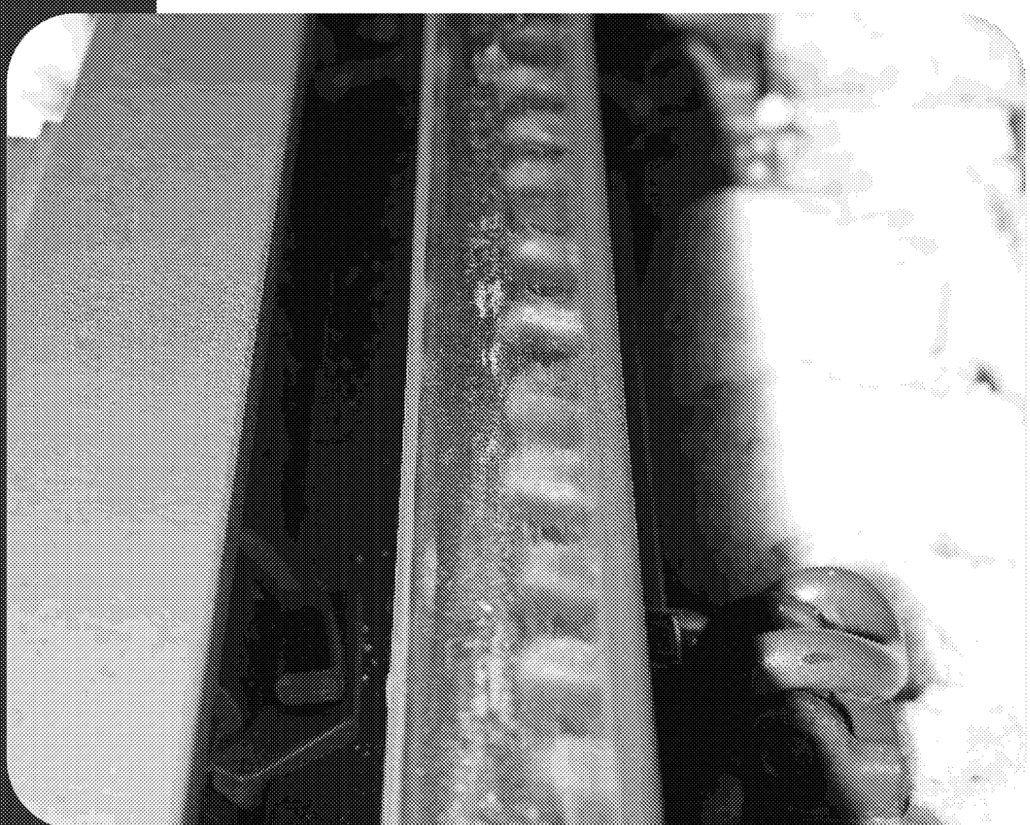
ALSTOM

Ligne de la Confédération Line

Rev3 Report for

Pre-Grind Inspection Optical Measurements



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Rev3 Report for

Pre-Grind Inspection Optical Measurements

Submitted by

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Winnipeg, MB

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1 OVERVIEW

Background

Alstom is responsible for the maintenance of the mainline corridor of the Confederation Line running from Blair Station to Tunney's Pasture Station. This alignment consists of 12.5 route kilometres of double track. The track is primarily ballasted and elevated with a short tunnel section through downtown Ottawa. Figure 1 depicts the route map for the Confederation Line and the Belfast Maintenance yard.

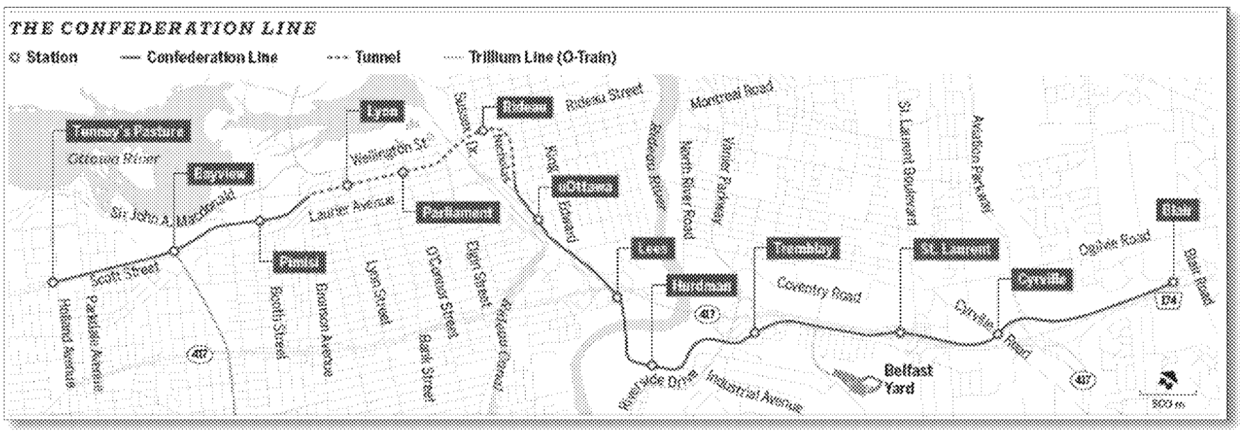


Figure 1: Confederation Line Route Map

The Confederation Line entered revenue service in Q4 of 2019 and is already seeing widespread corrugation, specifically in curves, along with evidence of wheel flanging. Alstom issued a request for pricing with a scope of work to complete a pre-grind optical rail measurement inspection. This pre-grind inspection will provide input on the severity of current rail conditions, improve understanding of the existing rail profiles, and provide a level of effort for rail grinding to restore the profiles to the original 115RE.

Purpose, Objectives, and Scope

The purpose of this work is to collect and analyze rail profile data for the main alignment (approximately 25 kilometres of mainline track) and tracks of interest in the Main Storage Facility (MSF). Based on this data, ARM will provide insight into the existing rail profile conditions (including potential root causes) and recommendations related to next steps including the level of effort to return to the profiles to 115RE 8" radius shape.

In order to complete this project, ARM has completed the following tasks:

1. **Objective 1** – Complete optical rail measurements using the ARM ORMV-2
    - **a.** One weekend of work to collect mainline and MSF data
    - **b.** Collect photographs of rail conditions to pair with collected data
2. **Objective 2** – Analyze data and provide report
    - a. Includes strip charts, 2-ups, and recommendations on grinding

2 November, 2020 Track Inspection Summary

ARM completed a one night visual track inspection before starting the grind program on the morning of November 27, 2020. The track inspection supported our Rail Maintenance Specialist by providing a better understanding of the overall system condition from a wheel/rail interface perspective. The inspection also helped identify the current condition of the proposed work locations and compare to other track sections along the alignment.

The driving factor for a rail grinding program is to re-establish the rail profiles to help gain back the intended benefits: prolonged rail life, improved ride quality and steering, wheel pummeling (when multiple rail profiles are installed), and reduced noise/vibration. In addition to restoring the rail profile, other issues to be addressed included removing corrugation and/or rolling contact fatigue. Details and the importance of removing these rail surface conditions include:

Rolling Contact Fatigue (RCF) – uncontrolled RCF can lead to more severe rail defects such as rail fractures, spalls, and squats and severe RCF can impede readings from ultrasonic testing. Light RCF will be removed in profile grinding while moderate/severe RCF will require additional work (see Figure 2 for visual examples). Our rail grinding specialist did not identify any major RCF on the Confederation Line but was shown photographs of some locations with more severe RCF. The RCF shown to the grinding specialist appears to be the result of high gauge corner contact stress caused by the low rail being very flat (close to 14 inch radius) which causes the wheels to increase their angle of attack into the high rail. In our experience, premium head hardened steel without a preventive grind program is prone to the development of RCF due to the light axle loads of transit agencies and low rail wear values along with high stress profiles. In systems like heavy haul where annual tonnage and axle weights are higher these rail surface features are naturally worn out. The high rail RCF could be controlled by re-establishing an 8 inch radius on the low rail and creating asymmetric profiles to support steering.

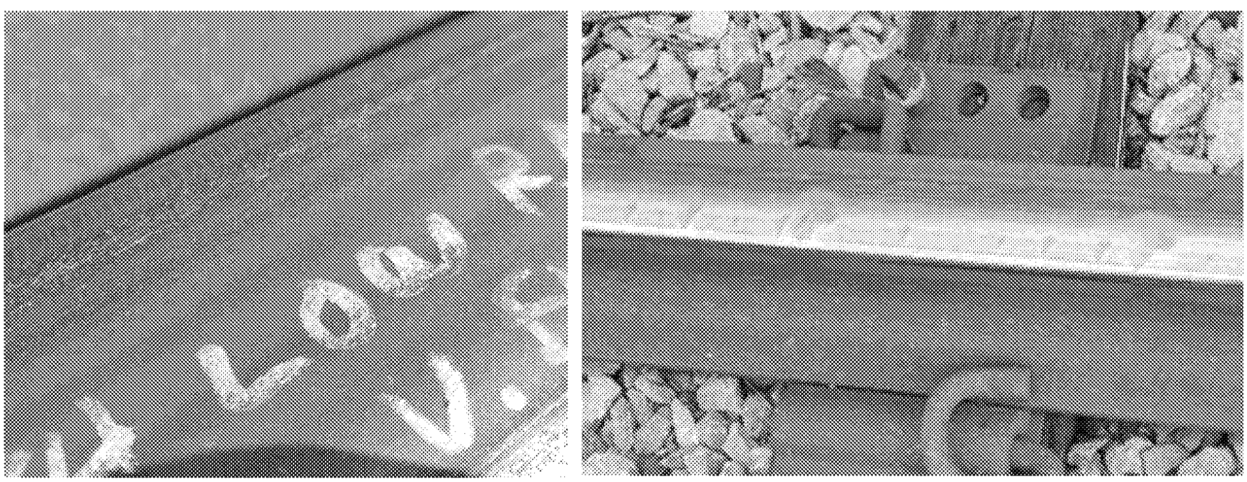


Figure 2: Example RCF (not from Confederation Line) of gauge corner cracking (left image) and top of rail surface defects (right image)

Corrugation – a repetitive pattern of shallow, wavelike depressions along the rail surface that can result in rough riding track, undesirable noise, and can lead to more severe defects such as crushed heads and head/web separation. Corrugation was prevalent throughout the

Confederation Line and most severe in curves. While low rails more commonly have corrugation (and more severe corrugation) due to the wheel/rail interaction, the high rails on the Confederation Line also demonstrated moderate to severe corrugation.

Figure 3 provides example corrugation from the Confederation Line on various track geometry including low rails, high rails, and restrained rails. The right two images show more severe corrugation on the restrained rails in sharper curves.

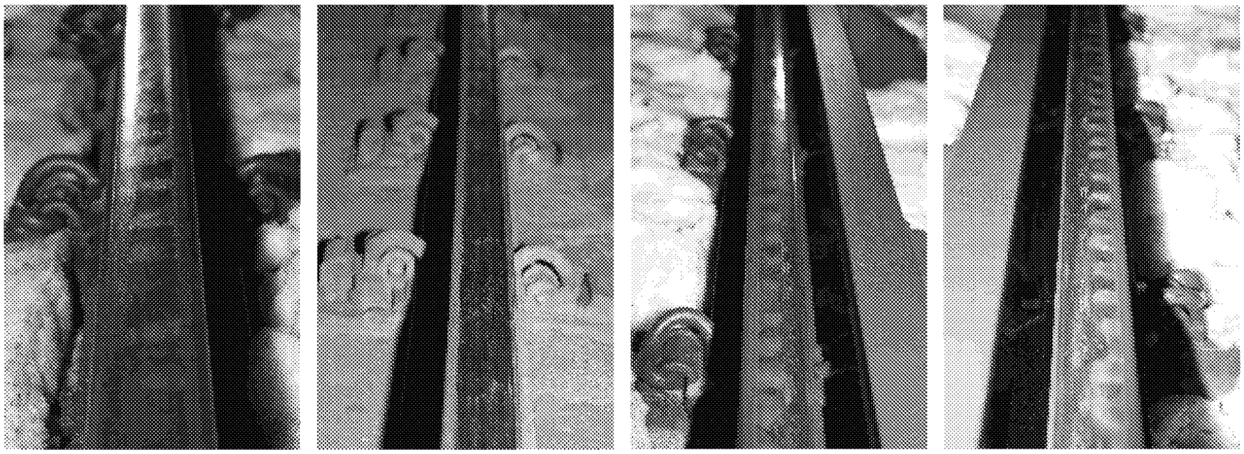


Figure 3: Example Corrugation from the Confederation Line

In addition to the heavy corrugation, which was quite surprising to the project team given the Confederation Line has only been in revenue service for approximately one year, ARM noticed the rail profiles were very flat and that in some instances severe flanging was occurring. The left image in Figure 4 shows the Confederation Line rail profiles compared to a new rail profile that would have an 8 inch crown radius. The light coming through between the template and the rail shows a gap indicating the crown radius is closer to 12 or 14 inches. Flat rails are prone to the development of corrugation due to the wheel/rail interaction. In the right image of Figure 4, the gauge corner shows wear and steel dust can be seen at the base of the rail adjacent to the fastener. This is indicative of gauge face contact with the wheel flange – this can be reduced with correct wheel and rail profiles to help steer the train through the curve and minimized by applying lubrication. In conjunction with the 1:60 tapered wheels being used on the vehicle fleet, the flat rails and high gauge wear are leading to, and indicating, lateral instability.

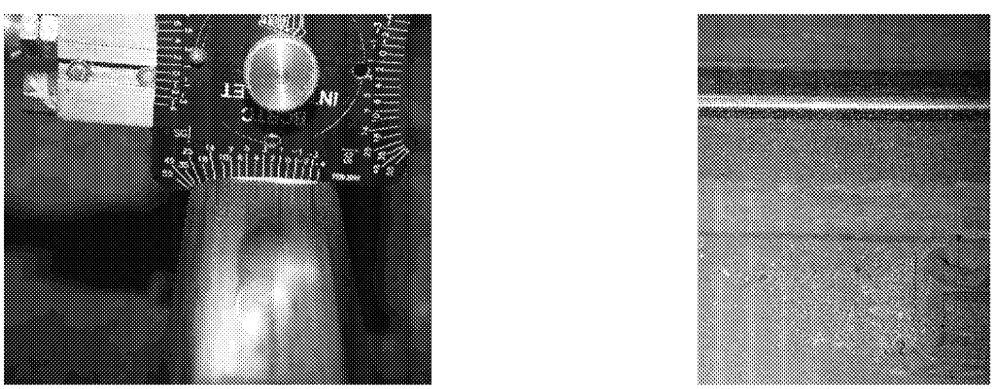


Figure 4: Flat rails (left image) and rail flanging showing steel dust by fasteners (right image)

The pre-grind inspection was informative and helped guide the project team on the most efficient use of the grinding shifts. The original work plan from Alstom requested grinding at curves 210, 240, and 280 but after the track inspections the work was re-ordered to address the more severe corrugation with a work order of:

1. Curve 230 – most severe corrugation
2. Curve 240 – most severe corrugation
3. Curve 280 – Alstom list and moderate/severe corrugation
4. Curve 220 – lower priority and only if time permits

Since grinding these curves back to the original 115RE rail profile, ARM noticed that corrugation is already beginning to return within three (3) months of traffic. Table 1 provides an example of the pre-grind and post-grind rail profiles (more profiles available in ARM's Post-Grind report). The high rail pre-grind images were significantly over-relieved on the gauge corner side which can also result in two-point contact. Gauge corner relief is not a major concern and high rails should be somewhat over-relieved to help prevent strong conformal contact. The grinding program helped correct some of the over-relief at the gauge corner to return to a more realistic level but full removal was not considered necessary as it would require far too much metal removal without any benefit. The high rail and low rails are not a perfect match as again, the level of effort to achieve this is much higher than the benefit. Furthermore, it appears the wheel/rail profile is not optimized for steering through the curves. The ARM Rail Maintenance Specialist worked the rail profiles to positions where high rail contact is more towards the gauge corner and low rail contact is towards the field side. This orientation helps promote steering through the curve to prevent poor wheel/rail contact forces and reduce flanging.

Table 1: Pre and Post Grind Profiles at Curve 230

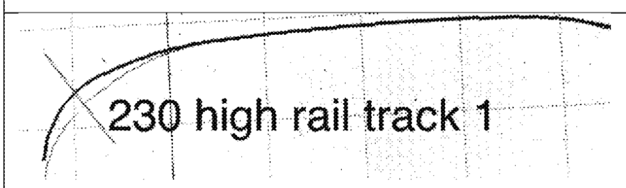
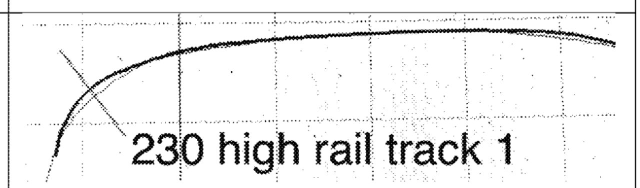
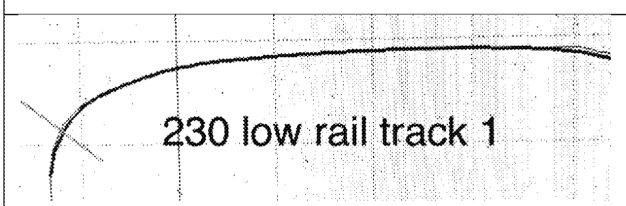
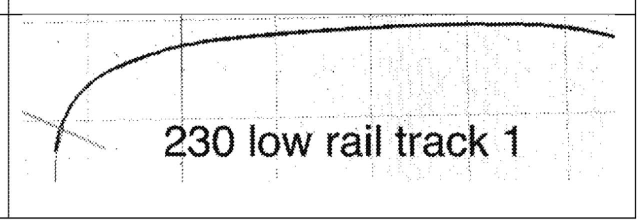
Pre-Grind	Post-Grind
	
	

Figure 5 shows the low and high rail as they look today. In general, the profiles are holding reasonably well after three months with some flattening perhaps occurring on the low rail. The strip charts of the same are on Figure 6 show no exceptional values through the curve but do highlight the gauge wear that is occurring on the high rail. The Confederation Line track standards indicate that at a gauge face wear level of 4.5 mm the rails should be transposed. Currently, the high rail gauge wear is reaching 3mm on average since the system opened.

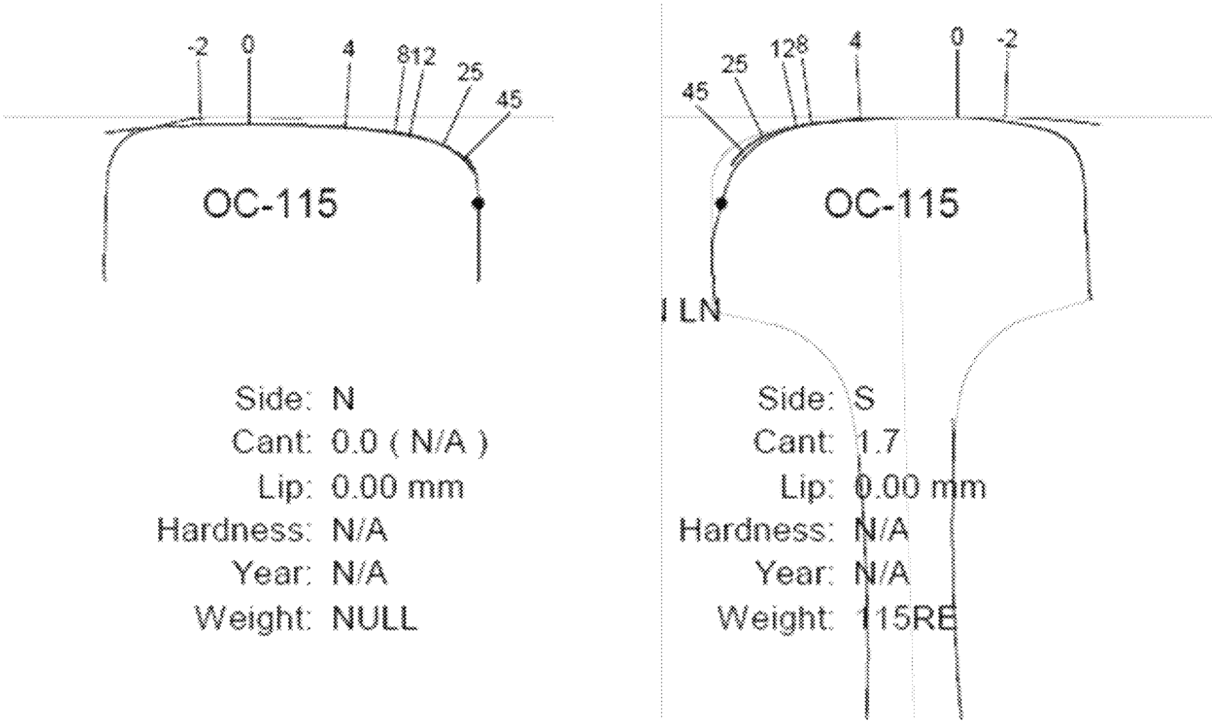


Figure 5: 2-Up profiles of Curve 230 (left rail is low rail, right rail is high rail)

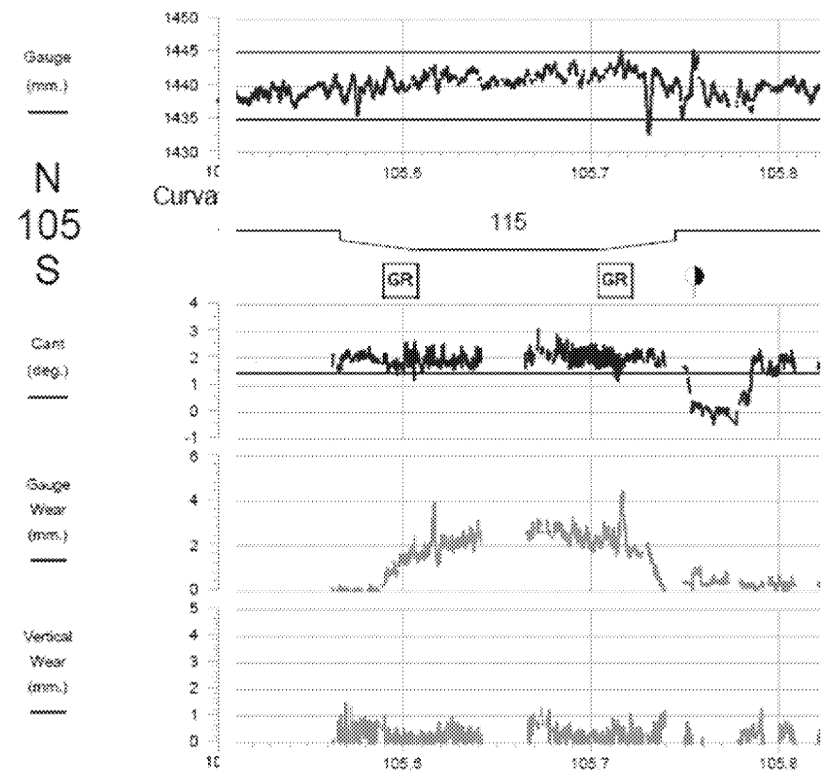


Figure 6: Strip chart of Curve 230 showing track gauge and hi-rail wear metrics

3 Optical Rail Profile Measurements February 2021

ARM collected a system-wide optical profile measurement the weekend of February 6, 2021. The mainline track took one full night to complete both Track 1 and Track 2 using the ARM ORMV-2 test vehicle (see Figure 7). Profile measurements were collected at one foot intervals to try to gather as many profile samples as possible. Traditionally, ARM would collect at five foot intervals but the Confederation Line guard rails and areas with snow can create limitations to the laser measurement system. At a higher collection density intervals, the potential for collecting at least some good profiles within a track segment are improved.

Figure 7: ORMV-2 Test Vehicle

The KLD Profile System on the ORMV-2 collects traditional rail wear and profile parameters as well as gauge face angle, rail cant, and track gauge data. This initial run is a “baseline” collection or “master” run that can be used to compare to future rail profile measurements to compare and evaluate profile performance and after rail grinding programs. ARM collects additional information during master runs to ensure future collection can be compared by including details about stations, crossings, interlocks, and any other trackside features that can be used for referencing future data.

The appendix folder includes the complete set of strip charts based on the collected data and representative “2-up” profiles. Details on both of these charts are provided in the following subsections of this report.

3.1 Rail Profile Strip Charts

ARM has prepared four (4) strip chart files in total, two (2) unique for each Track 1 and Track 2 along with a track segment report (TSR) for each track. These charts provide the following:

- Vertical wear in millimetres for left and right rails

- Gauge wear in millimetres for left and right rails
- Rail cant in degrees for left and right rails
- Gauge Face Angle (GFA) in degrees for left and right rail
- Percent head loss for both left and right rail
- Track gauge
- Track curvature showing left-hand and right-hand curves with degree of curvature
- Track features like stations, grade crossings, switches, etc.

Data gaps within the strip charts are either the result of snow in the guideway or the guard rails in sharp curves. Both of these conditions result in the laser being reflected prematurely and the system loses key reference points. The 2-ups provide an opportunity to still review the rail profile shapes so these features don't cause a complete loss of data but do require additional manual effort to thoroughly review these locations.

Vertical Wear

In general, ARM noticed very little total vertical wear and there is no risk of any grind program removing metal that would put the rail into a warning or condemnable condition. Vertical wear varies between 0 and 2 mm and Figure 8 provides an example section of data where vertical wear is approaching 2mm. While this is not high total wear, it is surprising to see vertical wear this high after only a year or two of traffic. Considering transit agencies may have a vertical wear condemning limit between 12mm and 16mm and expect rail to last 25+ years, the current wear measurements suggest Ottawa will not see rail lifespan anywhere near this limit under the current annual rate of wear.

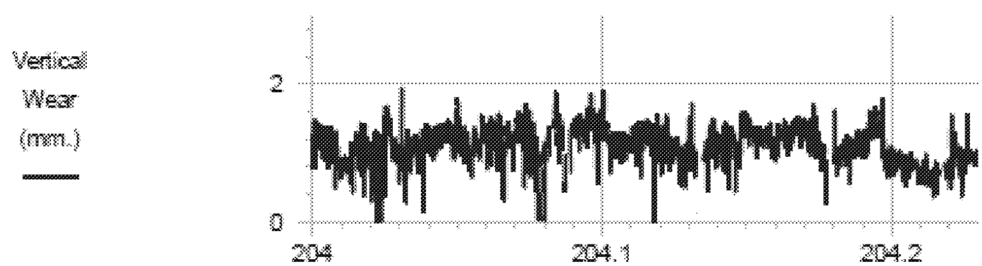


Figure 8: Sample vertical wear data

Higher or lower vertical wear showed little difference between tangent or curve track. It is possible this wear has been stable since the system opened but without historical data and a detailed history of how the initial rail grinding was performed it is not possible to create any trends from the existing data. Future profile measurement runs will help assist this process. ARM did notice that the rails were quite flat which is represented by a wide running band.

Figure 9 shows a typical 8 inch radius rail template (typical new rail) compared against the existing Ottawa profile. The gap between the template and the rail illustrates the rail crown radius is quite flat (approaching a 12 or 14 inch radius). The wide shiny running band also demonstrates the wheels are making broad contact with the rail. These conditions are conducive to the development of corrugation and consistent with reports of ride quality and noise issues on the system.

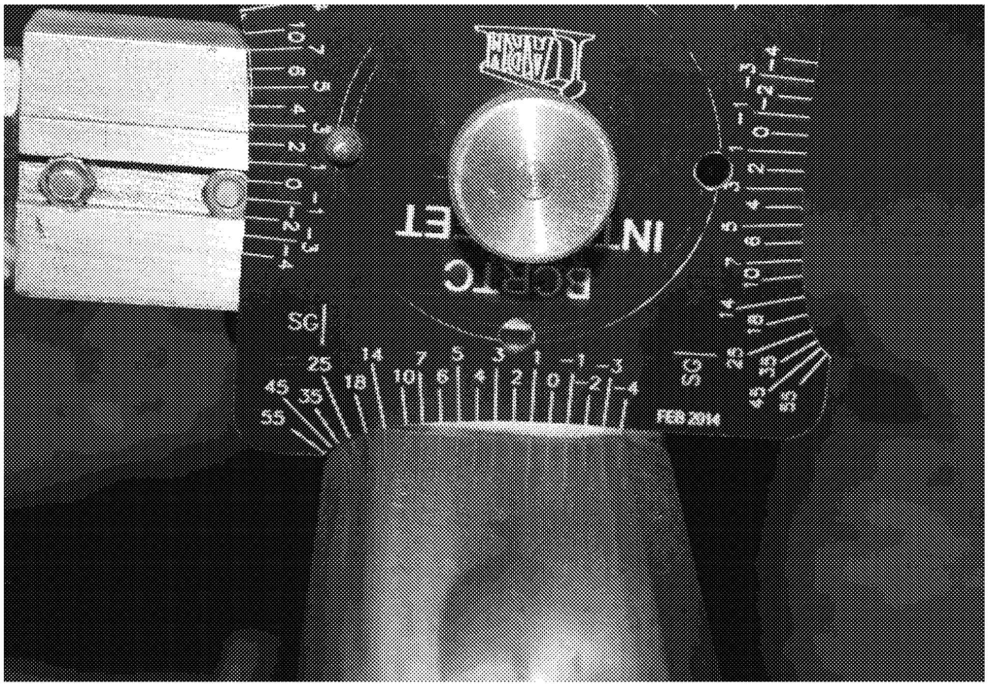


Figure 9: Bar gauge measurement with 8" radius template on Ottawa Rail

Vertical wear was generally seen to be 1mm or less and was not a concern in terms of reaching condemning limits of 12mm according to the Confederation Line Track Standards.

Gauge Wear

Gauge wear was mostly consistent and low (under 0.4mm) across the entire system with the exception of the high rails in sharper curves (approximately 7 degrees and sharper). The gauge wear is seen over 2mm in the sharpest curves. Figure 10 shows the climbing gauge wear through the 11.6 degree curve around MP 100.4 to 100.8. Similar to vertical wear, these are not particularly outstanding values but they are significant because of the young age of the system. This level of gauge wear is not expected within a year or two of operations.

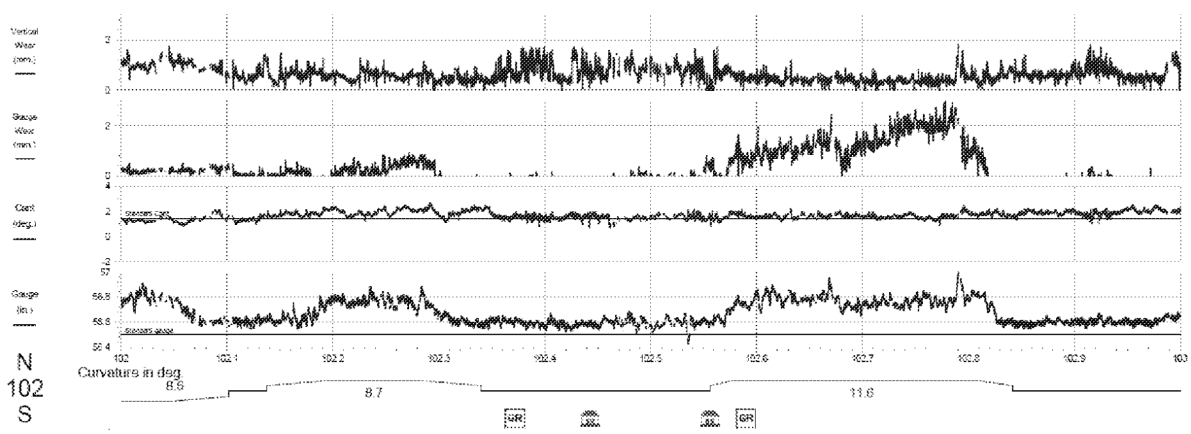


Figure 10: Example of high gauge wear in a sharp curve

The potential root causes for the high gauge wear in sharper curves could be one of, or a combination of, the following conditions:

1. Incorrect wheel/rail dynamics due to mismatched wheel and rail profiles which are not promoting steering through the curves
2. Incorrect operating speed for the superelevation in the sharper curves
    a. More likely to affect the low rail versus the high rail (unlikely to operate over the balance speed)
3. Steerable bogies may be 'attacking' these curves improperly and/or not steering through the sharper curves due to existing setup
    a. Vancouver SkyTrain went through steerable bogie issues
    b. LA Metro had issues with long wheel base and stiff bogies that resulted in higher noise and wear rates
4. Limited or no lubrication – dry rail conditions

Figure 11 shows the gauge corner of a high rail with a slight lip and a shiny gauge corner – both illustrated the contact occurring and the severity of the gauge corner wear. This condition was seen at many of the sharper curves with guard rails. Figure 12 illustrates the metal dust that accumulates at the base of the rail due to strong flanging forces and no lubrication.

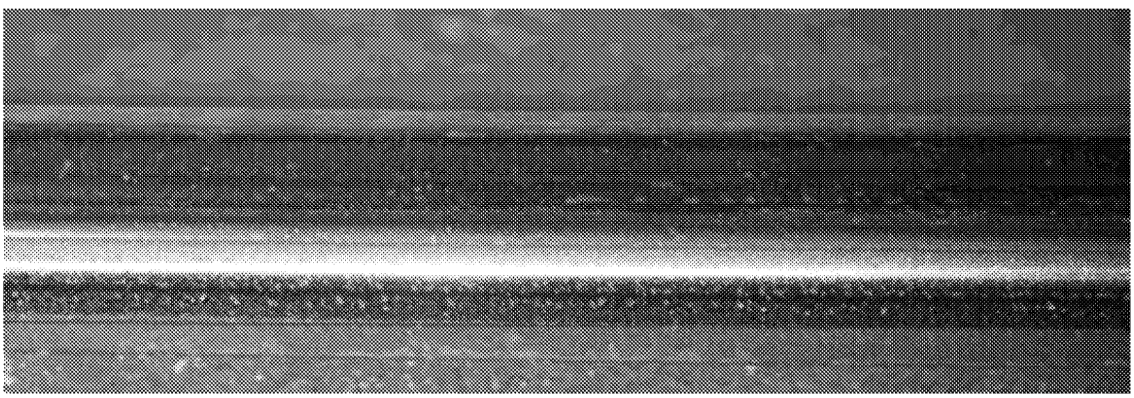


Figure 11: Gauge corner contact and gauge face wear (between red lines)

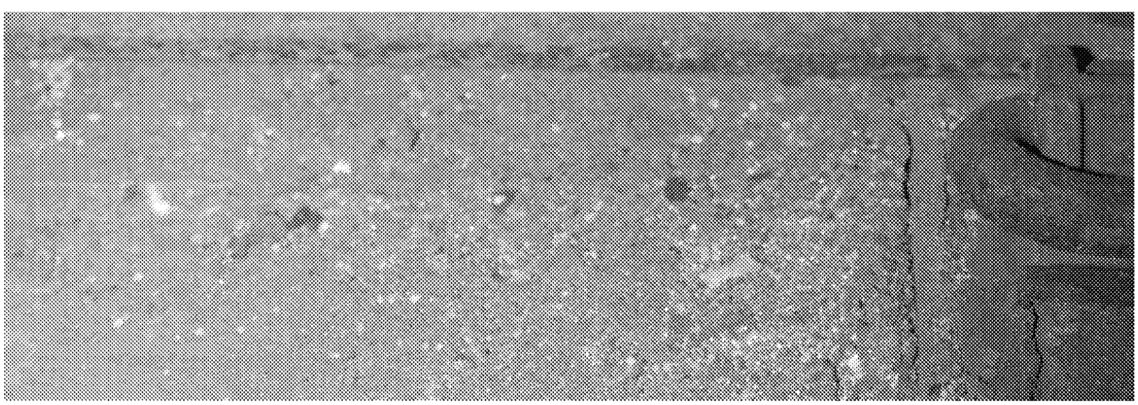


Figure 12: Resulting metal dust at base of rail from gauge wear

No exceptions to gauge wear were recorded according to the Confederation Track Standards limits of 9mm gauge face wear. However, some high rails in sharp curves exhibit wear of up to 3mm which is nearing the 4.5mm transpose limit.

Further review of this specific rail condition is required in addition to a review of wheel profiles. A future grind program could also provide interim rail profiles to help promote steering and a test set up in one or more curves to compare if a slight rail profile modification helps improve this condition versus rail profiles with only 115RE.

Rail Cant

Standard rail cant is 1.4 degrees – this is the cant of the rail itself and should not be confused with superelevation (track cant). Rail cant provides a stable base to resist rail rollover and wide-gage issues and typically achieved by the base plate holding the rail at a 1:40 cant. Reverse cant can occur due to wear, incorrect tie plates, or tie degradations. Reverse rail cant can lead to the improper use of grinding templates (most are already assuming a specific rail cant) which can lead to increased forces between the wheel and rail and reduce the safety margin for rail rollovers.

ARM observed no obvious issues with the existing rail cant.

Gauge Face Angle

Gauge face angle (GFA) becomes an issue with the slope of gauge face becomes too flat that wheel climb can occur. With an assumed flange angle of 75 degrees on the wheel, the rail should naturally wear to a 15degree GFA. But if the value climbs over 20 degrees, suggesting that at least some wheels have a flange angle of less than 70 degrees, the risk of wheel climb increases considerably. In general, the rail profiles do not exceed 15 degrees (example shown in Figure 13).

The current GFA values are not a safety concern but should be raised as a concern as soon as they start to exceed 20 degrees over any appreciable lengths of rails. The GFA is also another metric for gauge wear and follows similar recommendations and root causes.

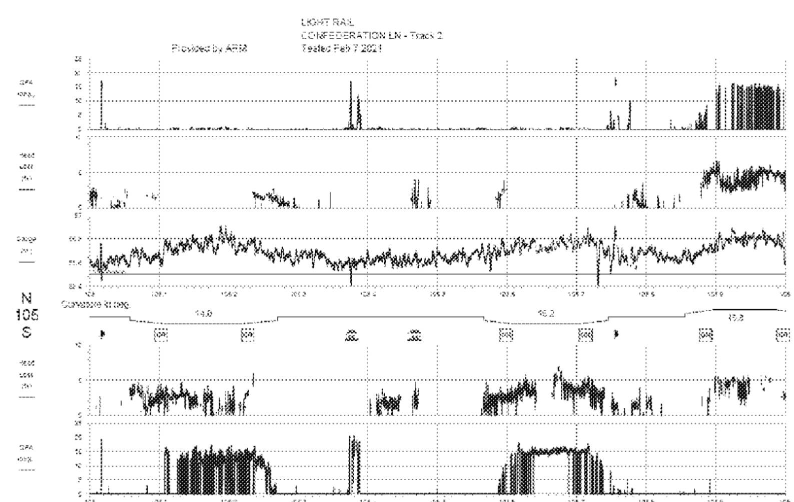


Figure 13: Sample date showing GFA at approximately 15 degrees on high rails

Track Gauge

Standard track gauge on the Confederation line is 1435mm and was observed to be between 1435mm and 1440mm through the network. In sharp curves with excessive gauge wear the track gauge was between 1440mm and 1445mm. Exceptions to the Confederation Line Track Standard limit of 1445mm are provided in the appendix report but these exceptions are only at and around switches/frogs where discrete locations of wide gauge would be expected in special track work like this.

Other Rail Observations

The remaining data collected from the optical rail measurements are primarily informational. The rail head loss is the total percent of metal lost from the head of the rail and is a reflection of the gauge and vertical wear parameters. The track gauge is all noted as being slightly wide which again is a reflection of the gauge wear occurring and is on average 0.1 inches wide.

The ARM Rail Maintenance Specialist collected several photos depicting the existing corrugation that is developing throughout the system. In some instances the corrugation is quite severe and as noted, the curves that were ground in December, 2020 already show signs of corrugation returning. Figure 14 provides several examples of corrugation on the Confederation Line on low rails, tangents, and high rails. While the types and root causes of corrugation can be quite complex, the end result is the same: high frequency vibrations resulting in an increase in noise emissions. Left unchecked, the corrugation can develop into more severe rolling contact fatigue (RCF), lead to broken fasteners and cracking in rolling stock undercarriage components.

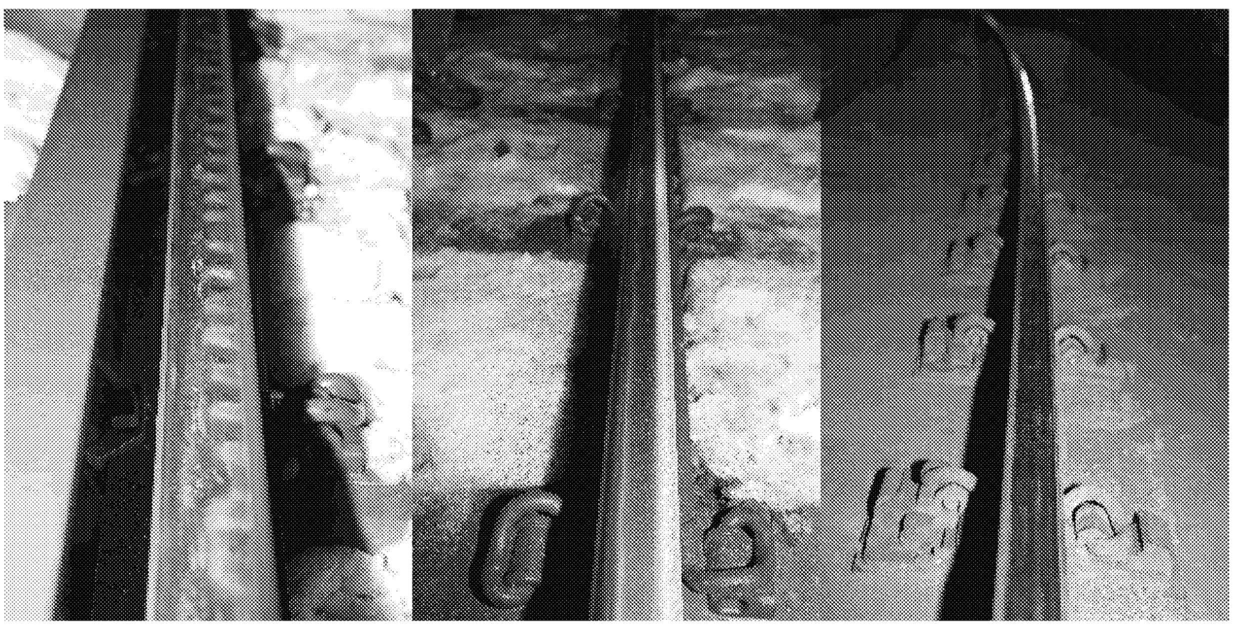


Figure 14: Example photographs of corrugation

3.2 Rail Profile 2-Ups

Due to the limitations of the equipment caused by the guard rail and the snow in the guideway, ARM conducted a review the rail profile 2-ups. The RangeCam software used to review profile data automatically selects and generates these near the mid-point of curves and tangents when the full rail profile is available. A grind profile (the 115RE shape) is applied to the worn rail to illustrate the amount of metal that is required to be removed. In areas where the base and web of the rail is not available, ARM manually reviews the profiles.

Figure 15 shows a typical 2-up plot of the left and right rail. The plot is broken into three general areas:

1. Metal Removal graphs – show where on the rail head work needs to be done to achieve the target profile (in this case 115RE)
2. Track Characteristics – general information about the location, curvature, and gauge
3. Rail Profiles – plot generated from scan shown the worn rail shape with the target profile overlaid (red line is the target profile)

These 2-ups are useful to the ARM rail grinding staff to review prior to starting a grind program and provide the basis on an estimate of the level of effort (number of passes per rail and total number of shifts) to complete a grinding program.

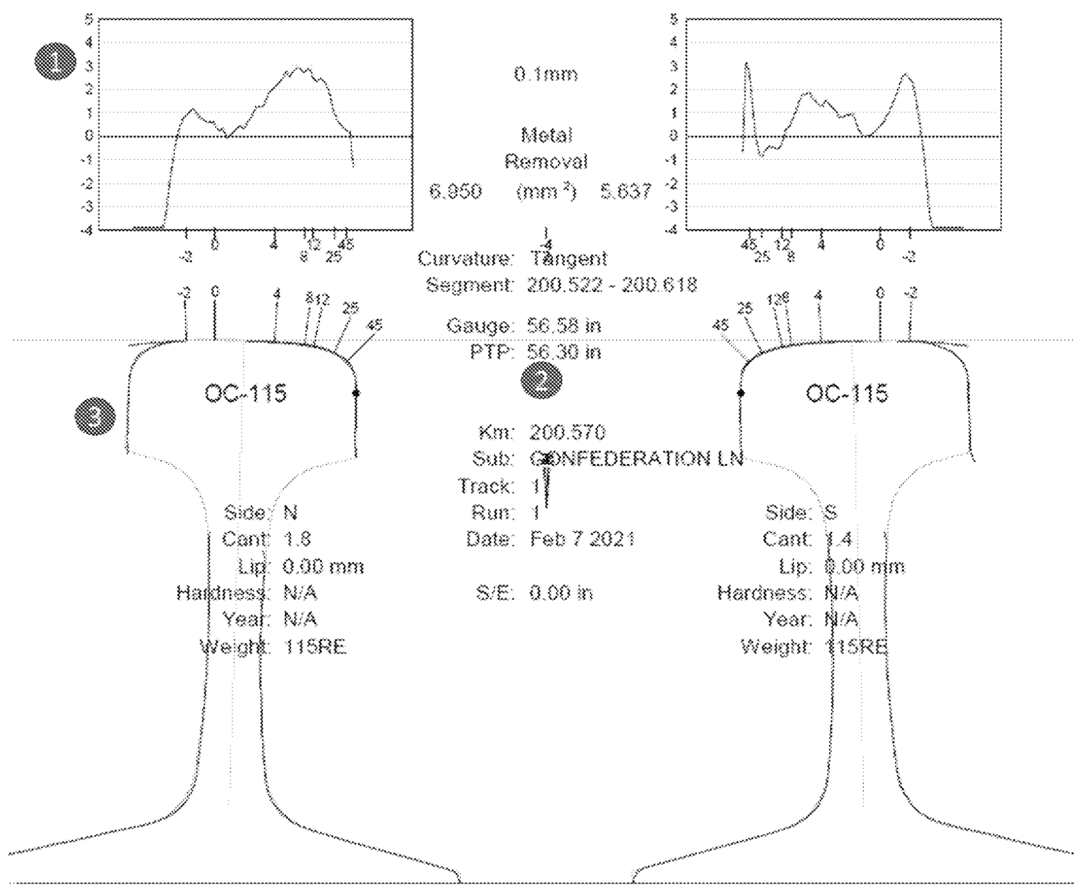


Figure 15: Typical 2-Up Plot

ARM has supplied representative 2-ups for all track segments as well as separate files for specific curves where multiple 2-ups are supplied through the body of the curve. Figure 16 shows Curve #090 on Track 2 which is a typical example of a sharp curve. The left rail (North) is the high rail and illustrates the gauge face angle while the right rail (South) shows a flat low rail. Figure 17 shows Curve #050 on Track 1 with similar conditions of gauge corner wear on the high rail and a flat low rail. In this figure, the optical laser is impeded from measuring the web and base of the low rail so some details are missing (like rail cant).

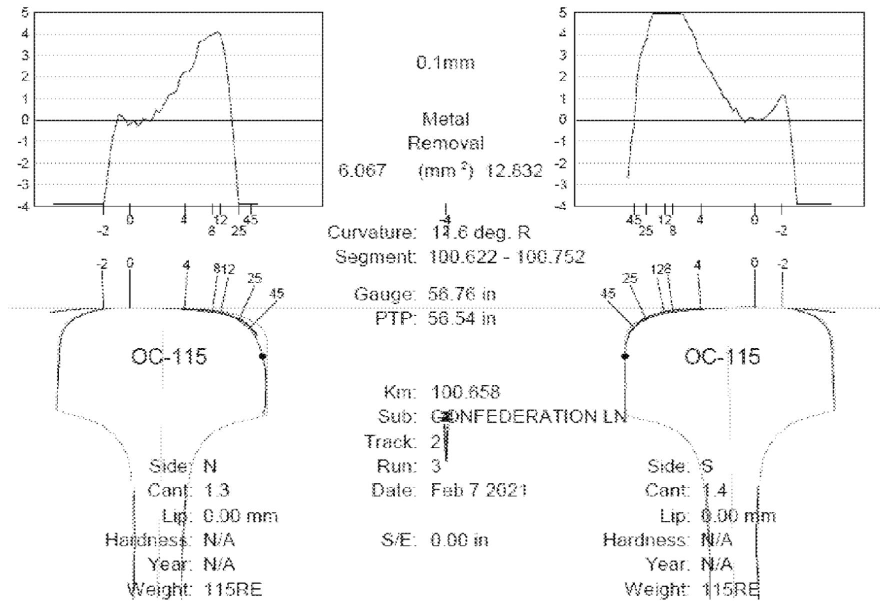


Figure 16: 2-Up of Curve #090 on Track 2

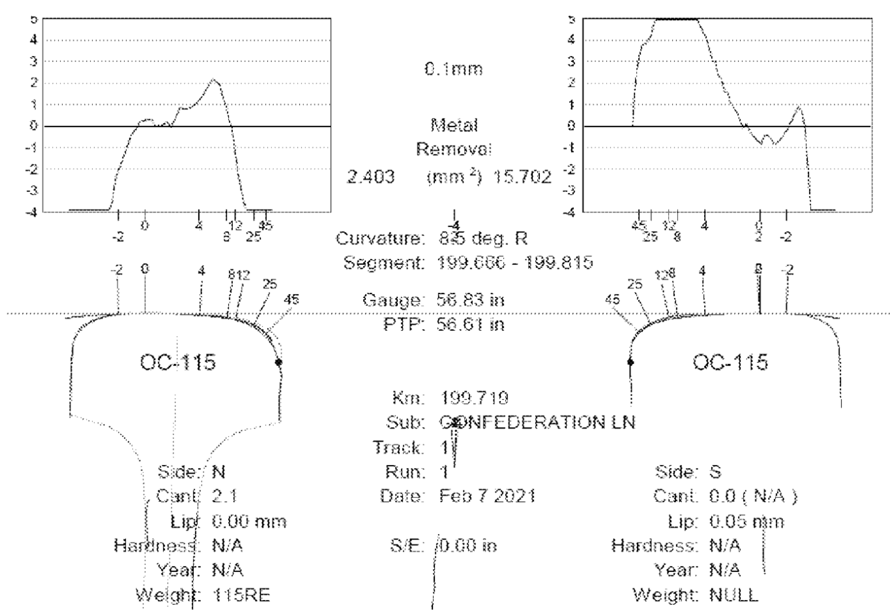


Figure 17: 2-Up of Curve #050 on Track 1

3.3 Low Speed Derailments in the Yard

ARM's inspection of the rail yard track did not identify any outstanding rail profile issues that could be leading to the low-speed derailments that have occurred in the yard. The Rail Maintenance Specialist on site did observe some conditions of poor track geometry including the presence of kinked rail so it may be that track geometry is a contributing factor. In addition, given the rail and wheel conditions occurring in the mainline, the low speed derailments may be resulting due to wheel/rail profile issues that are causing the same maintenance issues on the mainline. The wheel gauge may be too tight (similar issue that may be contributing to high gauge wear) could be resulting in wheel lift as well. Yard derailments are common because of very sharp curves (present in the yard) and high friction levels, particularly for wheels that have just come off the lathe.

ARM suspects that the use of a wayside lubricator in a tangent leading up to the curves causing derailments could help resolve some of these issues. The photographs shown to ARM indicate dry conditions and high forces against the gauge face of the high rail (see Figure 18 showing gauge face wear and metal shavings at base of rail). Grinding is unlikely to address the issues of these derailments as the wheel climb begins on the gauge face and grinding is intended to correct rail profiles. Other transit agencies have helped resolve yard issues using similar lubrication methods. Another option could be the use of a guard rail through these yard curves.

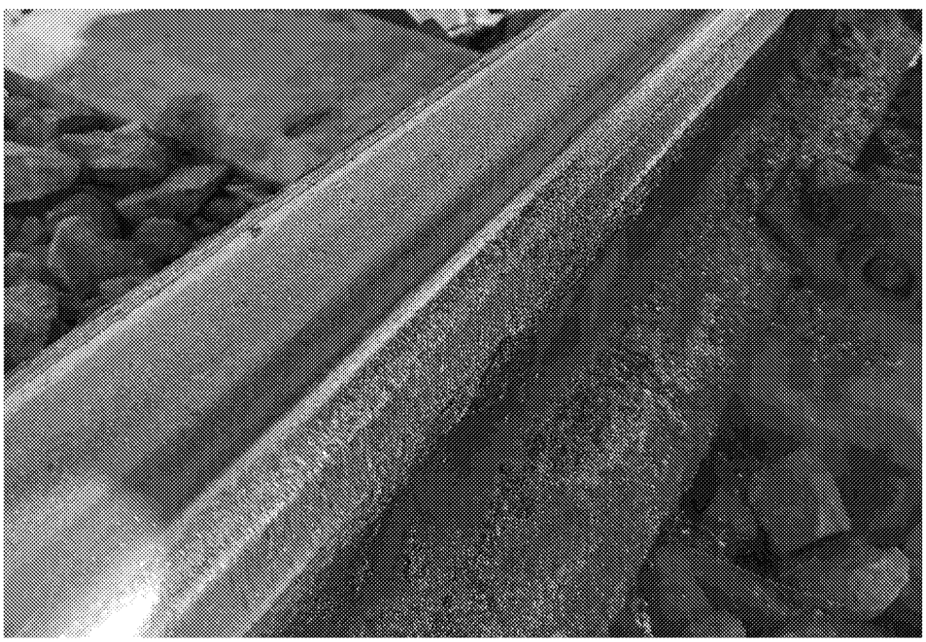


Figure 18: High rail of yard curve showing high degree of metal shavings

At this point in time, there is not enough information to determine a precise cause. Additional measurements should be taken in summer when the track guideway is clear of snow in addition to a review of wheel profiles.

4 Conclusions and Recommended Next Steps

The severity and extent of corrugation on the Confederation Line within one year of operations suggests the vehicle/track dynamics and/or the wheel/rail interface are not performing in an optimized way. Below are some of the observations made by the ARM project team based on our prior visit from grinding and the recent optical rail measurements on the Confederation Line:

1. The 1:60 tapered wheels do not create much positive steering through curves due to very little differential rolling radius. The field side corrugation noted on the system suggests hollow worn wheels and conformal contact across the rail head.
2. Flat rails are unlikely to have been worn to the level they are without some amount of grinding but without a history of rail profile measurements this is difficult to state with certainty. Flat rails also lead to more rapid corrugation growth due to more conformal contact between the wheel and rail.
    a. The combination of flat rails and 1:60 tapered wheels can create an environment for the rapid growth of corrugation on the rails.
3. Excessive gauge face wear suggests that the steering through curves and angle of attack of the wheels may not be optimized.
    a. ARM was told while on site that wheel retruing is occurring within 30,000 **kilometres** as is standard practice for Alstom and the Confederation Line to maintain the original wheel profile. ARM works with systems that retrue every 80,000 **miles** indicating there is an opportunity to optimize the current program to improve system performance and extend asset life.
    b. Wheel retruing for thin flanges is consistent with the presence of excessive gauge face wear. The wheel gauge may be too tight – a potential solution may be to mill the root (where the flange and tread meet) to widen the gauge. A similar problem was solved with this approach on Vancouver SkyTrain and Kuala Lumpur where steerable trucks were not operating as designed.

From our previous report in December 2020, Alstom has already completed ARM's first recommended next step which was to conduct a system-wide profile measurement. The results from the optical rail profile are highlighted in this report and the following general statements can be made:

1. Excessive rail wear (vertical and gauge), should it continue at the same rate, puts the rail at a condemning limit within 7 to 10 years. While it is unlikely it continues to wear at the same rate, the lack of historical data makes it difficult to confirm his statement. Ongoing monitoring should be completed on at least an annual basis to help guide maintenance decision and better understand the rate of change.
2. The gauge face angle is not presently a safety issue and is at a typical 15 degrees in high rails.
3. All the rails are flat which could be caused from natural wear or prior maintenance activities. The flat rails contribute to corrugation growth but even the recently ground curves are developing corrugation so the mechanism for corrugation growth extends beyond just flattened rails as these rails were ground to 115RE 8" radius.

4. Current bogies may not be steering correctly through tighter curves and may benefit from some level of adjustment.
5. The level of gauge wear could be reduced through a lubrication program and this type of wear is consistent with a dry system.
    a. The existing lubrication system (on-board wheel flange) is currently active but under review to increase application rate
    b. Wayside applicators could be introduced at locations more susceptible to gauge face wear and within the yard
    c. Wheel/rail friction could be temporarily reduced by manually applying product at locations with existing issues (a product like LB Foster Liquid LCF)

After reviewing the optical rail profile data, it is apparent to ARM that there is a wheel/rail profile incompatibility and a closer review of this interaction should be completed. A rail grinding program will provide temporary relief and improvement to overall system performance but with corrugation returning within three (3) months it is not the long-term solution. At the current traffic level of approximately 6 MGTs, the rate of wear for both rails and wheels is too high and root cause investigation should be undertaken.

The observations at the Confederation Line are closely in line with some of the issues experienced at LA Metro in the1990s. LA Metro was retruing wheels within 20,000 miles due to thin flanges and hollow wear (even with wheel flange stick lubricators), replacing or transposing tight radius curve rails within 1.5 years, excessive corrugation development, and experiencing low-speed derailments caused by the wheel/rail interaction. Some of the work ARM was involved with at LA Metro to help address their issues included:

- Review of the vehicles side bearing plates that were causing excessive binding
    - Changed steel side bearing to Teflon so trucks could rotate more freely
- Review of the Original AAR Standard Wheel (similar to the 1:60 taper)
- Review of truck axle spacing and wheel diameters
- Conducted in-depth analysis of the running rail design vs wheel truck design
- Review of wheel hardness versus rail hardness

LA Metro set out to identify the root causes of their slow speed yard issues and corrugation problems. The detailed wheel/rail interface study helped resolve both issues and resulted in a custom rail profile and change in wheel profile being implemented as a long term solution. LA Metro developed a system distribution of custom rail grinding profiles so the wheel profiles and rail profiles merged and crated a slight wheel movement across the top of the rail and wheel tread (Called wheel pummeling) so that wear was evenly distributed across the tread.

Next Steps

ARM has previously submitted a set of recommended next steps and the recent optical rail profile measurements further confirm the benefits of completing the following:

1. **Rail Grinding Program to restore 115RE 8" radius profile**
    a. This program is tentatively scheduled for **June, 2021** using an 8-stone rail-bound grinder supplied by LORAM
    b. The grind program will help remove corrugation before it develops into more severe RCF as well as restore the rail profile, both of which will result in reduce noise and improved ride stability
    c. ARM estimates the following level of effort:
        i. Mild curves and tangent profiles: 9 to 13 passes
        ii. Sharp curves and severe corrugation: 15 to 19 passes
    d. In total, the grind program will need 40 to 50 spark hours
        i. To complete the program in 15 shifts, ARM would need a minimum 4 to 5 hour work window per night with single tracking
        ii. A key challenge is that there is no location to park the grinder on track nightly which means the grinder will travel from the MSF every night
    e. A corrective grind program will use a coarse grit stone to maximize metal removal but this stone can be prone to leave behind a grind signature that produces a post-grind 'hum' or 'buzz' when trains travel over it
        i. An alternative medium grit stone leaves behind a smoother rail surface finish with less post-grind noise but is less effective for metal removal and more expensive. If the coarse grit stones create an issue for the Confederation Line then consideration could be given after one or two grinding shifts to switch stones.
2. **Conduct a wheel/rail interaction study** to determine if the rail profiles or wheel profiles can be re-designed to optimize system performance.
    a. Custom wheel and/or rail profiles may be required. . The system-wide assessment will provide a better indicator of the project cost.
    b. New profiles could drastically improve ride quality, reduce noise and vibration, and increase the life of assets.
3. Consider a **review of friction management program** in terms of wayside or on-board lubrication and/or top of rail friction management (**budget TBD** may be able to be wrapped up in the wheel/rail interaction study.)
4. **Review wheel retruing procedures.** Wheel profile measurements should be collected and reviewed covering new wheels to well-worn wheels. 5. **Conduct an annual optical rail pr ofile measurement run.**

Appendix

A

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Appendix B