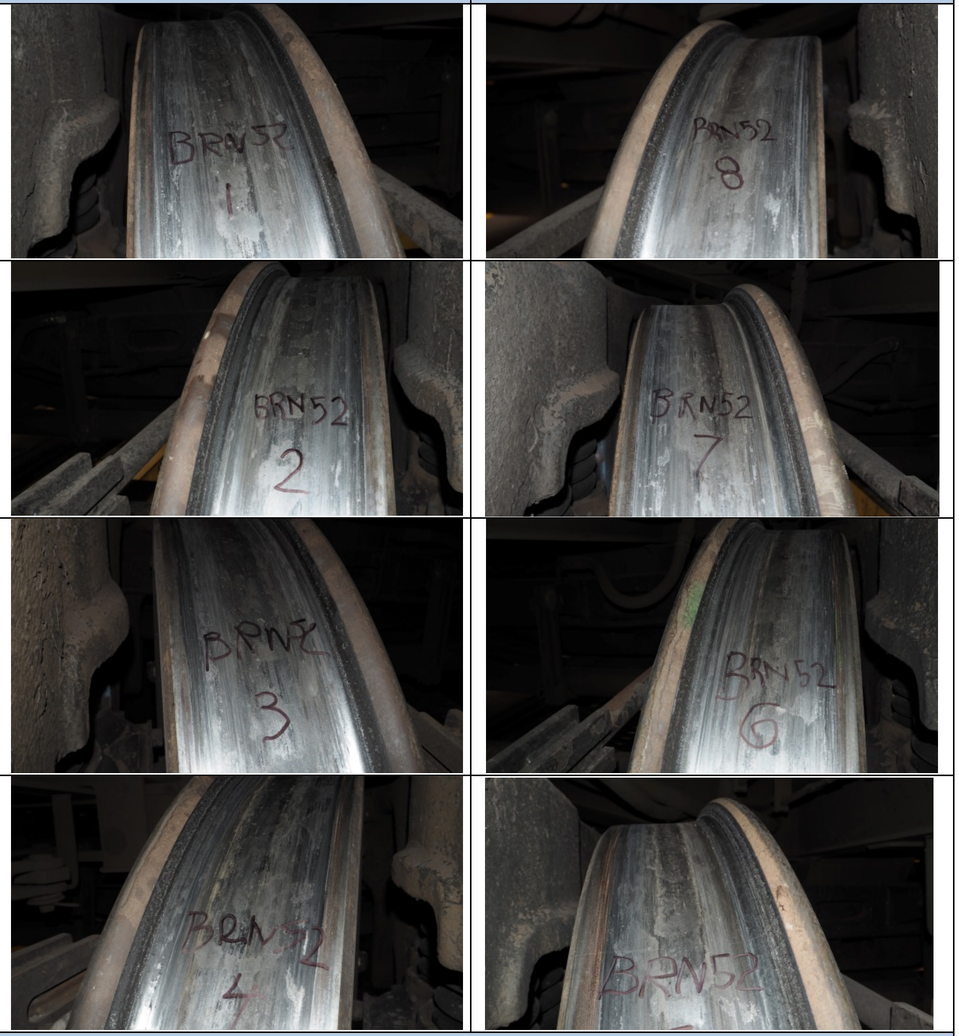
CAR NUMBER: BRN52	STOCK: N TYPE COACH	DATE INSPECTED: 19/01/2016

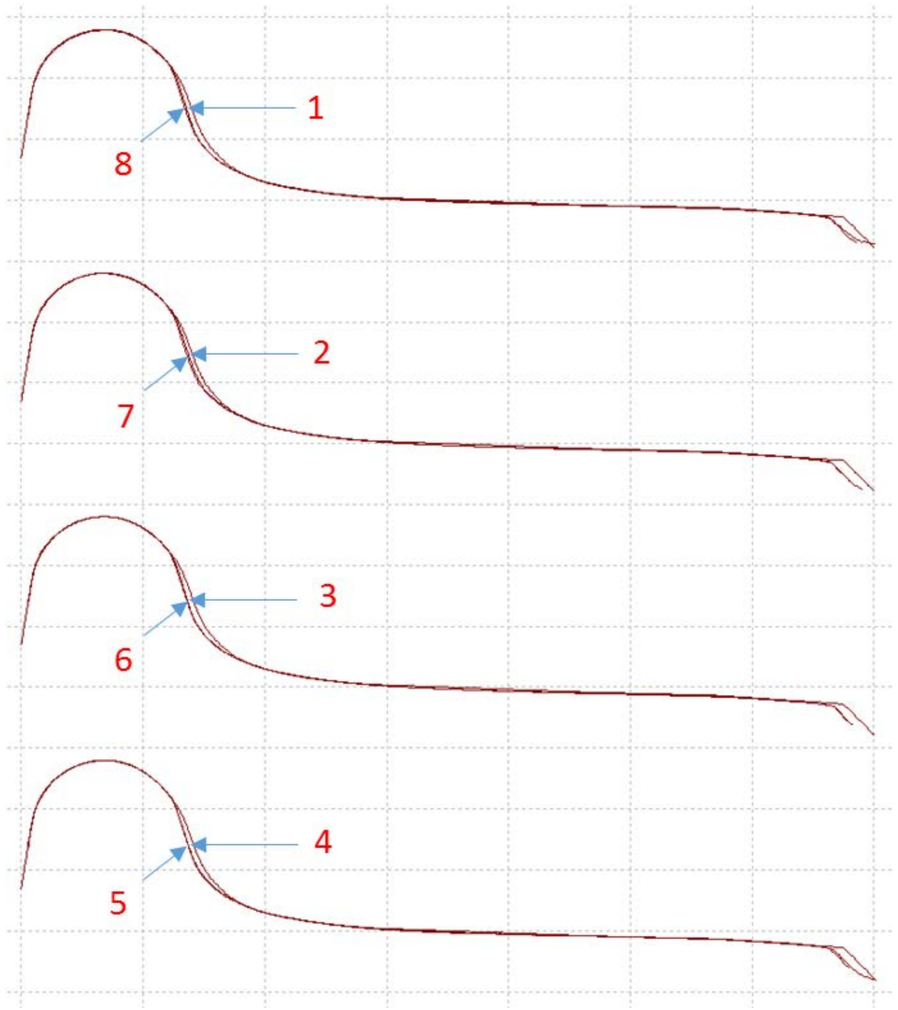




PROFILE OVERLAY (ON INSPECTION)	SURFACE CONDITION (ON INSPECTION)

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

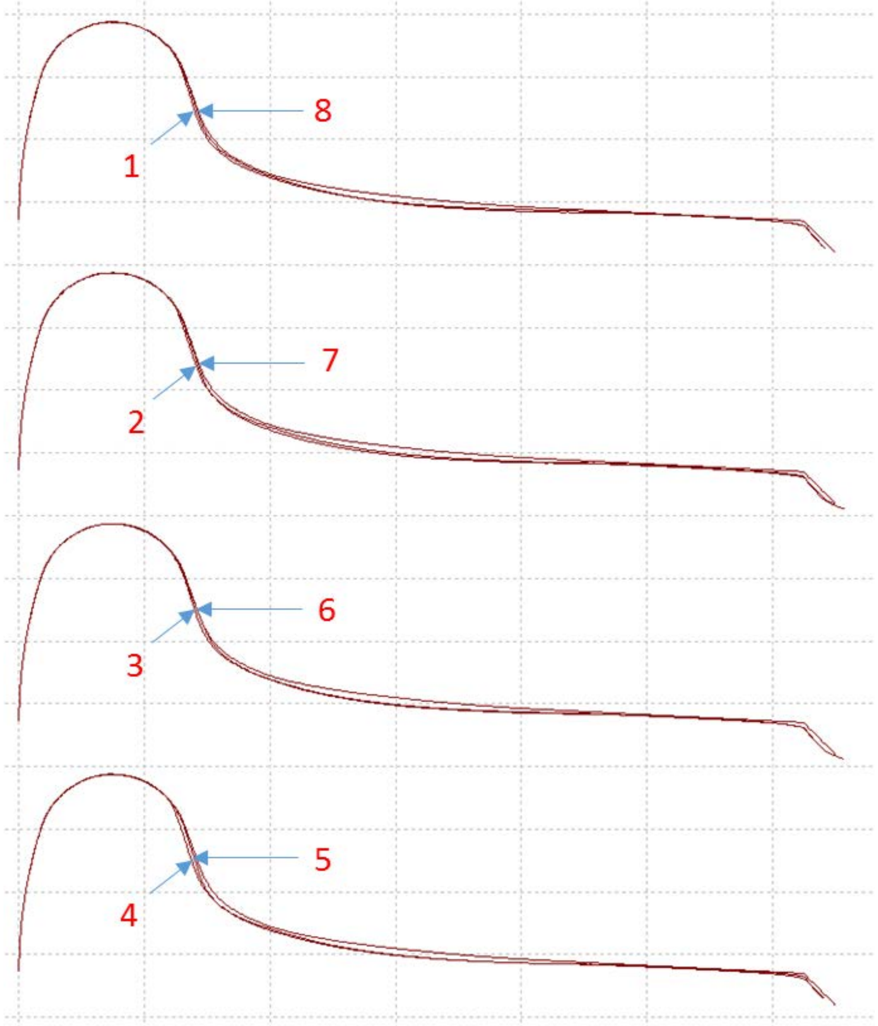
Car Number: BN1	Stock: N Type Coach	Date Inspected: 19/01/2016

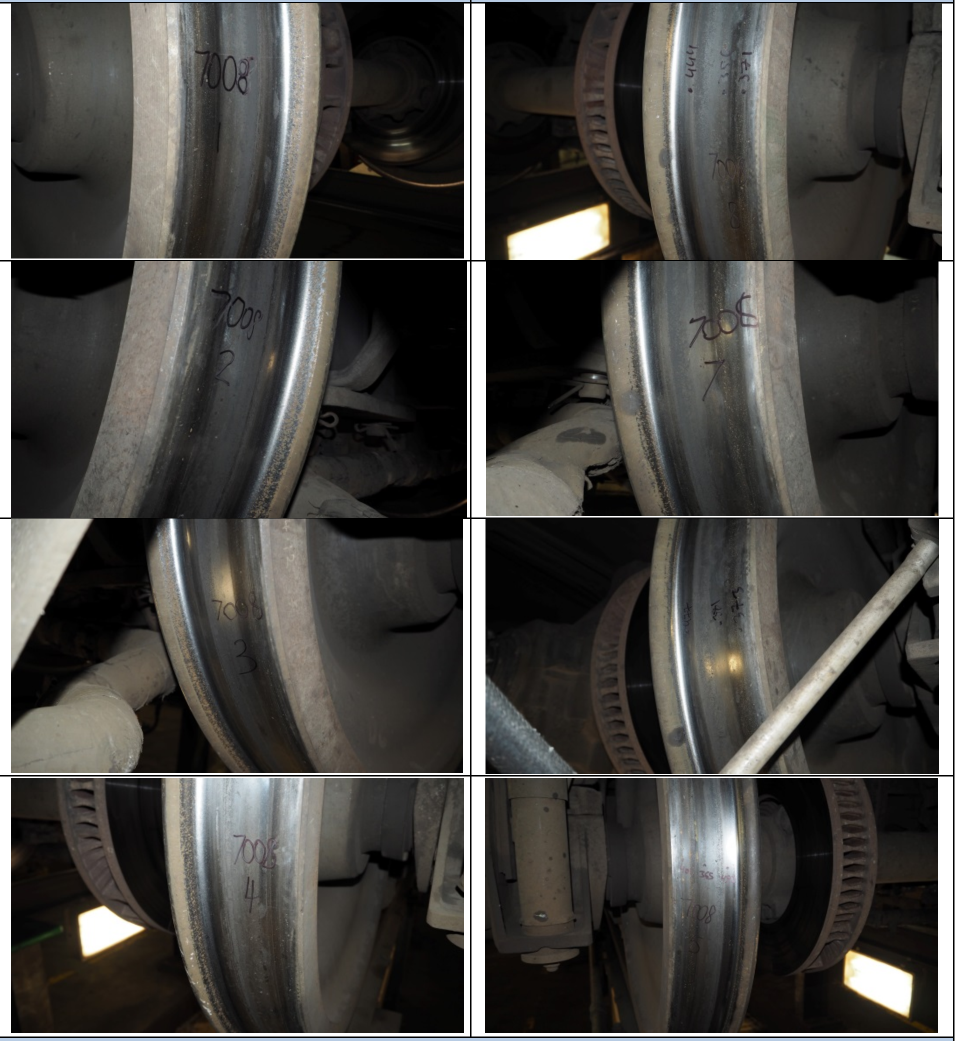


Profile Overlay (On Inspection)	Surface Condition (On Inspection)

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

CAR NUMBER: 7008	STOCK: SPRINTER DMU	DATE INSPECTED: 21/01/2016





PROFILE OVERLAY (ON INSPECTION)	SURFACE CONDITION (ON INSPECTION)

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

<table>
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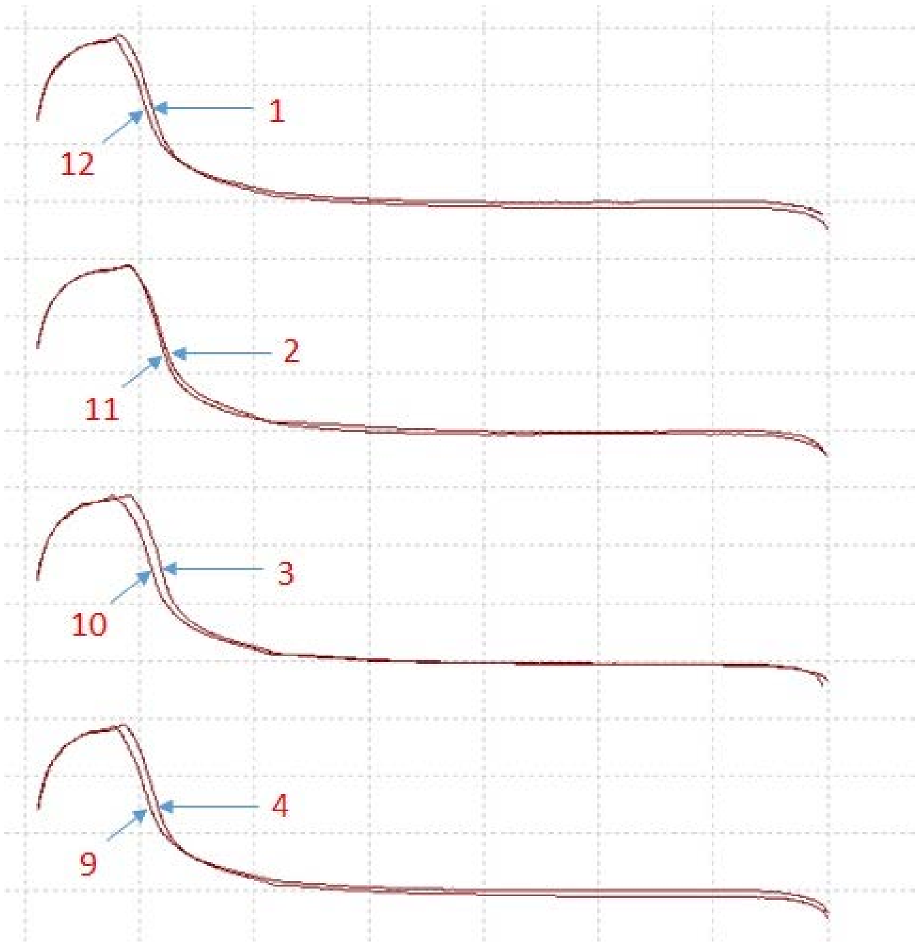
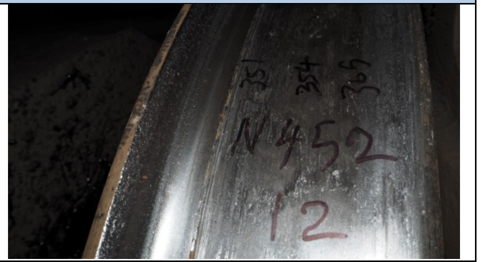
<tr><td rowspan="4">
</td><td>NO IMAGE</td><td>
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<tr><td>NO IMAGE</td><td>
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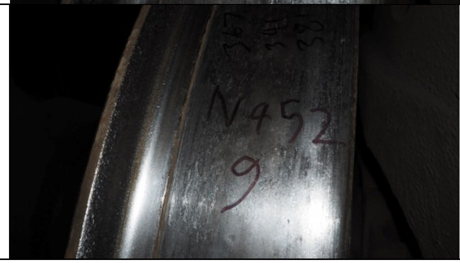
<tr><td>NO IMAGE</td><td>
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Institute of Railway Technology
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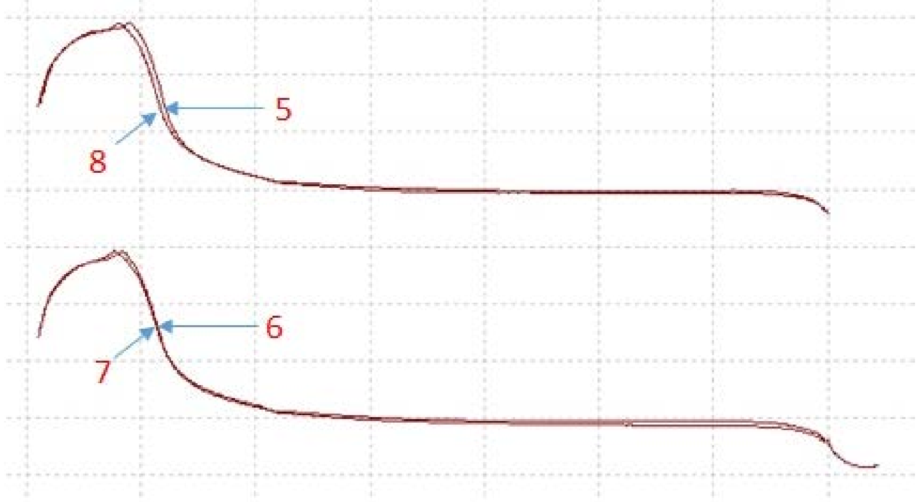
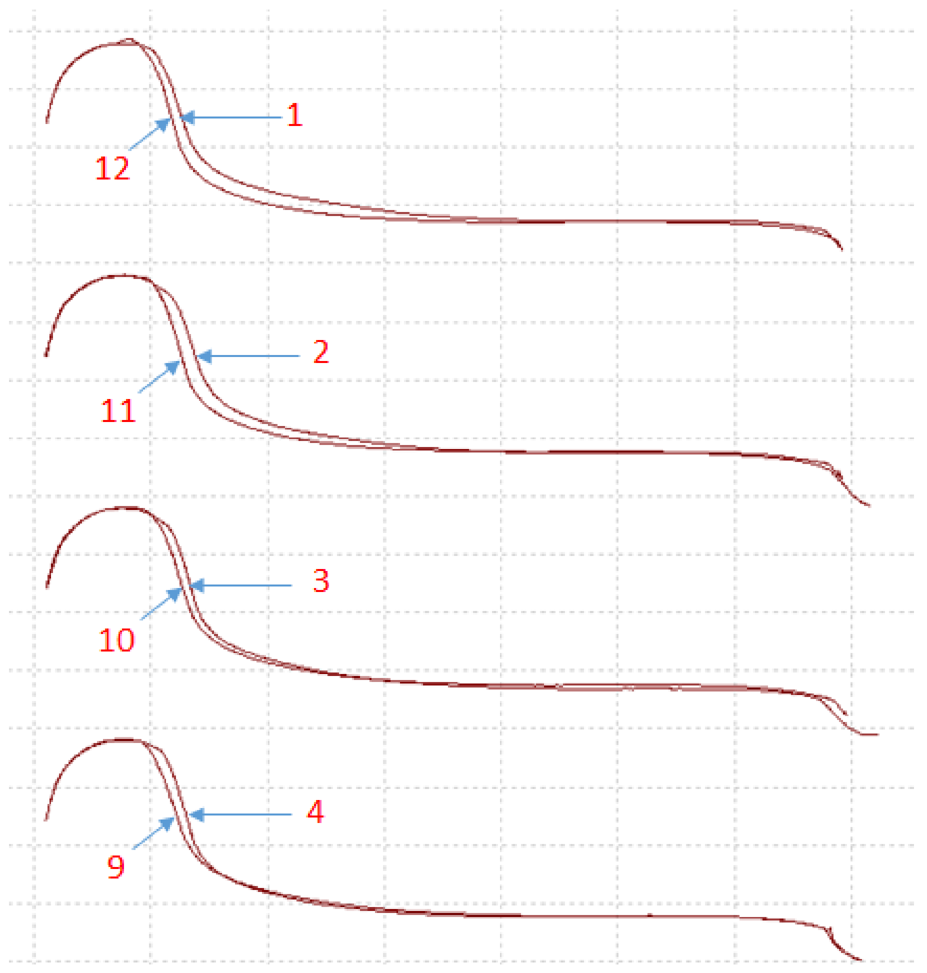
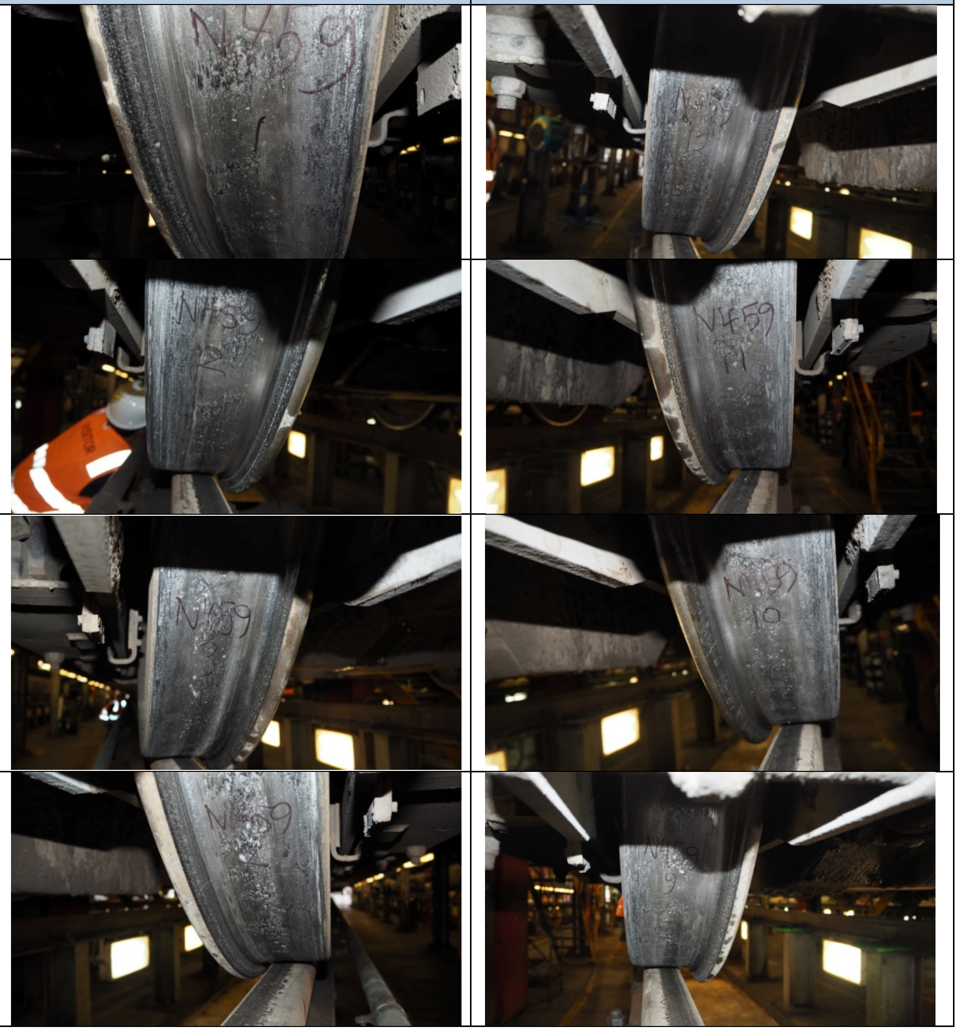
	NO IMAGE	
	NO IMAGE	
PROFILE OVERLAY (PRE-MACHINING)	**SURFACE CONDITION (ON INSPECTION)**	

Institute of Railway Technology
Department of Mechanical and Aerospace Engineering, Monash University

CAR NUMBER: N459	STOCK: N CLASS LOCOMOTIVE	DATE INSPECTED: 21/01/2016





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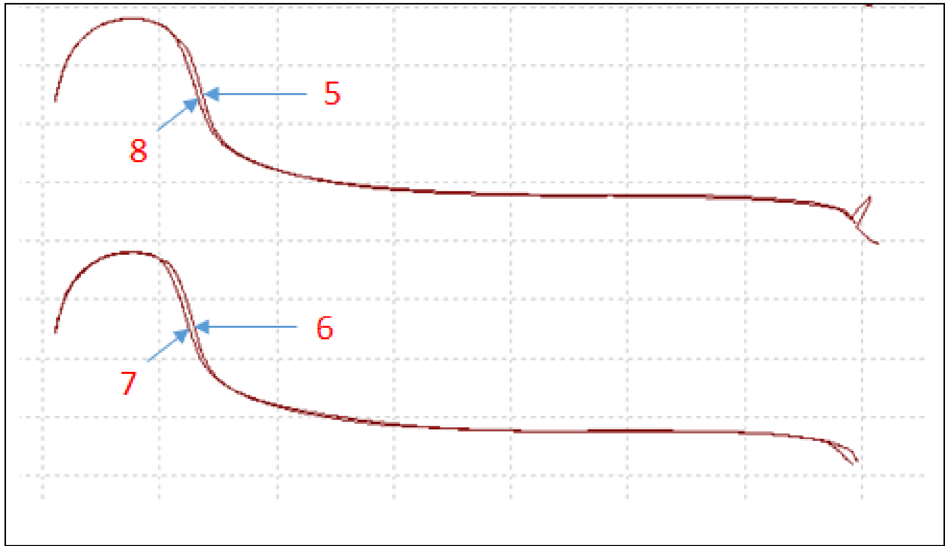

PROFILE OVERLAY (ON INSPECTION)

SURFACE CONDITION (PRE-MACHINING)

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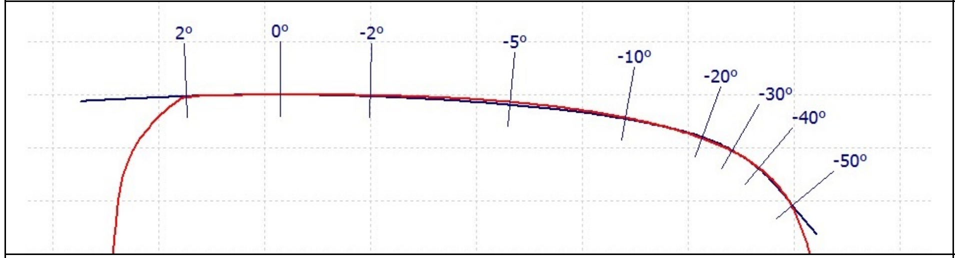
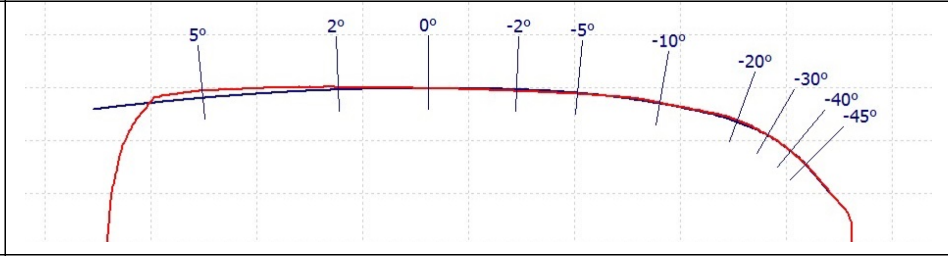
APPENDIX E

RAIL INSPECTION RESULTS

LOCATION: 1352.2 M	TRACK: UP	MEASURED GAUGE: 1608 MM	CURVE RADIUS: 180 M	CURVE LENGTH: 139 M	LINE: SCS (FLYOVER) – SPION KOP

HIGH RAIL	**LOW RAIL**
	
MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)	MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)
	
NOTES: • TOP WEAR = 2.6 MM • SIDE WEAR = 3.9 MM • HEAD LOSS = 8.8 %	NOTES: • TOP WEAR = 3.0 MM • HEAD LOSS = 6.4 %

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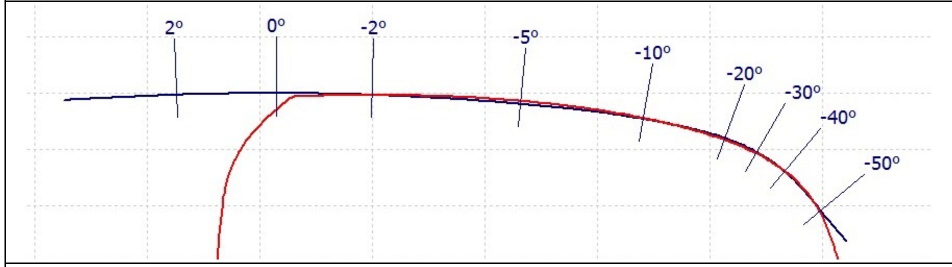
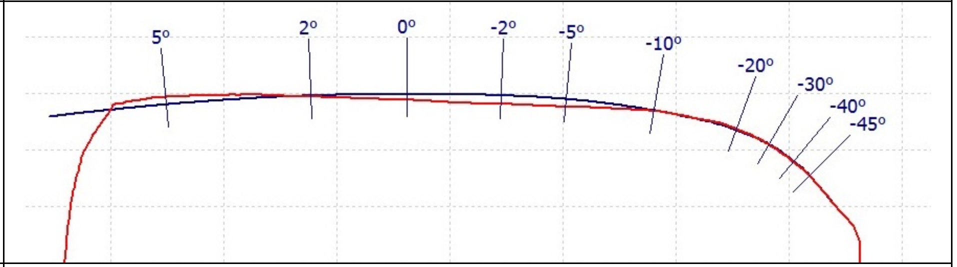
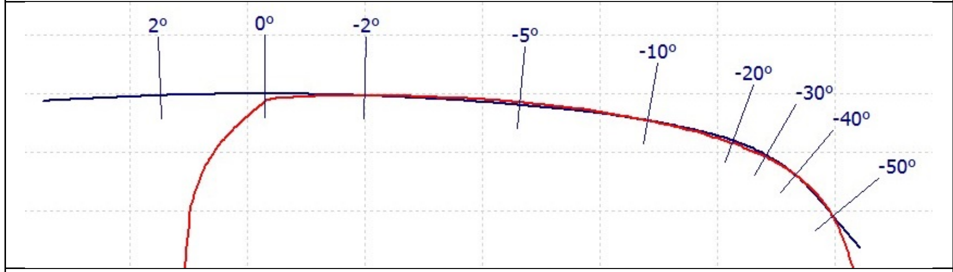
<table>
<tr><th>LOCATION: 1362 M</th><th>TRACK: UP</th><th>MEASURED GAUGE: 1620 MM</th><th>CURVE RADIUS: 180 M</th><th>CURVE LENGTH: 139 M</th><th>LINE: SCS (FLYOVER) – SPION KOP</th></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 3.2 MM
• SIDE WEAR = 14.0 MM
• HEAD LOSS = 19.2 %</td><td colspan="3">NOTES:
• TOP WEAR = 3.1 MM
• HEAD LOSS = 5.9 %</td></tr>
</table>

LOCATION: 1398.7 M	TRACK: UP	MEASURED GAUGE: 1622 MM	CURVE RADIUS: 180 M	CURVE LENGTH: 139 M	LINE: SCS (FLYOVER) – SPION KOP

HIGH RAIL

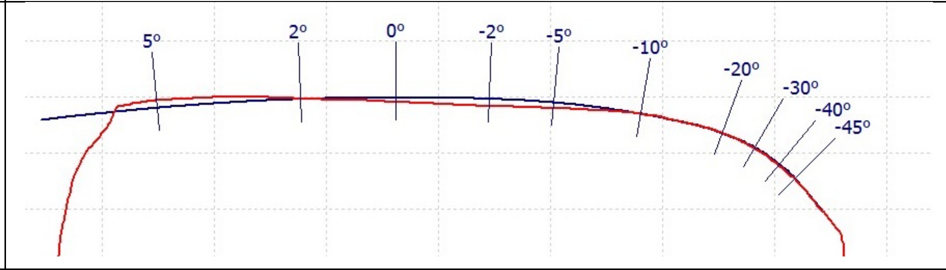


MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)

NOTES:

- TOP WEAR = 2.8 MM
- SIDE WEAR = 12.5 MM
- HEAD LOSS = 16.8 %

LOW RAIL



MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)

NOTES:

- TOP WEAR = 1.7 MM
- HEAD LOSS = 3.0 %

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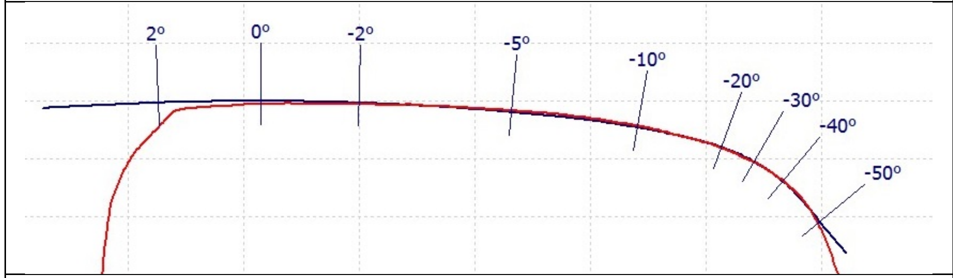
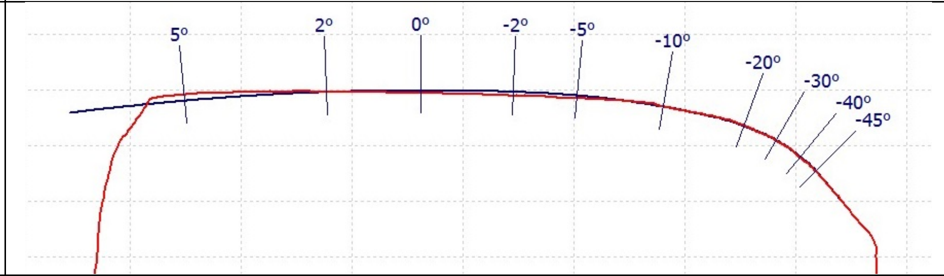
LOCATION: 1398.7 M	TRACK: DOWN	MEASURED GAUGE: 1614 MM	CURVE RADIUS: 180 M	CURVE LENGTH: 139 M	LINE: SCS (FLYOVER) – SPION KOP

HIGH RAIL	LOW RAIL
	
MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)	MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)
	
NOTES: • TOP WEAR = 1.9 MM • SIDE WEAR = 6.0 MM • HEAD LOSS = 8.9 %	NOTES: • TOP WEAR = 2.4 MM • HEAD LOSS = 5.3 %

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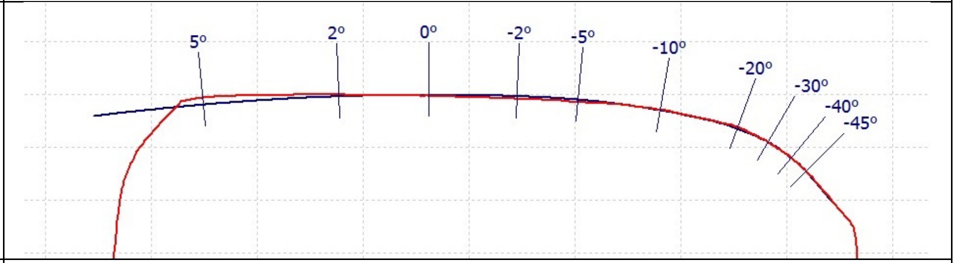
LOCATION: 1577.2 M	TRACK: UP	MEASURED GAUGE: 1616 MM	CURVE RADIUS: 181 M	CURVE LENGTH: 122 M	LINE: SCS (FLYOVER) – SPION KOP

HIGH RAIL	LOW RAIL
	
MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)	MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)
	
NOTES: • TOP WEAR = 1.1 MM • SIDE WEAR = 7.2 MM • HEAD LOSS = 8.3 %	NOTES: • TOP WEAR = 1.4 MM • HEAD LOSS = 2.9 %

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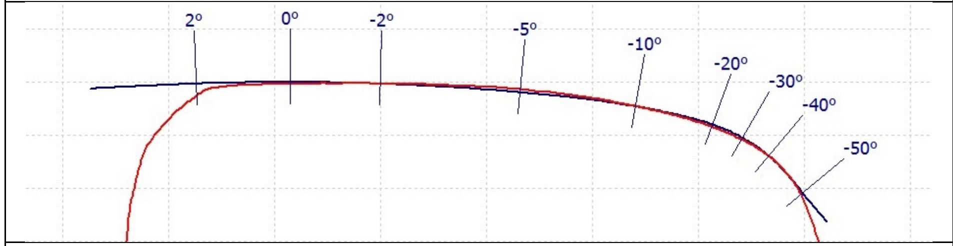
LOCATION: 1577.2 M	TRACK: DOWN	MEASURED GAUGE: 1614 MM	CURVE RADIUS: 185 M	CURVE LENGTH: 125 M	LINE: SCS (FLYOVER) – SPION KOP

HIGH RAIL

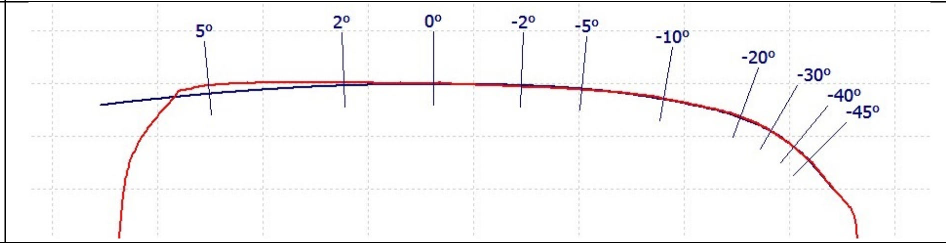


MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)

NOTES:

- TOP WEAR = 1.7 MM
- SIDE WEAR = 4.6 MM
- HEAD LOSS = 7.4 %

LOW RAIL

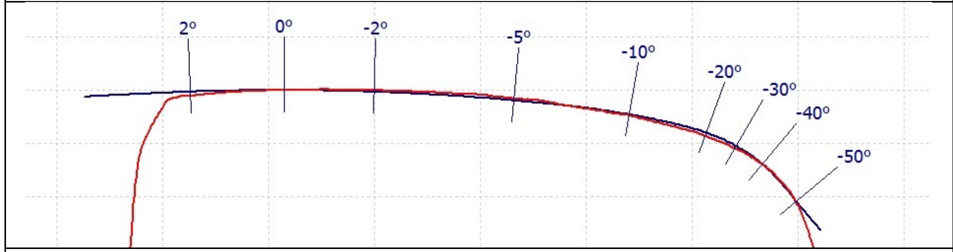
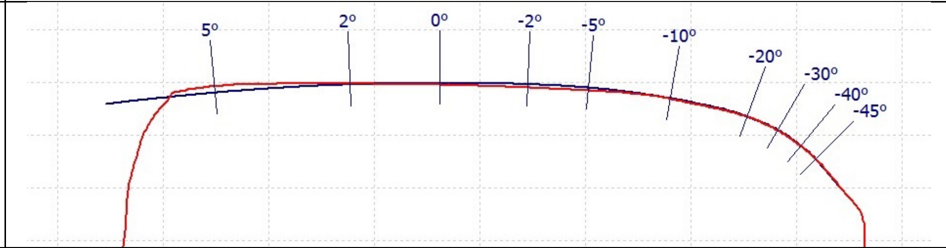


MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)

NOTES:

- TOP WEAR = 1.7 MM
- HEAD LOSS = 3.8 %

LOCATION: 1769.7 M	**TRACK: UP**	**MEASURED GAUGE: 1615 MM**	**CURVE RADIUS: 180 M**	**CURVE LENGTH: 112 M**	**LINE: SCS (FLYOVER) – SPION KOP**

HIGH RAIL	**LOW RAIL**
	
MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)	MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)
	
NOTES: • TOP WEAR = 3.9 MM • SIDE WEAR = 5.2 MM • HEAD LOSS = 11.6 %	NOTES: • TOP WEAR = 2.5 MM • HEAD LOSS = 5.0 % • CONTACT BAND = APPROX. MM

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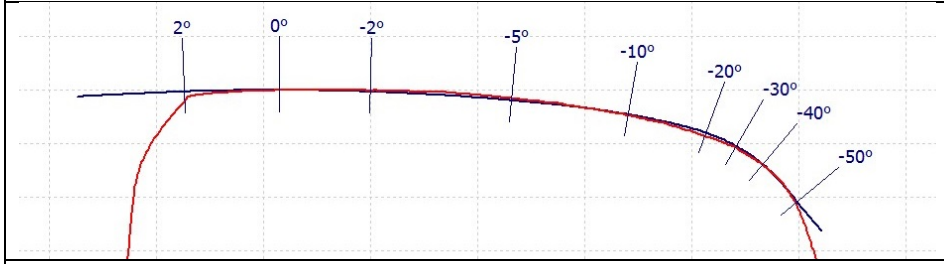
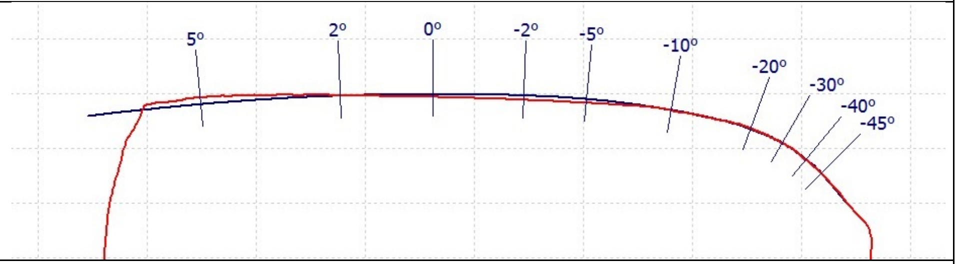
<table>
<tr><th>LOCATION: 1769.7 M</th><th>TRACK: DOWN</th><th>MEASURED GAUGE: 1614 MM</th><th>CURVE RADIUS: 180 M</th><th>CURVE LENGTH: 110 M</th><th>LINE: SCS (FLYOVER) – SPION KOP</th></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
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<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 2.2 MM
• SIDE WEAR = 5.8 MM
• HEAD LOSS = 8.6 %</td><td colspan="3">NOTES:
• TOP WEAR = 2.8 MM
• HEAD LOSS = 5.2 %</td></tr>
</table>

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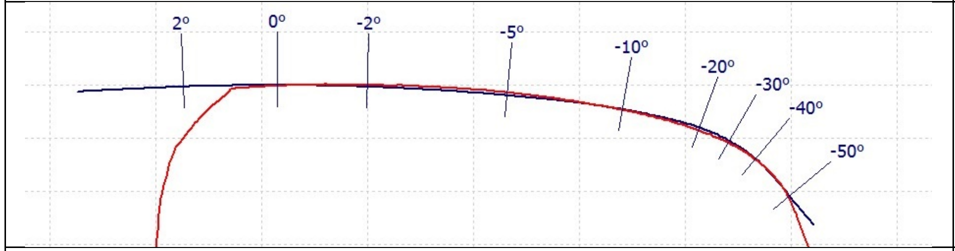
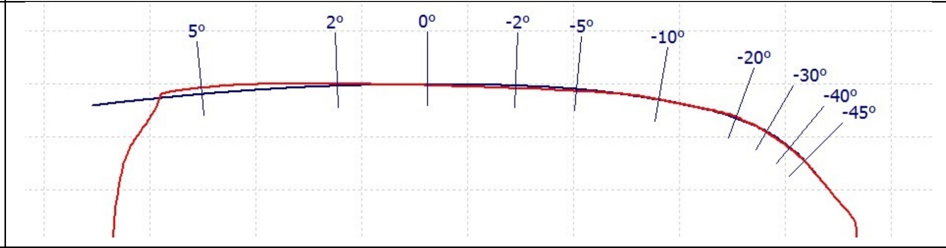
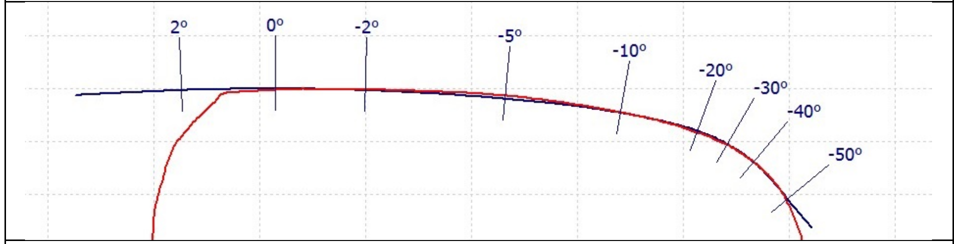
<table>
<tr><th>LOCATION: 1909 M</th><th>TRACK: UP</th><th>MEASURED GAUGE: 1616 MM</th><th>CURVE RADIUS: 400 M</th><th>CURVE LENGTH: 147 M</th><th>LINE: SCS (FLYOVER) – SPION KOP</th></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 2.2 MM
• SIDE WEAR = 8.2 MM
• HEAD LOSS = 10.4 %</td><td colspan="3">NOTES:
• TOP WEAR = 1.6 MM
• HEAD LOSS = 3.0 %</td></tr>
</table>

LOCATION: 1909 M	TRACK: DOWN	MEASURED GAUGE: 1618 MM	CURVE RADIUS: 181 M	CURVE LENGTH: 144 M	LINE: SCS (FLYOVER) – SPION KOP

HIGH RAIL

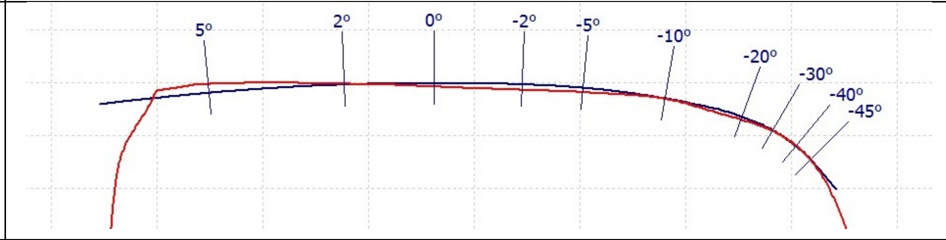


MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)

NOTES:

- TOP WEAR = 1.9 MM
- SIDE WEAR = 8.0 MM
- HEAD LOSS = 10.0 %

LOW RAIL



MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)

NOTES:

- TOP WEAR = 2.2 MM
- HEAD LOSS = 3.9 %

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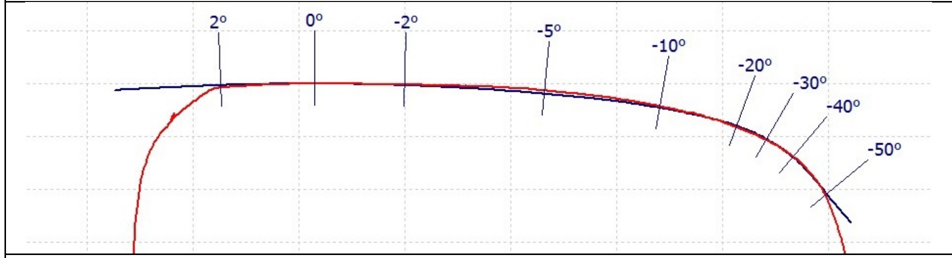
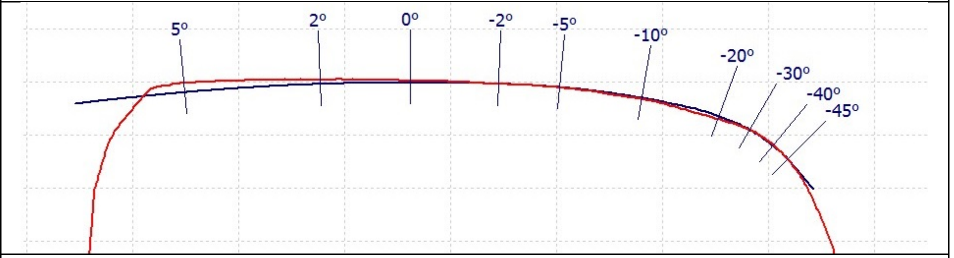
LOCATION: 2180 M	**TRACK: UP**	**MEASURED GAUGE: 1606 MM**	**CURVE RADIUS: 396 M**	**CURVE LENGTH: 174 M**	**LINE: SCS (FLYOVER) – SPION KOP**

<table>
<tr><th>HIGH RAIL</th><th>LOW RAIL</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td>MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td></td><td></td></tr>
<tr><td>NOTES:
• TOP WEAR = 1.7 MM
• SIDE WEAR = 3.0 MM
• HEAD LOSS = 5.5 %</td><td>NOTES:
• TOP WEAR = 1.5 MM
• HEAD LOSS = 3.1 %</td></tr>
</table>

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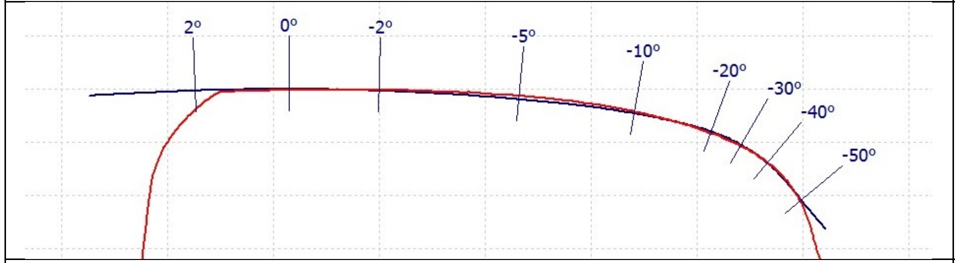
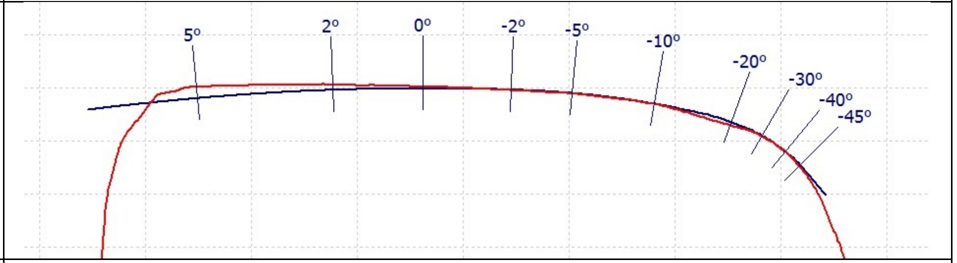
<table>
<tr><th>LOCATION: 2180 M</th><th>TRACK: DOWN</th><th>MEASURED GAUGE: 1609 MM</th><th>CURVE RADIUS: 400 M</th><th>CURVE LENGTH: 175 M</th><th>LINE: SCS (FLYOVER) – SPION KOP</th></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 1.7 MM
• SIDE WEAR = 6.1 MM
• HEAD LOSS = 8.0 %</td><td colspan="3">NOTES:
• TOP WEAR = 1.9 MM
• HEAD LOSS = 4.2 %</td></tr>
</table>

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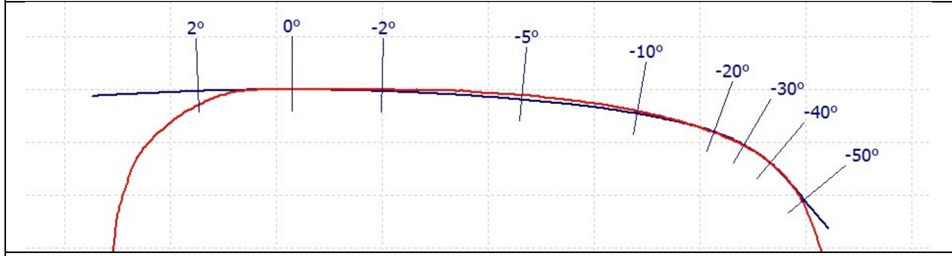
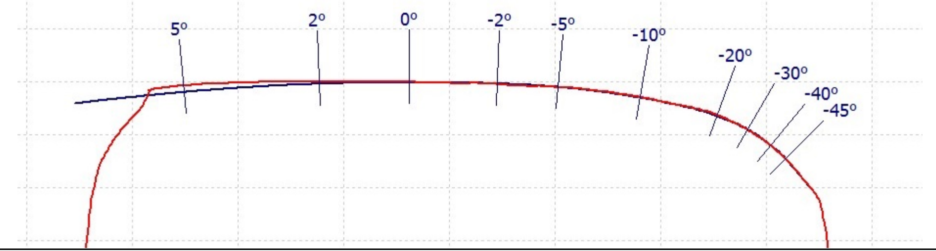
<table>
<tr><td>LOCATION: 2350 M</td><td>TRACK: UP</td><td>MEASURED GAUGE: 1609 MM</td><td>CURVE RADIUS: 380 M</td><td>CURVE LENGTH: 86 M</td><td>LINE: SCS (FLYOVER) – SPION KOP</td></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 1.2 MM
• SIDE WEAR = 2.9 MM
• HEAD LOSS = 4.6 %</td><td colspan="3">NOTES:
• TOP WEAR = 1.6MM
• HEAD LOSS = 3.2 %</td></tr>
</table>

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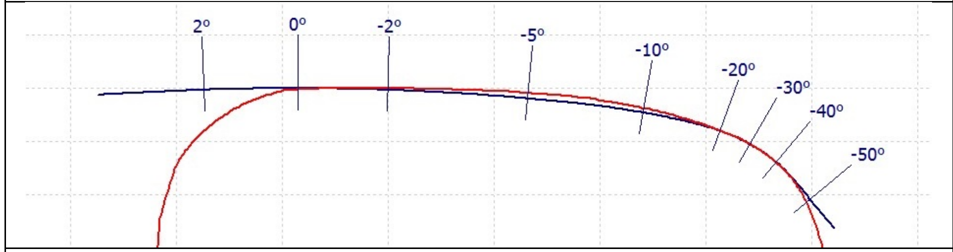
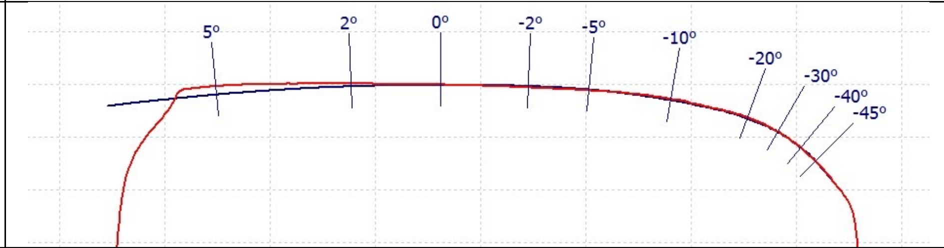
<table>
<tr><td>LOCATION: 2350 M</td><td>TRACK: DOWN</td><td>MEASURED GAUGE: 1610 MM</td><td>CURVE RADIUS: 400 M</td><td>CURVE LENGTH: 94 M</td><td>LINE: SCS (FLYOVER) – SPION KOP</td></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 1.3 MM
• SIDE WEAR = 6.9 MM
• HEAD LOSS = 7.7 %</td><td colspan="3">NOTES:
• TOP WEAR = 1.7 MM
• HEAD LOSS = 3.2 %</td></tr>
</table>

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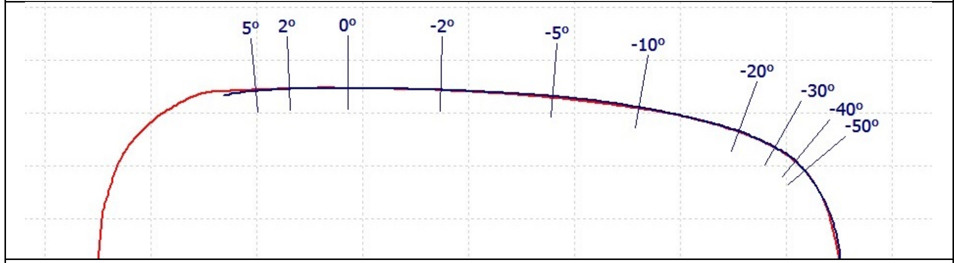
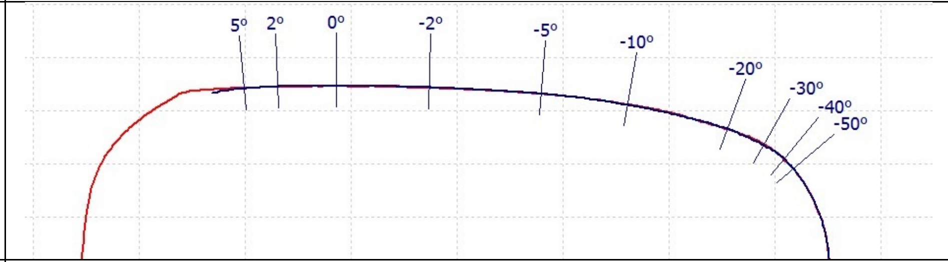
<table>
<tr><td colspan="3">LOCATION: 5000 M | TRACK: UP | MEASURED GAUGE: 1600 MM</td><td colspan="3">CURVE RADIUS: 1104 M | CURVE LENGTH: 321 M | LINE: SCS (PLAT. 5-16) - SUNSHINE</td></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 1.3 MM
• SIDE WEAR = 0.1 MM
• HEAD LOSS = 2.7 %</td><td colspan="3">NOTES:
• TOP WEAR = 1.2 MM
• HEAD LOSS = 2.2 %</td></tr>
</table>

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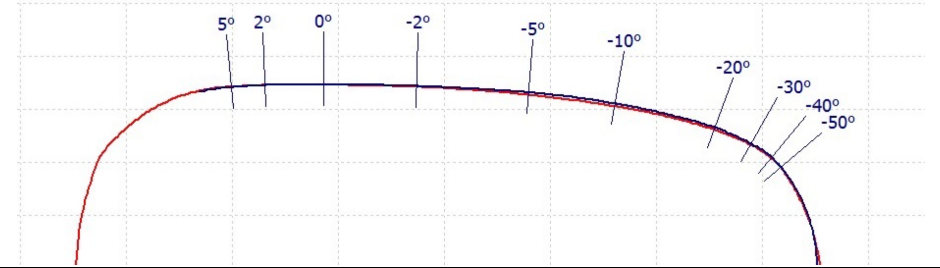
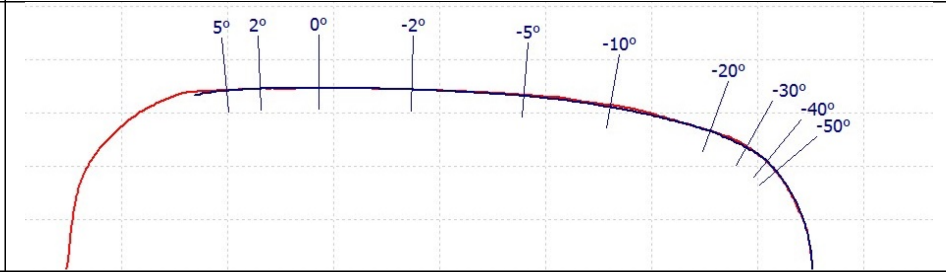
<table>
<tr><td colspan="3">LOCATION: 5000 M</td><td>TRACK: DOWN</td><td>MEASURED GAUGE: 1604 MM</td><td>CURVE RADIUS: 1100 M</td><td>CURVE LENGTH: 327 M</td><td colspan="2">LINE: SCS (PLAT. 5-16) - SUNSHINE</td></tr>
<tr><td colspan="4">HIGH RAIL</td><td colspan="5">LOW RAIL</td></tr>
<tr><td colspan="4"></td><td colspan="5"></td></tr>
<tr><td colspan="4">MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td><td colspan="5">MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="4"></td><td colspan="5"></td></tr>
<tr><td colspan="4">NOTES:
• TOP WEAR = 0.9 MM
• SIDE WEAR = 0.2 MM
• HEAD LOSS = 1.7 %</td><td colspan="5">NOTES:
• TOP WEAR = 0.8 MM
• HEAD LOSS = 1.7 %
• CONTACT BAND = APPROX. MM</td></tr>
</table>

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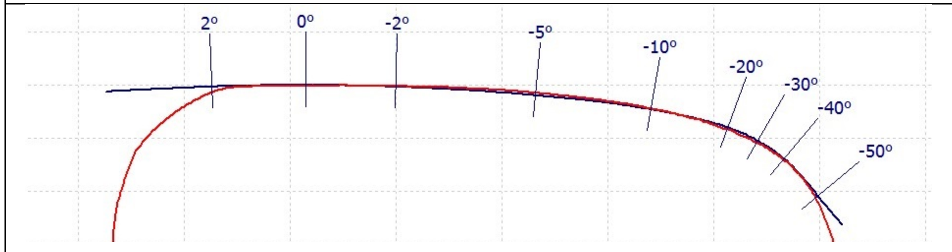
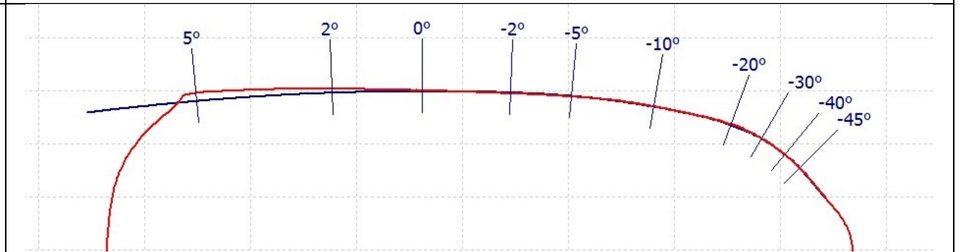
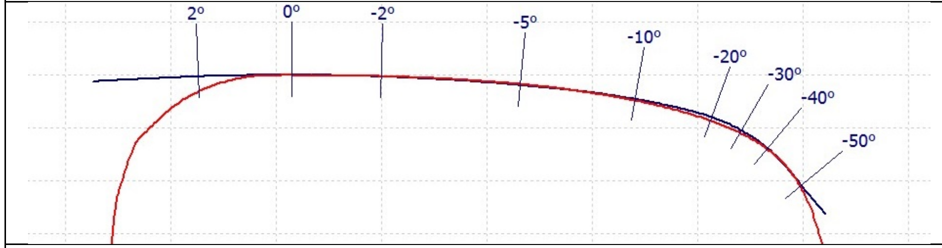
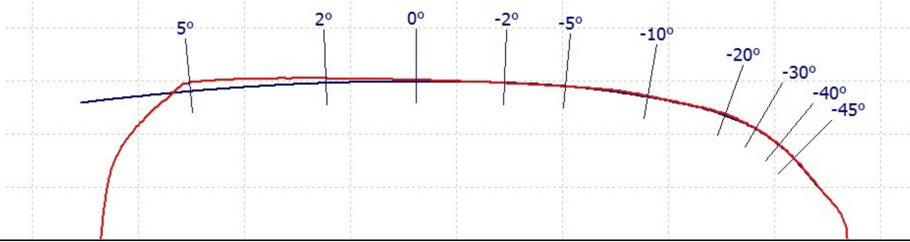
<table>
<tr><td>Location: 5200 m</td><td>Track: Up</td><td>Measured Gauge: 1606 mm</td><td>Curve Radius: 522 m</td><td>Curve Length: 150 M</td><td>Line: SCS (Plat. 5-16) - Sunshine</td></tr>
<tr><td colspan="3">High Rail</td><td colspan="3">Low Rail</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">Measured (red) vs. RPH2000 Rail Template (blue)</td><td colspan="3">Measured (red) vs. RPL2000 Rail Template (blue)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">Notes:
• Top Wear = 1.4 mm
• Side Wear = 1.7 mm
• Head Loss = 4.0 %</td><td colspan="3">Notes:
• Top Wear = 1.9 mm
• Head Loss = 3.8 %</td></tr>
</table>

<table>
<tr><th>LOCATION: 5200 M</th><th>TRACK: DOWN</th><th>MEASURED GAUGE: 1606 MM</th><th>CURVE RADIUS: 518 M</th><th>CURVE LENGTH: 150 M</th><th>LINE: SCS (PLAT. 5-16) - SUNSHINE</th></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 1.1 MM
• SIDE WEAR = 2.6 MM
• HEAD LOSS = 4.1 %</td><td colspan="3">NOTES:
• TOP WEAR = 1.7 MM
• HEAD LOSS = 3.3 %</td></tr>
</table>

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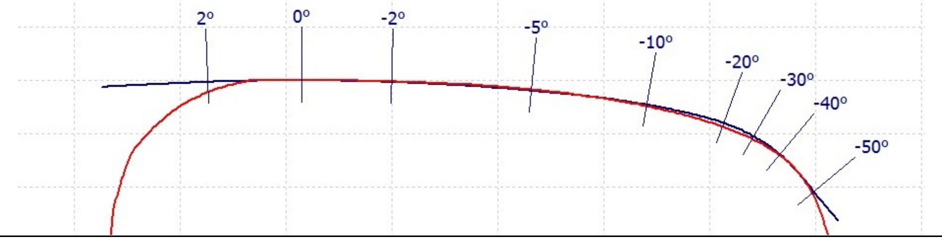
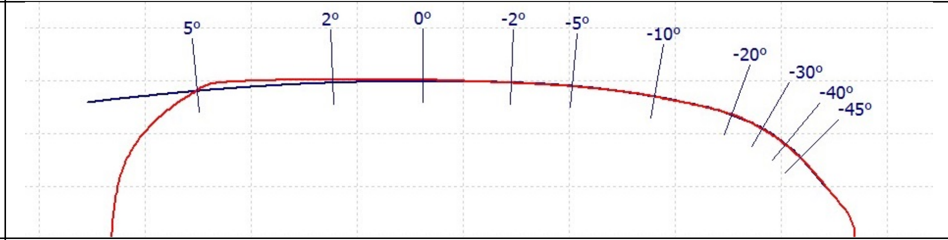
LOCATION: 5500 M	TRACK: UP	MEASURED GAUGE: 1605 MM	CURVE RADIUS: 840 M	CURVE LENGTH: 155 M	LINE: SCS (PLAT. 5-16) - SUNSHINE

HIGH RAIL	LOW RAIL
	
MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)	MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)
	
NOTES: • TOP WEAR = 1.1 MM • SIDE WEAR = 1.8 MM • HEAD LOSS = 3.5 %	NOTES: • TOP WEAR = 1.2 MM • HEAD LOSS = 2.7 %

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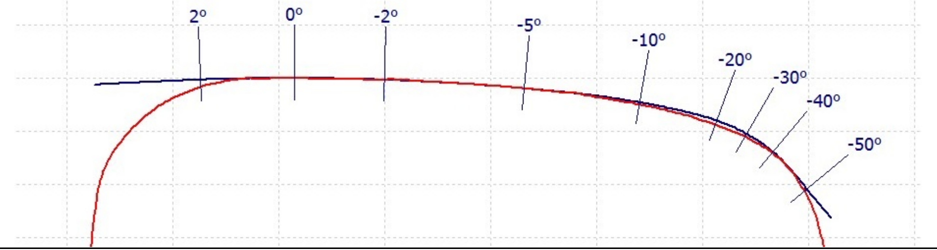
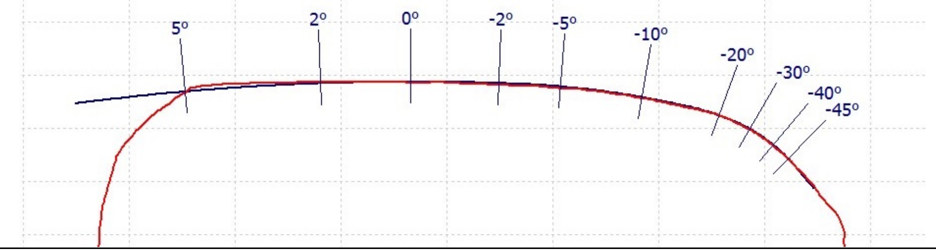
Location: 5500 m	Track: Down	Measured Gauge: 1606 mm	Curve Radius: 844 m	Curve Length: 155 M	Line: SCS (Plat. 5-16) - Sunshine

<table>
<tr><th>High Rail</th><th>Low Rail</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Measured (red) vs. RPH2000 Rail Template (blue)</td><td>Measured (red) vs. RPL2000 Rail Template (blue)</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Notes:
• Top Wear = 1.1 mm
• Side Wear = 0.9 mm
• Head Loss = 2.8 %</td><td>Notes:
• Top Wear = 1.4 mm
• Head Loss = 2.9 %</td></tr>
</table>

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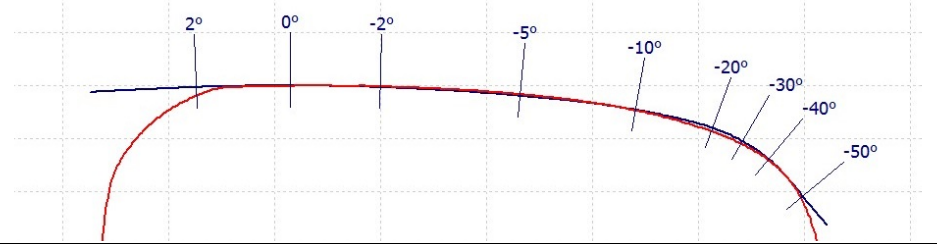
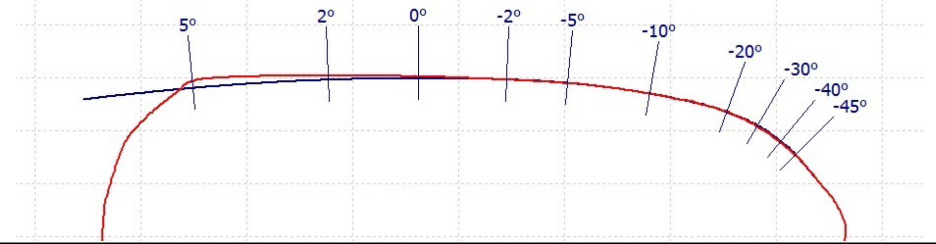
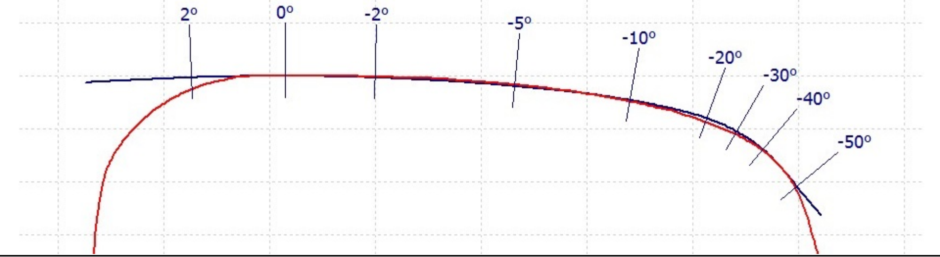
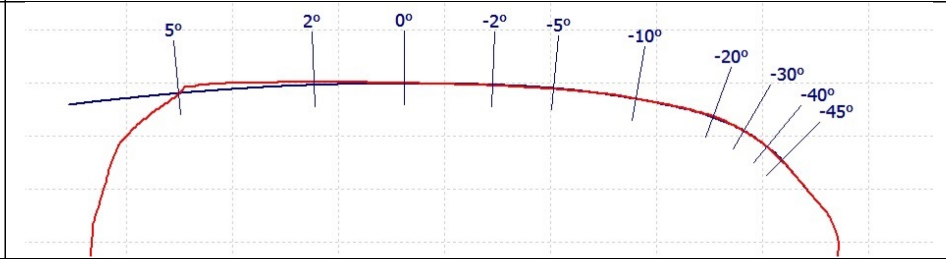
LOCATION: 5757 M	TRACK: UP	MEASURED GAUGE: 1605 MM	CURVE RADIUS: 510 M	CURVE LENGTH: 177 M	LINE: SCS (PLAT. 5-16) - SUNSHINE

HIGH RAIL	LOW RAIL
	
MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)	MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)
	
NOTES: • TOP WEAR = 1.3 MM • SIDE WEAR = 2.0 MM • HEAD LOSS = 4.1 %	NOTES: • TOP WEAR = 1.2 MM • HEAD LOSS = 2.5 %

LOCATION: 5757 M	TRACK: DOWN	MEASURED GAUGE: 1609 MM	CURVE RADIUS: 514 M	CURVE LENGTH: 177 M	LINE: SCS (PLAT. 5-16) - SUNSHINE

HIGH RAIL	LOW RAIL
	
MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)	MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)
	
NOTES: • TOP WEAR = 1.0 MM • SIDE WEAR = 1.9 MM • HEAD LOSS = 2.6 %	NOTES: • TOP WEAR = 1.2 MM • HEAD LOSS = 2.6 % • CONTACT BAND = APPROX. MM

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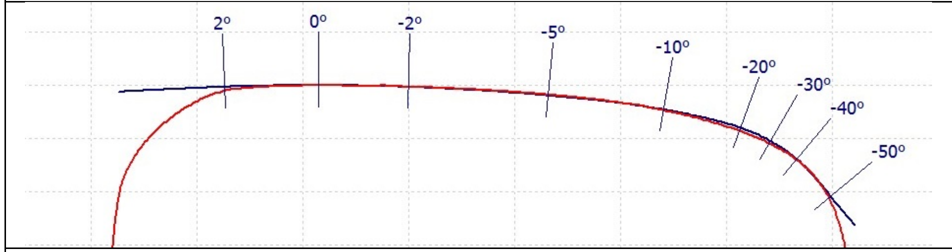
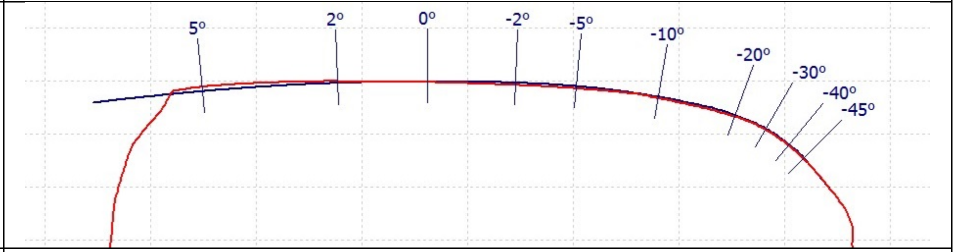
LOCATION: 11700 M	TRACK: UP	MEASURED GAUGE: 1605 MM	CURVE RADIUS: 650 M	CURVE LENGTH: 263 M	LINE: SCS (PLAT. 5-16) - SUNSHINE

HIGH RAIL	**LOW RAIL**
	
MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)	MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)
	
NOTES: • TOP WEAR = 1.4 MM • SIDE WEAR = 0.7 MM • HEAD LOSS = 3.4 %	NOTES: • TOP WEAR = 1.6 MM • HEAD LOSS = 3.3 %

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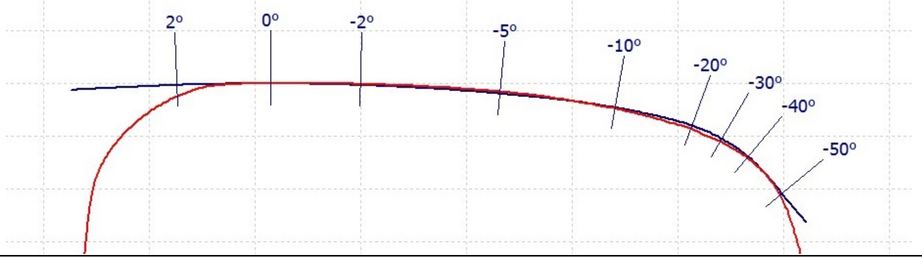
Location: 11700 m	Track: Down	Measured Gauge: 1607 mm	Curve Radius: 625 m	Curve Length: 249 M	Line: SCS (Plat. 5-16) - Sunshine

High Rail

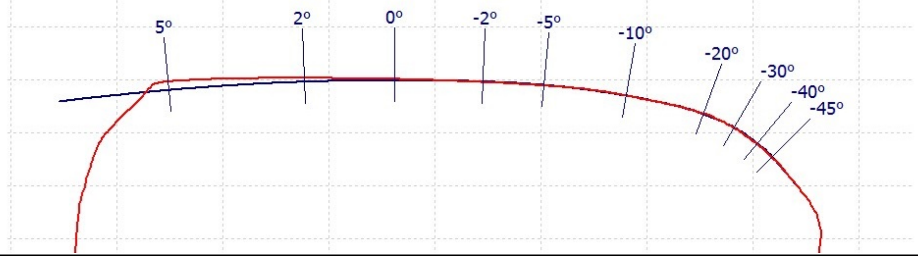


Measured (red) vs. RPH2000 Rail Template (blue)

Notes:

- Top Wear = 1.1 mm
- Side Wear = 2.3 mm
- Head Loss = 3.9 %

Low Rail



Measured (red) vs. RPL2000 Rail Template (blue)

Notes:

- Top Wear = 1.4 mm
- Head Loss = 2.9 %

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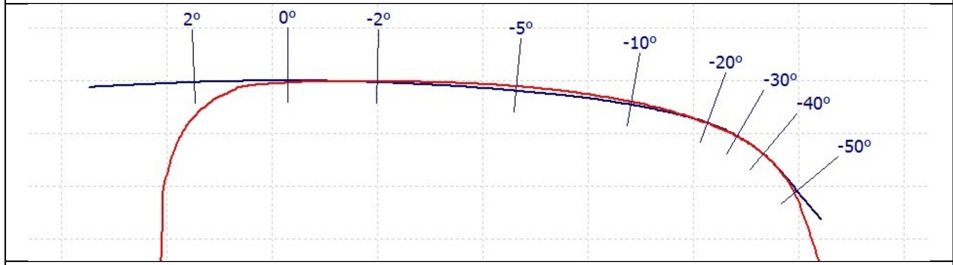
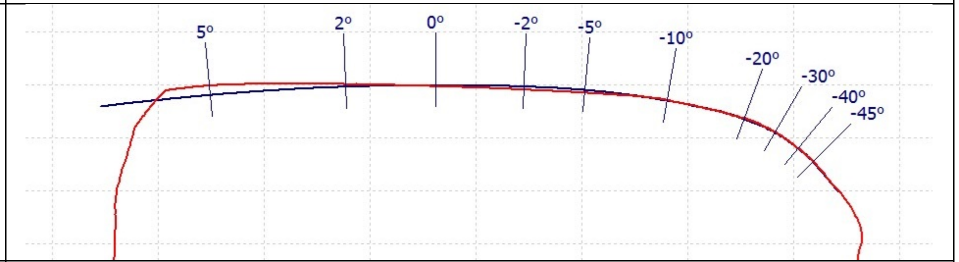
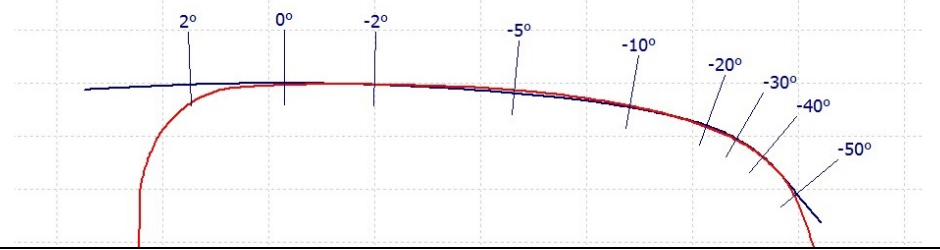
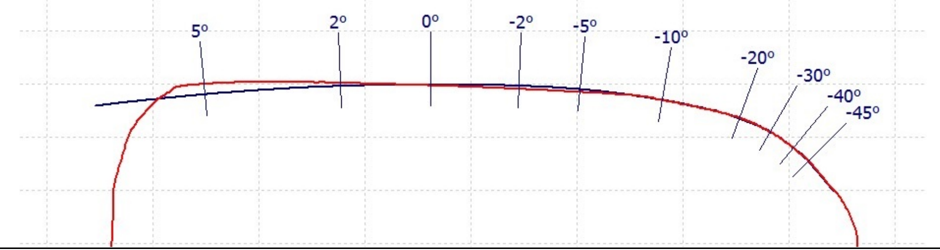
<table>
<tr><td>LOCATION: 12500 M</td><td>TRACK: UP</td><td>MEASURED GAUGE: 1614 MM</td><td>CURVE RADIUS: 250 M</td><td>CURVE LENGTH: 238 M</td><td>LINE: SUNSHINE - BALLARAT</td></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 0.9 MM
• SIDE WEAR = 7.9 MM
• HEAD LOSS = 9.2 %</td><td colspan="3">NOTES:
• TOP WEAR = 1.3 MM
• HEAD LOSS = 3.6 %</td></tr>
</table>

<table>
<tr><th>LOCATION: 12500 M</th><th>TRACK: DN</th><th>MEASURED GAUGE: 1616 MM</th><th>CURVE RADIUS: 254 M</th><th>CURVE LENGTH: 238 M</th><th>LINE: SUNSHINE - BALLARAT</th></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 0.8 MM
• SIDE WEAR = 6.0 MM
• HEAD LOSS = 7.4 %</td><td colspan="3">NOTES:
• TOP WEAR = 1.2 MM
• HEAD LOSS = 3.4 %</td></tr>
</table>

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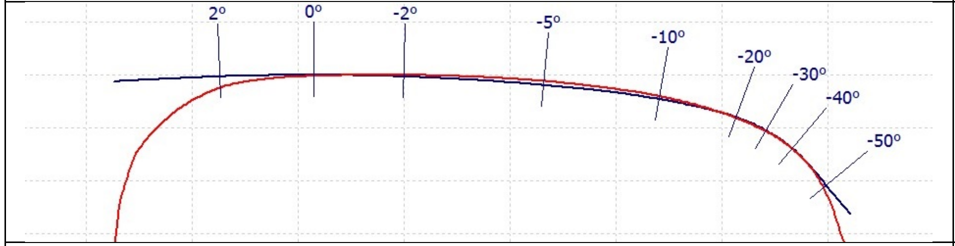
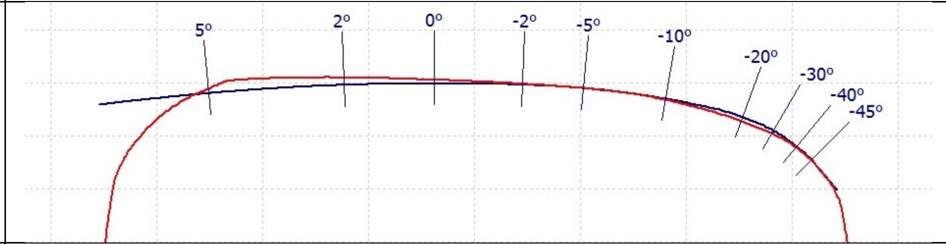
<table>
<tr><td>LOCATION: 19650 M</td><td>TRACK: UP</td><td>MEASURED GAUGE: 1608 MM</td><td>CURVE RADIUS: 455 M</td><td>CURVE LENGTH: 327 M</td><td>LINE: DEER PARK - MANOR JUNCTION</td></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 0.5 MM
• SIDE WEAR = 1.3 MM
• HEAD LOSS = 2.1 %</td><td colspan="3">NOTES:
• TOP WEAR = 0.7 MM
• HEAD LOSS = 1.3 %</td></tr>
</table>

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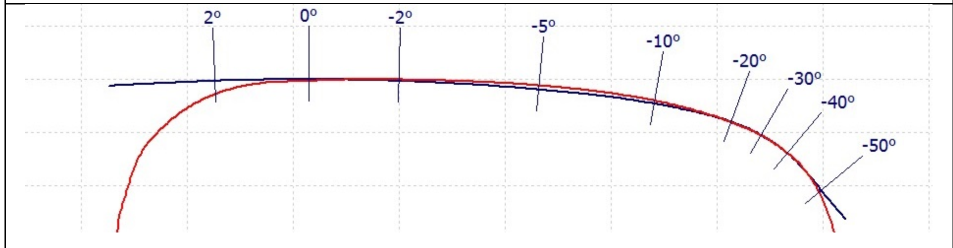
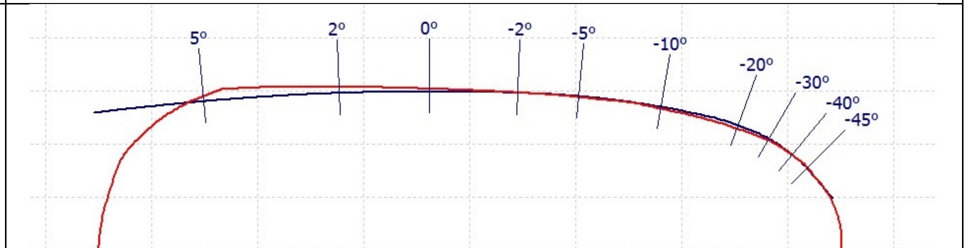
<table>
<tr><th colspan="2">LOCATION: 19650 M</th><th colspan="2">TRACK: DOWN</th><th>MEASURED GAUGE: 1608 MM</th><th>CURVE RADIUS: 455 M</th><th>CURVE LENGTH: 60 M</th><th>LINE: DEER PARK - MANOR JUNCTION</th></tr>
<tr><td colspan="4">HIGH RAIL</td><td colspan="4">LOW RAIL</td></tr>
<tr><td colspan="4">
</td><td colspan="4">
</td></tr>
<tr><td colspan="4">MEASURED (RED) VS. RPH2000 RAIL TEMPLATE (BLUE)</td><td colspan="4">MEASURED (RED) VS. RPL2000 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="4"></td><td colspan="4"></td></tr>
<tr><td colspan="4">NOTES:
• TOP WEAR = 0.6 MM
• SIDE WEAR =1.8 MM
• HEAD LOSS = 2.7 %</td><td colspan="4">NOTES:
• TOP WEAR = 0.8 MM
• HEAD LOSS = 1.4 %
• CONTACT BAND = APPROX. MM</td></tr>
</table>

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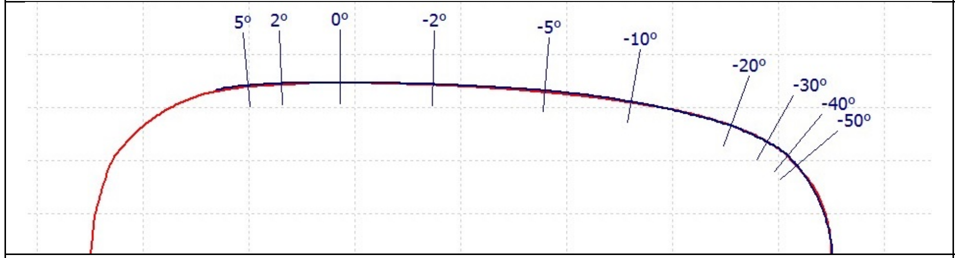
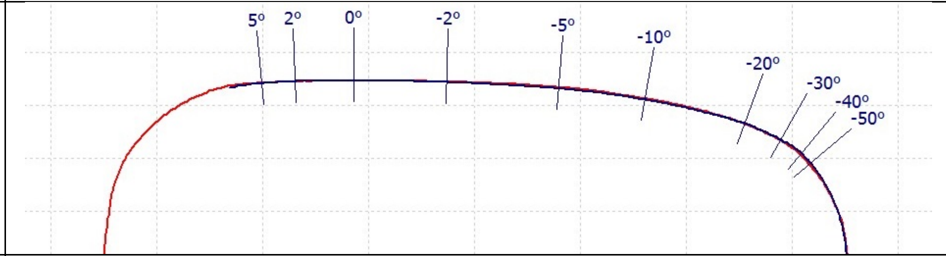
Location: 20350 m	Track: Up	Measured Gauge: 1603 mm	Curve Radius: 1304 m	Curve Length: 1491 m	Line: Deer Park - Manor Junction

High Rail	Low Rail
	
Measured (red) vs. RFR101 Rail Template (blue)	Measured (red) vs. RFR101 Rail Template (blue)
	
Notes: • Top Wear = 0.7 mm • Side Wear = 0.1 mm • Head Loss = 1.7 %	Notes: • Top Wear = 0.5 mm • Head Loss = 1.3 %

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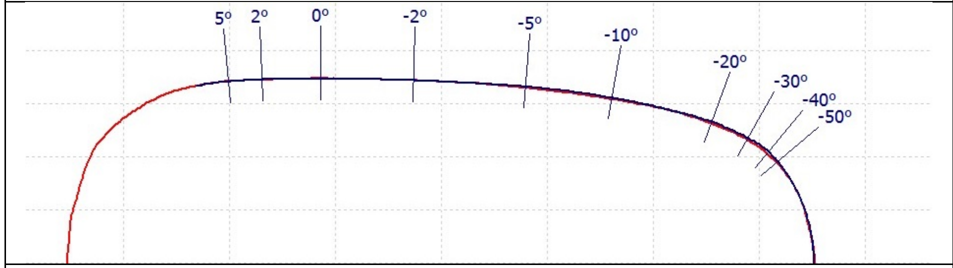
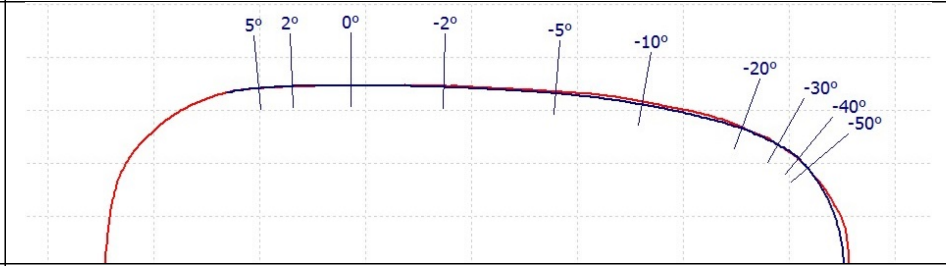
<table>
<tr><td>LOCATION: 20350 M</td><td>TRACK: DOWN</td><td>MEASURED GAUGE: 1602 MM</td><td>CURVE RADIUS: 1300 M</td><td>CURVE LENGTH: 1655 M</td><td>LINE: DEER PARK - MANOR JUNCTION</td></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 0.8 MM
• SIDE WEAR = 0.1 MM
• HEAD LOSS = 1.8 %</td><td colspan="3">NOTES:
• TOP WEAR = 0.5 MM
• HEAD LOSS = 1.3 %</td></tr>
</table>

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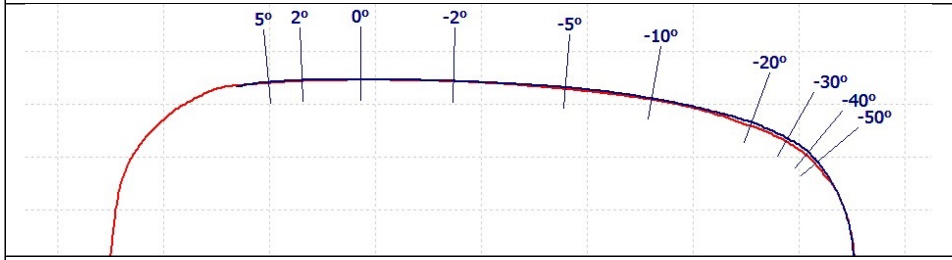
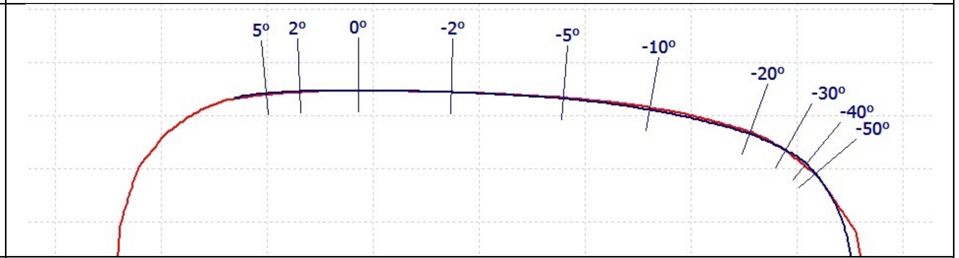
Location: 36900 m	Track: Up	Measured Gauge: 1602 mm	Curve Radius: 2000 m	Curve Length: 2508 M	Line: Deer Park - Manor Junction

High Rail	Low Rail
	
Measured (red) vs. RFR101 Rail Template (blue)	Measured (red) vs. RFR101 Rail Template (blue)
	
Notes: • Top Wear = 0.8 mm • Side Wear = 0.0 mm • Head Loss = 1.8 %	Notes: • Top Wear = 0.7 mm • Head Loss = 1.7 %

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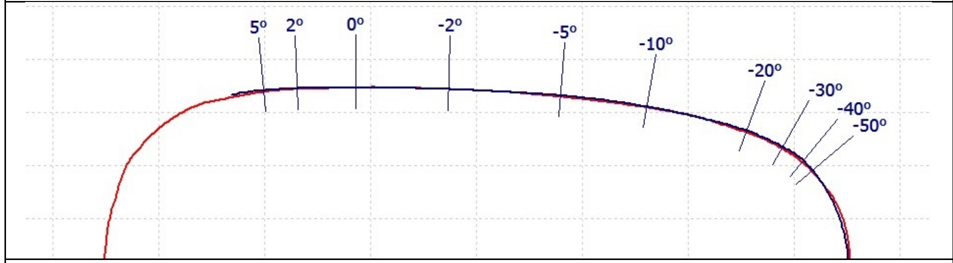
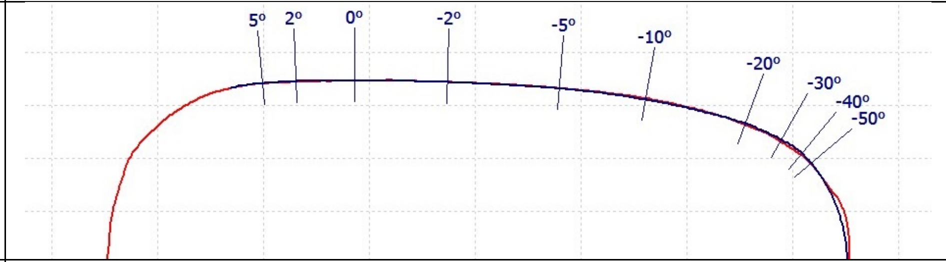
LOCATION: 36900 M	TRACK: DOWN	MEASURED GAUGE: 1604 MM	CURVE RADIUS: 1995 M	CURVE LENGTH: 2502 M	LINE: DEER PARK - MANOR JUNCTION

HIGH RAIL	LOW RAIL
	
MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)	MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)
	
NOTES: • TOP WEAR = 0.6 MM • SIDE WEAR = 0.0 MM • HEAD LOSS = 1.4 %	NOTES: • TOP WEAR = 0.4 MM • HEAD LOSS = 1.1 %

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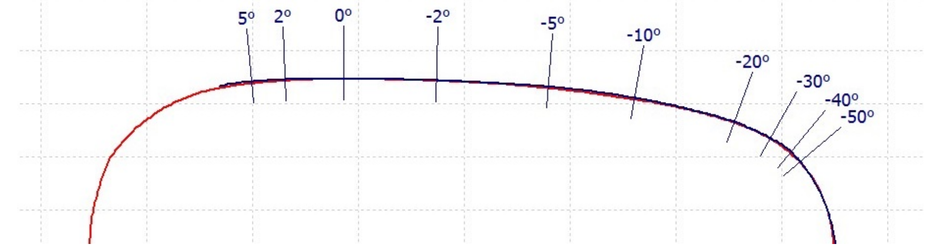
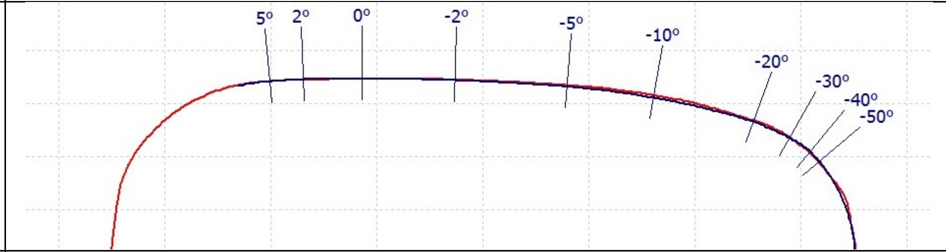
LOCATION: 46000 M	TRACK: UP	MEASURED GAUGE: 1605 MM	CURVE RADIUS: 2000 M	CURVE LENGTH: 2104 M	LINE: DEER PARK - MANOR JUNCTION

<table>
<tr><th>HIGH RAIL</th><th>LOW RAIL</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td><td>MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td></td><td></td></tr>
<tr><td>NOTES:
• TOP WEAR = 0.5 MM
• SIDE WEAR = 0.0 MM
• HEAD LOSS = 1.0 %</td><td>NOTES:
• TOP WEAR = 0.6 MM
• HEAD LOSS = 1.3 %</td></tr>
</table>

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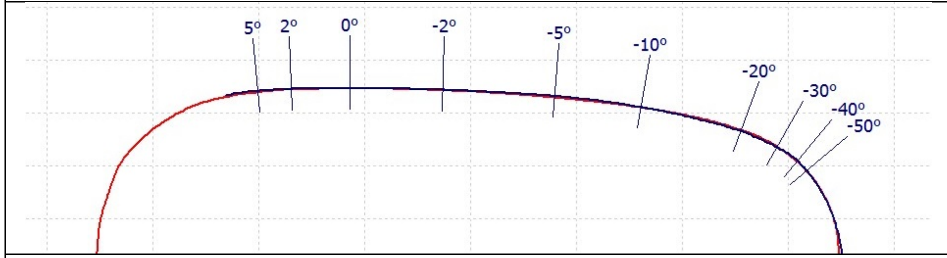
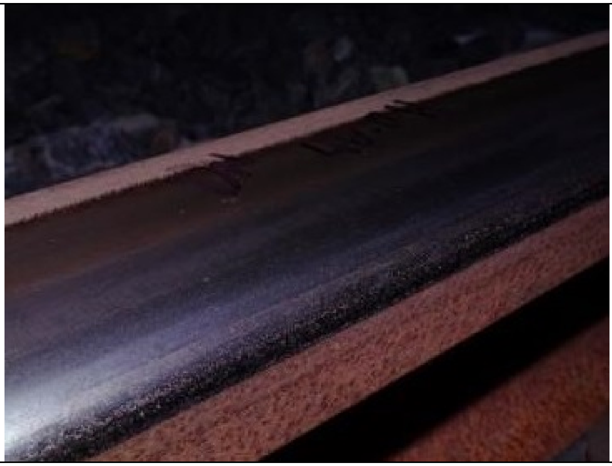
<table>
<tr><td>LOCATION: 46000 M</td><td>TRACK: DOWN</td><td>MEASURED GAUGE: 1602 MM</td><td>CURVE RADIUS: 2004 M</td><td>CURVE LENGTH: 2108 M</td><td>LINE: DEER PARK - MANOR JUNCTION</td></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td><td colspan="3">MEASURED (RED) VS. RFR101 RAIL TEMPLATE (BLUE)</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 0.4 MM
• SIDE WEAR = 0.0 MM
• HEAD LOSS = 0.9 %</td><td colspan="3">NOTES:
• TOP WEAR = 0.9 MM
• HEAD LOSS = 1.6 %</td></tr>
</table>

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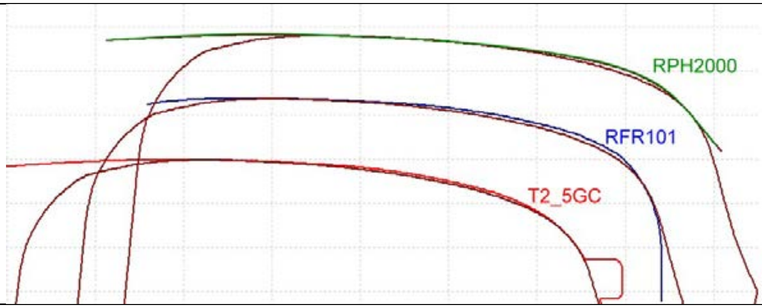
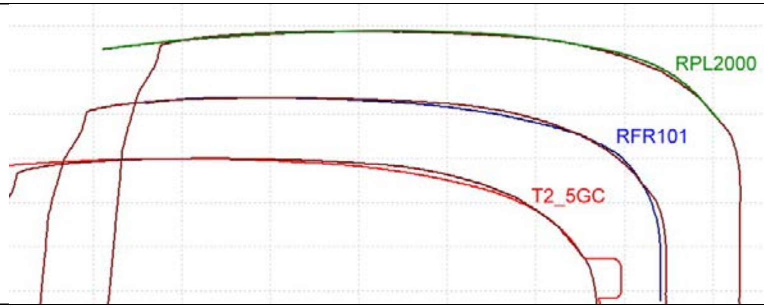
<table>
<tr><td>LOCATION: 56300 M</td><td>TRACK: SINGLE</td><td>MEASURED GAUGE: 1607 MM</td><td>CURVE RADIUS: 664.4 M</td><td>CURVE LENGTH: 159 M</td><td>LINE: SUNSHINE - BALLARAT</td></tr>
<tr><td colspan="3">HIGH RAIL</td><td colspan="3">LOW RAIL</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">MEASURED VS. POSSIBLE RAIL TEMPLATES</td><td colspan="3">MEASURED VS. POSSIBLE RAIL TEMPLATES</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">NOTES:
• TOP WEAR = 0.6 MM
• SIDE WEAR = 4.0 MM
• HEAD LOSS = 4.3 %</td><td colspan="3">NOTES:
• TOP WEAR = 0.7 MM
• HEAD LOSS = 1.9 %</td></tr>
</table>

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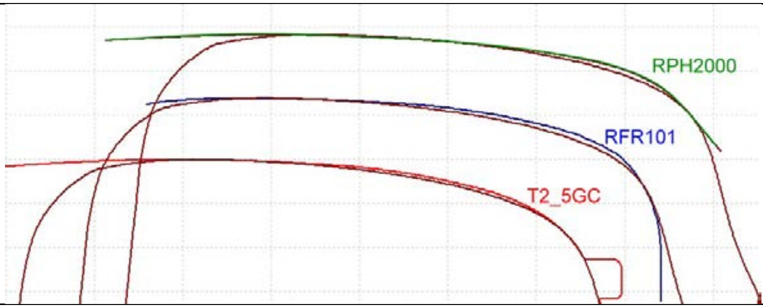
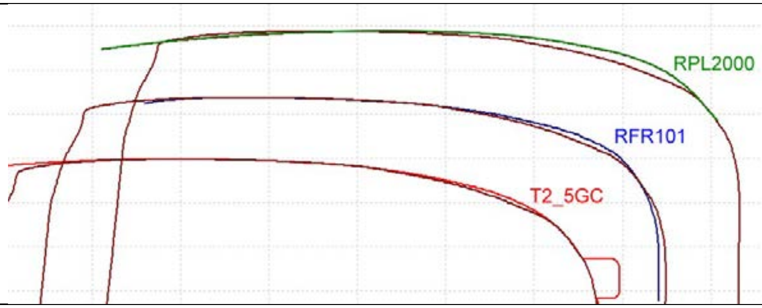
LOCATION: 57000 M	TRACK: SINGLE	MEASURED GAUGE: 1608 MM	CURVE RADIUS: 680.7 M	CURVE LENGTH: 148 M	LINE: SUNSHINE - BALLARAT

HIGH RAIL	LOW RAIL
	
MEASURED VS. POSSIBLE RAIL TEMPLATES	MEASURED VS. POSSIBLE RAIL TEMPLATES
	
NOTES: • TOP WEAR = 0.7 MM • SIDE WEAR = 4.3 MM • HEAD LOSS = 4.6 %	NOTES: • TOP WEAR = 0.7 MM • HEAD LOSS = 2.0 %

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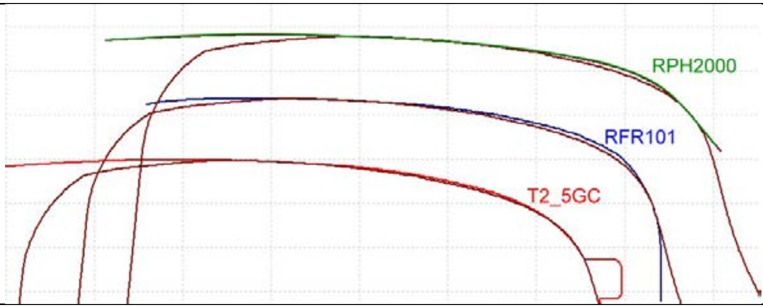
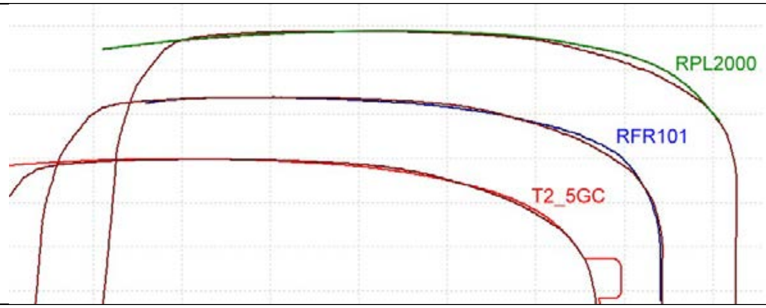
<table>
<tr><th>Location: 58300 m</th><th>Track: Single</th><th>Measured Gauge: 1607 mm</th><th>Curve Radius: 700 m</th><th>Curve Length: 200 M</th><th>Line: Sunshine - Ballarat</th></tr>
<tr><td colspan="3">High Rail</td><td colspan="3">Low Rail</td></tr>
<tr><td colspan="3">
</td><td colspan="3">
</td></tr>
<tr><td colspan="3">Measured vs. Possible Rail Templates</td><td colspan="3">Measured vs. Possible Rail Templates</td></tr>
<tr><td colspan="3"></td><td colspan="3"></td></tr>
<tr><td colspan="3">Notes:
• Top Wear = 0.4 mm
• Side Wear = 4.4 mm
• Head Loss = 4.5 %</td><td colspan="3">Notes:
• Top Wear = 0.7 mm
• Head Loss = 1.9 %</td></tr>
</table>

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APPENDIX F
FRICTION MEASUREMENTS

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TABLE F1: SUMMARY OF TRIBOMETER RESULTS

Description		**Up Track (Towards Southern Cross Station)**			**Down Track (Towards Spion Kop)**		
		Low Rail Top	**High Rail Gauge**	**High Rail Top**	**Low Rail Top**	**High Rail Gauge**	**High Rail Top**
Curve start and end (m)	1371 to 1510	0.53	0.27	0.39	0.42	0.42	0.42
Radius (m)	180	0.56	0.27		0.45	0.43	0.46
Actual start and end (m)	1368.8 to 1404.3	0.52	0.25		0.49	0.47	0.45
Signal location	Up track (West Melbourne Depot)	0.56			0.48	0.47	0.46
Comments	Graphite film on Up Track High rail gauge	0.59			0.45	0.45	0.49
	Dry on Down Track	0.53			0.52		
	Mean	***0.55***	***0.26***	***0.39***	***0.47***	***0.45***	***0.46***
Curve start and end (m)	1525 to 1650		0.31	0.35		0.35	
Radius (m)	181 (Up) 185 (Down)		0.39	0.39		0.36	
Actual start and end (m)	1569.7 to 1609.9		0.29			0.33	
Signal location	Down track (North Melbourne Station)		0.31			0.37	
Comments	Graphite on Down Track		0.32			0.27	
			0.31			0.28	
						0.28	
	Mean		***0.32***	***0.37***		***0.32***	
Curve start and end (m)	1723 to 1835		0.21			0.24	
Radius (m)	180		0.23			0.24	
Actual start and end (m)	1769.7 to 1787.8					0.22	

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Description		Up Track (Towards Southern Cross Station)			Down Track (Towards Spion Kop)		
		Low Rail Top	High Rail Gauge	High Rail Top	Low Rail Top	High Rail Gauge	High Rail Top
Signal location	Up track (Dynon Road Underpass)					0.25	
	Mean		***0.22***			***0.24***	

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