

NRC Publications Archive Archives des publications du CNRC

A rail data integration and analytics system and its application to heavy haul railway

Liu, Yan; Dai, Chengbi; Wahba, Albert; Sirois, Dominique

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

Proceedings of 12th International Heavy Haul Conference (IHHA 2023), 2023-08-29

NRC Publications Archive Record / Notice des Archives des publications du CNRC :

<https://nrc-publications.canada.ca/eng/view/object/?id=d9a5a4fd-5bb9-4a24-984b-9637b98d71b3>
<https://publications-cnrc.canada.ca/fra/voir/objet/?id=d9a5a4fd-5bb9-4a24-984b-9637b98d71b3>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

A Rail Data Integration and Analytics System and its application to heavy haul railway

Yan LIU, Chengbi DAI, Albert WAHBA
National Research Council Canada, Ottawa, Canada

Dominique SIROIS
Quebec North Shore and Labrador (QNS&L) Railway, Sept-Îles, Canada

ABSTRACT: With the increasing deployment of technologies such as accelerometers and other sensors on freight cars during revenue operations, the data that reflects the performance of the vehicle-track system under varying conditions becomes readily available. Recently, one of the longest demonstrations of using an instrumented wheelset (IWS) in revenue operation has been reported by the present authors, which shows that IWS technology has sufficient durability for continuous and long-term monitoring of track conditions. To overcome challenges related to the integration of the large volume of time series data collected by IWS, accelerometers and other sensors with the many other existing railway datasets that are usually collected under different conditions, the National Research Council of Canada (NRC) has developed an advanced data fusion tool called rail data integration and analytics system (RDIAS). The tool has been successfully applied to the data collected during a one-year period of track monitoring using an instrumented iron ore car in a mountainous area with heavy grades and many sharp curves. A number of successful case studies are presented to demonstrate how the RDIAS has assisted in improving the operational performance and safety of the railway system. These include identification and mitigation of high wheel climbing risks, recommendation of proper lubrication and friction management based on evidence generated by the RDIAS system, demonstration of how the system can be used to assess maintenance effectiveness, and some findings regarding unfavourable truck warping conditions.

1 INTRODUCTION

Combining the unprecedented advancement of technologies with the new era of big data and data analytics, the railroad industry is presented with a novel tool to improve operational efficiency and safety. By identifying the correlations and anomalies from the data collected by various technologies, railways can make targeted and timely decisions for operation, inspection and maintenance (Zarembski 2020).

A variety of sensors installed on rolling stock have been used to identify unfavourable conditions of vehicle and track interaction. For example, by using data collected from the accelerometer sensors installed on a locomotive wheel axle, bogie frame and carbody, a Vehicle/Track Interaction (V/TI) monitoring system has been developed and applied to both freight and passenger railways. Based on the pre-set thresholds for different type of conditions, daily exception lists are sent to railways after a validation process to remove false positives. A cluster algorithm has been developed to identify high derailment risk locations where repeated low V/TI exceptions happen (Clark et al. 2015). Another system, Instrumented Revenue Vehicle (IRV), uses accel-

erometers, stain gauges and displacement sensors mounted on the wheelset, bogie, coupler and carbody. It has been used by heavy haul freight railways especially in iron ore operations (Thompson et al. 2016). A web-based reporting system is used to communicate the exception and other results to railways. The use of data visualization provides a useful tool to prioritize track maintenance. Besides using acceleration responses of rolling stock, another method to monitor vehicle / track interaction more directly is to measure the wheel / rail forces using the Instrumented Wheelset (IWS). The IWS technology turns a regular wheelset into a dynamic load measurement device for recording real time forces during operation along the entire track length. It has been widely applied by the industry since the 1980's to assess the operational safety of newly designed rail vehicles in short-term field tests and under specified conditions (Association of American Railroads 2015, International Union of Railways, 2019). A recent review paper (Bernal et al. 2019) has summarized a number of other application cases by IWS or an alternative force sensor.

Two demonstrations of using IWS technology in revenue operation have recently been reported

(MTA/New York City Transit et al. 2019, Liu et al. 2019, Liu et al. 2020). These demonstrations, of the longest reported duration to date, show that IWS technology has sufficient durability for continuously monitoring track conditions during long-term revenue service. Deploying IWS in revenue operation opens some new opportunities to uncover the previously unknown issues that are closely associated with operational safety (MTA/New York City Transit et al. 2019). It also poses some challenges. First, an efficient tool is required to manage, clean, and align large volumes of time series data collected by IWS in the long term operation. In order to identify track locations of high risk, development of effective algorithms is needed. It is essential to overcome the difficulty associated with the large scatter due to varying speed, car loads, weather and other uncontrolled conditions.

A rail data integration and analytics system (RDIAS) developed to address these challenges is presented in this paper. The system has been successfully applied to the data collected during a one-year period of track monitoring using an instrumented iron ore car in a mountainous area with heavy grades and sharp curves. A number of successful case studies will be presented to demonstrate how RDIAS has assisted the railway to improve the system operational performance and safety.

2 TEST OF INSTRUMENTED CAR IN REVENUE SERVICE

2.1 Heavy Haul Railway QNS&L

The data used in the present study was collected by an instrumented iron ore car equipped with IWS and other sensors. The test car as shown in Figure 1 was used in revenue operation for approximately one year on the Quebec North Shore and Labrador (QNS&L) railway. Canada's largest iron producer, Iron Ore of Canada (IOC) relies on QNS&L for maintaining an efficient and safe railway service between its mining and processing facilities, located near Labrador City (in the province of Newfoundland and Labrador), and the company's shipping port in Sept-Îles, Quebec. The QNS&L is a heavy haul railway, running 10 trains per day over 260 miles (418 km) of track in a mountainous area with 45% being in curves. Among 542 curves 18% are higher than 5 degrees. The highest grade is about 1.32%. A regular QNS&L unit train hauls up to 25,200 tonnes of iron ore with 240 cars and spans four kilometres. Operating in a mountain territory with heavy grades and many sharp curves, QNS&L has been facing challenges of gauge widening and plate cutting in recent years.



Figure 1 Ore Car Instrumented by IWS

2.2 Test using Instrumented Wheelset (IWS)

Two instrumented wheelsets, as well as other sensor technologies to measure acceleration, weight, displacement and coupler forces were installed on an ore car in long-term revenue operation. The instrumentation hardware design and implementation were proved to be sufficiently durable to tolerate harsh operating conditions on track and when unloading by car dumper at the port. The instrumented ore car was deployed intermittently by QNS&L in operation between November 2018 and November 2019. Overall, 41 round trips of good quality data were acquired. A detailed description about the instrumentation and test can be found in a previous paper (Liu et al. 2020).

An IWS is a standard railway wheelset that is instrumented with sensors. A special algorithm, combined with an on-board data acquisition unit, make the wheelset as a dynamic load measurement device. When placed under a railcar it provides continuous measurement of vertical, longitudinal, and lateral forces acting at the wheel/rail contact point. In its current state of development, the IWS is a powerful research and certification tool that is typically used for limited durations and during manned operations in freight and passenger systems. Implementing the IWS in long-term revenue service will bring tremendous benefits to the railway industry as demonstrated in the present and previous studies.

3 RAIL DATA INTEGRATION AND ANALYTICS SYSTEM (RDIAS)

3.1 Traditional data processing method

The traditional method for processing IWS data is a manual one, where data files are collected and stored in a directory or ftp site. Engineers scan and review the files using various analysis and plotting tools. Procedures are developed in various software platforms, such as Excel, MatLab, Datasp, imc Studio and LabView. Manual processes are applied to re-

move bad data, align files according to their track location, apply filters and calculate relevant performance indices. The analysis process can take from a few days to a few weeks, dependent on data volume. A report with the obtained results is then prepared and delivered to railway operators to support their business processes.

Manual manipulation and review of large datasets is cumbersome, slow and subject to human error. Although various functions and procedures can be developed in the software packages for processing multiple data files, there exist no autonomous information flow from IWS sensor to the railway operators. The timely information such as high risk locations or previously unknown issues is essential for railway managers to make prompt operation and maintenance decisions. Although the manual approach is sufficient for the design assessment and research purpose, it cannot provide the information in a timely manner.

3.2 Automatic data processing method

The RDIAS, a data management, processing and analytics system, has been developed based on Microsoft's SQL Server Integration Services (SSIS) which is an enterprise-level data integration and data transformation solution. The RDIAS is consisting of data pipeline ETL (extraction, transformation and loading), multi-dimension database, data analytics and result dashboard (Figure 1Figure 2). The data pipeline uses the SSIS solution to extract and transform information from IWS raw data and other data sources, then perform raw data cleaning, location aligning and data filtering. RDIAS integrates raw data in a variety of formats and consolidates data from an IWS instrumented car, track geometry car, infrastructure data, maintenance information and weather stations. The load process then packs the processed data into a multidimensional database (MDB). Various analytics processes are applied to transform the raw data into result database where the performance indicators are aligned with various dimensions (or conditions). The data in the result database gets queried and retrieved with data report and visualization tools such as Tableau. The report in plot or tabular format can be readily retrieved from a number of interactive dashboards that are refreshed on a weekly, daily, or even hourly basis.

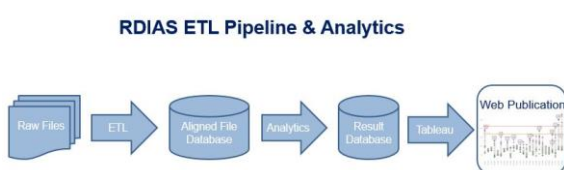


Figure 2 RDIAS Data Pipeline

3.3 RDIAS Application in revenue service

In the one year of revenue service on QNS&L track, a big dataset of more than 640 million rows with 38 columns has been recorded by the IWS instrumented car. A hybrid method that stores data in database and file system are used to efficiently handle such large datasets. The metadata for the IWS and other sensors is first extracted from raw data in the data pipeline (Figure 1Figure 2). The different runs over the same track segment are then aligned by the track milepost which is converted from GPS coordinates using a fast geography algorithm developed for RDIAS.

A segmentation process is important to identify the track conditions associated with the measured IWS and other exceptions. The applied segmentation method in the present study is mainly based on track curvature. The other track features such as track fastener type, maintenance status and track geometry have been also taken into account. Although not included in the following case studies, two IWS force based parameters, truck side lateral force (TSLF) and peak to peak vertical force (PPVF), have been proposed and applied to identify high force curves for the targeted track maintenance (Liu et al. 2020). These parameters, together with lateral to vertical force ratios are calculated for all track segments and stored in a multidimensional SQL database. An important feature of the RDIAS is its flexibility for adding data from other sources such as maintenance records, the latest track geometry measurement and weather stations. The available data reflecting various track and operation conditions can be easily integrated into the multidimensional database for the better analytics.

The analytics is done by querying and correlating the result in the database with various dimensions (conditions). An important method used in RDIAS is to design multiple dashboards for querying and exploring relationships. A modern analytics and visualization platform, Tableau (Tableau Software 2021), is used in RDIAS for this purpose. Well-designed Tableau dashboards allow the analytics being performed graphically and interactively by a few mouse clicks. The Tableau is also used as reporting tool for QNS&L managers to filter and retrieve results directly from web dashboards.

As an example, Figure 3 shows a dashboard used in RDIAS. Each point in the figure represents a force value measured from a separate run over the same track location. It is designed to trend the force changes for assessing the effectiveness of maintenance. In the prior remote monitoring study for a subway system (MTA/New York City Transit et al. 2019), it has been found that such trending method has been very effective to monitor some unexpected changes in the railway system. In the present example, Figure 3 illustrates the lateral force reduction after a tamping activity. The user first selects what

force parameter as performance indicator. The truck side lateral force, or TSLF, is selected in Figure 3. Then the interested track segment (curve 46B in the example) and time period (21 June – 28 November) are selected. It can be seen that the lateral force TSLF has been reduced after the maintenance. One particularly high force point after tamping is shown on October 13. After checking the raw data it is determined that the instrumented car has been overloaded in operation that day. Using the bigger and smaller circles to represent, respectively, loaded and empty trains, the dashboard in Figure 3 indicates that the tamping activity has helped to reduce the lateral force of the loaded trains more than the empty trains.

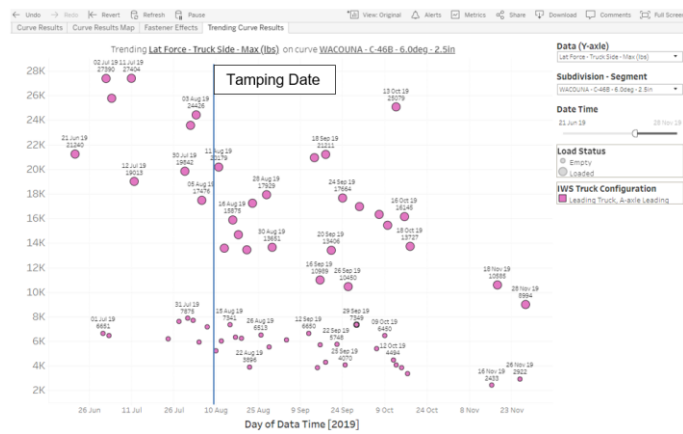


Figure 3 A Sample RDIAS Dashboard

In addition to the analytics conducted by using the Tableau dashboards, comprehensive correlation and comparison analyses have been performed for the time history force data. The large scope analysis for the big time series datasets (more than 640 million rows) have been empowered by the integrated database and a number of RDIAS tools developed in Python, Excel and C#. Most case studies in the following section have been conducted by using these tools. By applying the RDIAS system, timely analysis has been performed and some important findings have been reported to QNS&L for making maintenance decisions during the in-service test period.

4 CASE STUDIES

4.1 Mitigation of high L/V risk on multiple curves

The lateral to vertical force ratio (L/V) measured by IWS can be used to identify curves that have higher risk of wheel climbing. The leading high wheel L/V is widely applied by the railway industry as an important indicator of wheel climbing risk. A threshold of $L/V \geq 1.0$ is used to identify sites with excessive L/V, which is considered as the condition for high risk of wheel climbing (Association of American Railroads 2015).

For empty train operation, 22 curves have been identified by RDIAS system that poses higher wheel

climbing risk. The L/V ratio recorded on these curves has been found to be higher than 1.0 as shown in Figure 4. The large scatter in L/V ratios shown in the figure at the same location has been discussed in previous studies (Huang et al. 2011, Stock et al. 2015). It has been found that the friction condition and wheel / rail profile are the dominant factors, while car weight and speed also play important roles. A method to classify the curves (as shown in Figure 4) based on 95th percentile of L/V values has been employed in RDIAS in order to overcome the difficulty related with large variance.

The 2019 maintenance plan of QNS&L has been developed from the previous track geometry data and field inspections. By comparison, it is found that only 9 of these curves (as marked by yellow circles) have been included in the 2019 tamping plan. It is therefore recommended that other 13 curves be included in the 2020 maintenance plan in order to reduce wheel climb risk for empty trains.

For the loaded trains, only one curve (C93E) has been found to have L/V ratio values close to 1.0 at the leading high wheel. This curve has not been identified by manual and track geometry car inspection. In order to mitigate the risk, QNS&L has decided to add the curve in the 2019 tamping plan. This case study indicates that, using data collected from the in-service test by IWS instrumented car, RDIAS can help identify high L/V curves with potential risk of derailment that are unknown to the railway. With this information the railway can apply a predictive maintenance activity to reduce the risk in its operation.

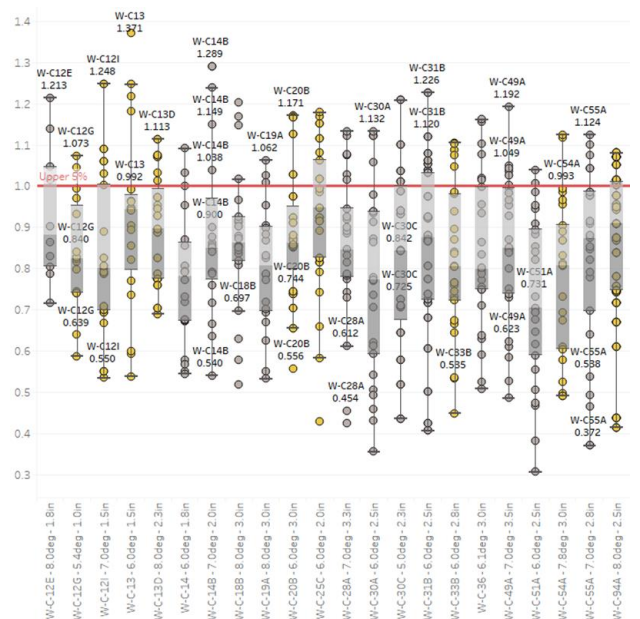


Figure 4 High L/V Sites (22 curves)

4.2 Lubrication and High L/V Ratio

To further examine curves where high L/V has occurred, the measured L/V are plotted against milepost in Figure 5 and Figure 6 for two curves. In these figures, one or two high L/V zones or “bumps” can be seen on the high rail side where the L/V has risen above the quasi-static level to a value greater than 1.0. The length of the high L/V zones are typically 20 to 80 feet.

L/V versus milepost relationships collected from different runs are also shown in Figure 5 and Figure 6. The consistent curves confirm good alignment of test data integrated in RDIAS and also demonstrate the excellent repeatability of the IWS technology. The repeat high L/V events have validated the concerns regarding wheel climb risk. Most of the high L/V runs have occurred during the middle of summer where dry and therefore high friction on the rail surface is expected. Previous studies (Roney et al. 2009, Stock et al. 2015) have concluded that high rail surface friction is one of the main causes for high lateral force and L/V ratio.

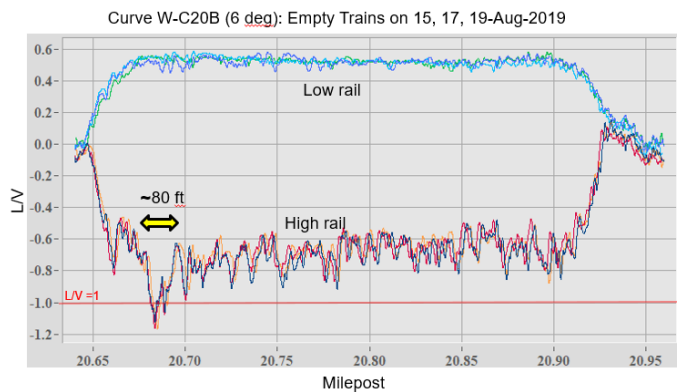


Figure 5 L/V vs Milepost on Curve C20B

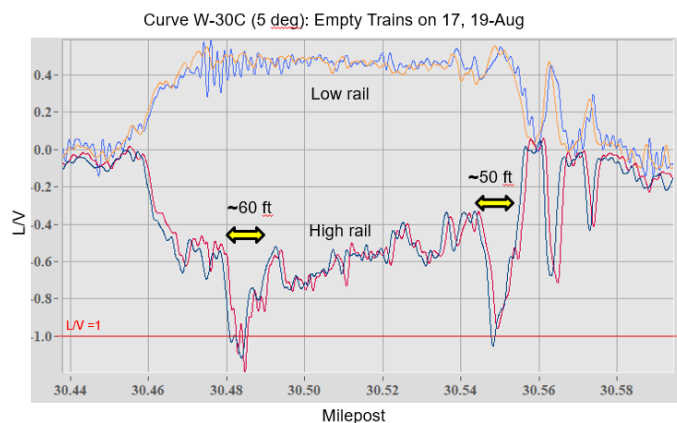


Figure 6 L/V vs Milepost on Curve C30C

With the L/V information, QNS&L conducted a number of thorough inspections to these curves. It has found that all the high L/V curves, except curve C20B, have experienced some track geometry issues. However, these track geometry variations have not been categorized as high priority defects. The

L/V results have therefore provided the previously unknown information for inclusion of these curves in QNS&L’s planning process.

Consider Curve C20B (Figure 5) where three IWS measurements conducted on 15th, 17th and 19th August 2019, repeatedly have identified a high L/V peak at the south end of curve body on the 6-degree curve. However, a review of track geometry data collected on July 11 July 2019 has not found any noticeable track geometry issue. Two walking track inspections on the track segment conducted since then have found more grease in this area on the high rail side. The L/V ratio on high rail in curves can be higher for the lubricated than the dry gauge face, especially when the top of low rail is under a dry (high friction) condition. This could be the case at C20B as QNS&L inspectors have observed the evidence of grease contamination at the rail base of the curve. They also observe that track sites with excessive wide gauge and plate cutting often have more grease on high rails.

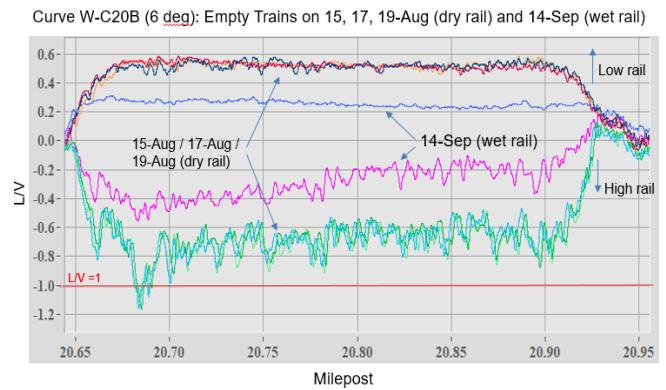


Figure 7 L/V of Dry and Wet Rails on Curve C20B

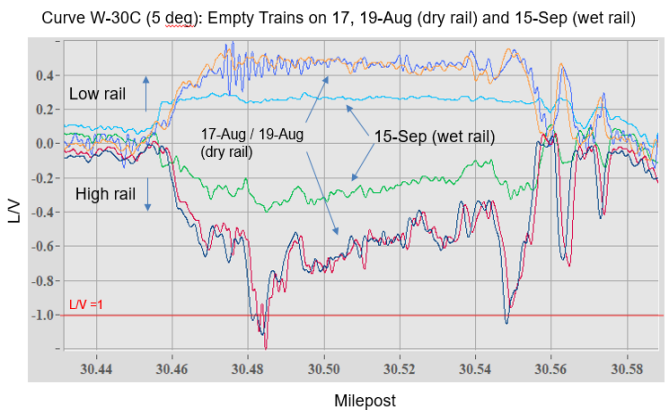


Figure 8 L/V of Dry and Wet Rails on Curve C30C

According to the industry’s best practices, high lateral forces and L/V ratios on curves can be reduced by managing friction level on top of low rail to a proper value (0.3 – 0.35) (International Heavy Haul Association 2015). Figure 7 and Figure 8 show the comparison of the measured L/V ratios under dry (no rain) and wet (with rain) conditions, for curve C20B and C30C respectively. It can be seen that L/V values under the wet condition are much lower

than under the dry condition. The results clearly demonstrated the impact of friction condition on wheel / rail forces. When the top of rails is “lubricated” by rain the high L/V peak under the dry condition disappeared.

The dry and wet conditions have been identified by the weather station data integrated in the RDIAS system. By aligning the train passing date and time with weather station records, it has been found that the three August trains have been under dry conditions as the recorded precipitation values being all zero from the morning to the afternoon. On the other hand, the empty train pass on September 14 has been clearly under wet rail condition because of rain (non-zero precipitation) recorded continuously in the last 6 hours including the time when the train running over the curve. This suggests a lower friction on the top of rails.

Based on IWS data measured under wet and dry conditions, the present case study suggests the need to apply the best industry practise to manage the friction on top of rail in order to reduce high L/V ratio. The IWS measurements during rain condition shows that the reduced friction can result in a significant reduction in the forces on curves and will allow the railway to extend the life of rail assets. QNS&L is considering the implementation of Top-of-Rail friction management program.

4.3 Effects of Track Geometry and Maintenance

A special track geometry survey has been conducted by QNS&L to support the present study. The measured track geometry variations, such as curvature, gauge, crosslevel, super-elevation, surface and alignment have been integrated into the RDIAS system. The correlation between IWS force and track geometry is an important topic for the industry. While this correlation is not the focus of this paper, an example is shown in Figure 9 for a 6-degree curve (C46B). Clearly, the 5 repeated track alignment waves starting from about mile 46.67 induced some dynamic responses of lateral forces on both high and low rails. The peak to peak value of the dynamic lateral force on high rail is about 19 kips and results in the peak lateral force being more than 50% higher than its quasi-static level. A good example demonstrating how the measured IWS forces can be used to assess the effectiveness of maintenance is shown in Figure 10, which compares the lateral forces before and after tamping. It can be seen that the high peak to peak value of the dynamic lateral forces have been reduced to quasi-static levels after an effective tamping program.

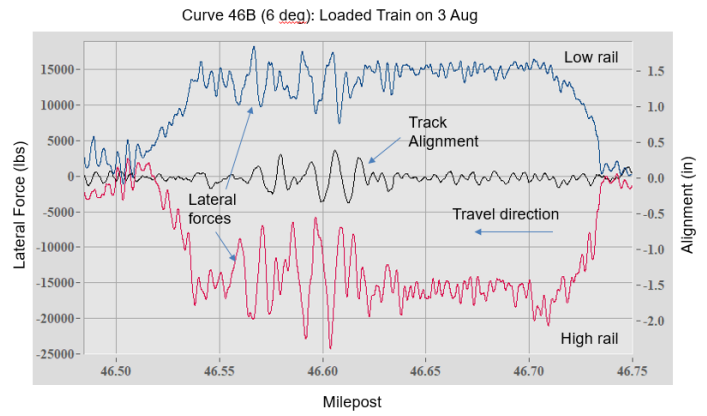


Figure 9 Lateral Force and Track Alignment

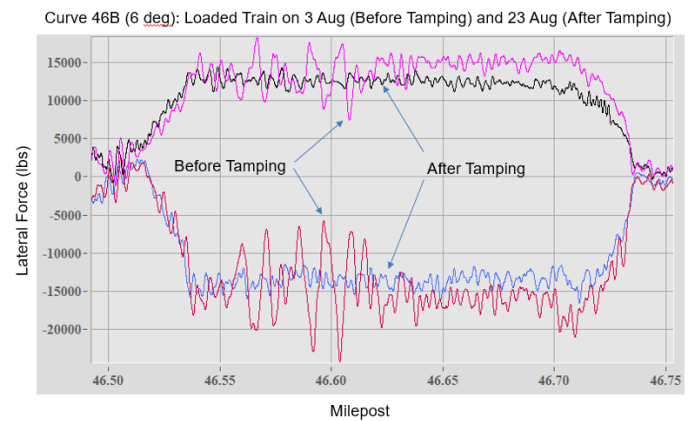


Figure 10. Lateral Forces Before and After Tamping

4.4 Monitoring Truck Warping

In the normal curving case the freight railcar truck keeps the bolster and two sideframes oriented approximately 90 degrees, or a “rectangle” shape. The shape is maintained by a stiff wedge connection between the bolster and two sideframes. In this case, the high lateral force only occurs at the leading axle. Truck “warping” could happen if the wedge connection is not rigid enough to prevent the rectangle shape (blue line) of truck being forced into a lozenge shape (red line), as illustrated in Figure 11. Under the warping condition, the truck can generate high lateral force also on trailing axle (Wolf 2015) because the warping shape increases the angle of attack of the trailing axle.

As shown in Figure 11, the lozenge shape (red line) of a warping truck is produced by a relative rotation between the bolster and two sideframes. By assuming that angle of attack on the leading axle remains the same before and after warping, a movement of the trailing axle toward high rail is required when the original rectangle shape (blue line) is warped into the lozenge shape (red line) as illustrated in Figure 11.

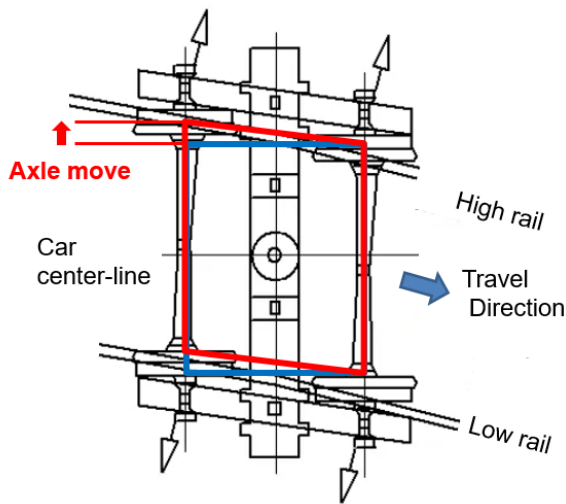


Figure 11. Illustration of Truck Warping (Wolf 2015; the blue and red lines have been added by the present authors)

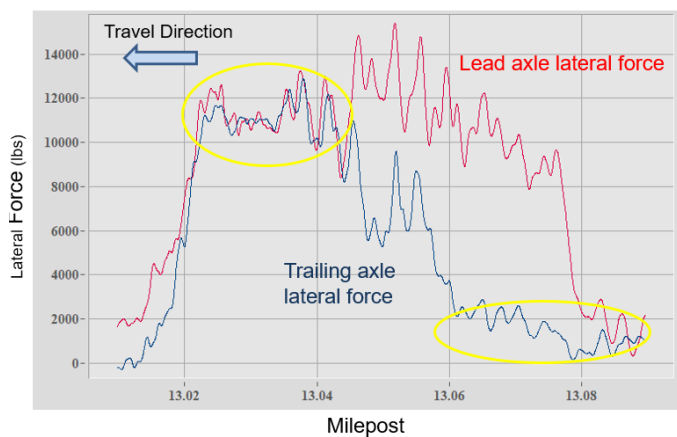


Figure 12. Increased Lateral Force on Trailing Axle

By monitoring lateral forces on both leading and trailing axles under loaded condition, it is found that high lateral forces on the trailing axle have occurred on many curves. An example is shown in Figure 12 for curve C13. The lateral force on the trailing axle of the IWS truck can be seen to be much lower than the leading axle. This represents a normally steering truck without warping behaviour. However, the force on trailing axle increases dramatically in the middle of the curve and reaches the same level as the leading axle. Therefore it is suspected that truck warping has occurred when negotiating the curve. Leveraging the established data integration in the RDIAS system, records from multiple trains passing the same curve have been examined. The similar increases of the lateral force on trailing axle have been observed.

The contact position recorded by the IWS sensor are further reviewed by using the analysis tool for time series data in the RDIAS system. As shown in Figure 13, it is found that the high wheel contact points of all the 6 loaded runs move toward gauge side in the middle of the curve. The milepost where the contact points make the move in Figure 13 corresponds well with the milepost where the force on the trailing axle reaches the same level as the leading

axle in Figure 12. As illustrated in Figure 11, this result is a convincing evidence that the truck has experienced a warping change when negotiating the curve. To the authors' best knowledge, this is the first time that the warping process and the accompanying axle moving feature of a freight truck have been recorded in service. The data accumulated in the RDIAS system can be used for the future study on the complicated mechanism of truck warping and its triggers. This could help to reduce the unfavourable curving forces caused by the warping behaviour.

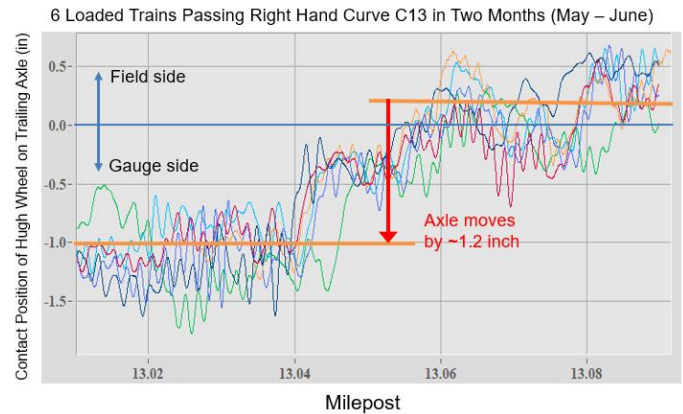


Figure 13. Trailing Axle Movement

Since the warping behaviour can increase the lateral force on the trailing axle considerably, it can lead a high ratio for gauge widening and place cutting. The IWS truck has been equipped with the same elastomeric pads used in QNS&L's iron ore car fleet. The pad allows some flexibility between axlebox and sideframe, enabling the two axles a limited ability to "self-steer", in theory reducing rolling resistance and decreasing wheel and rail wear. To maintain a high-warping stiffness, the elastomeric pad is normally installed on freight trucks equipped with a stiff wedge system such as Motion Control, Super Service Ride and Split Wedge (Schorr 2015). The wedge system used in QNS&L's fleet is not particularly stiff, and so it has been suggested to test the performance of the IWS truck without elastomeric pads. If the warping stiffness is improved by removing those pads, it would be a simple and cost-effective solution to the truck warp and high force problem. More studies are required to evaluate the truck warping performance under a controlled condition to understand the impact of elastomeric pads. A potential penalty of increased wheel wear and fuel consumption after removing the pad also need to be assessed.

5 CONCLUSIONS

A rail data integration and analytics system (RDIAS) has been developed. It has been applied to wheel / rail force data collected by an IWS and other sensors

over a one-year in-service test for a heavy haul railway. Based on the advanced data management, alignment and analytics technology, RDIAS can timely and accurately transform the collected data into the actionable information. By using such information the railway can make maintenance and other business decisions in a timely manner.

Wheel climbing and other risks can be directly and timely identified by applying the RDIAS analytics to big data collected by IWS technology. The case studies have demonstrated that the system can help heavy haul railways to accurately identify the high L/V force locations so as to address the related track issues, therefore reducing the derailment risk.

Trending high force data collected continuously during revenue service provides an effective method to monitor the stress on track in heavy haul rail systems. Adding maintenance efforts focusing on the high stress track segments can help to extend the life of the rail asset. In order to make sure the high stress condition is eased or removed, trending force before and after the maintenance is necessary.

The desired correlation between track geometry and wheel / rail forces, when established, can help the industry shift to a performance-based track maintenance strategy for higher efficiency and safety. The force and track geometry data integrated in the RDIAS database can be used to explore and improve the correlation in the future.

The characteristics of truck warping process recorded in the middle of curves for a rail freight car, probably unidentified in previous tests, has been revealed by the RDIAS based analytics. The accumulated data can be used in the future study to understand the vehicle, track and operation conditions that trigger such a warping process. Future efforts are also needed to study the effect of the elastomeric pad on the truck warping process.

6 ACKNOWLEDGMENTS

The authors would like to thank Erik Oxelgren, Kevin Mackie, Guy Charbonneau, Shane Wallace, Larry Hill, Scott Wallace from the National Research Council of Canada (NRC) and other NRC testing team members who made great contributions to the in-server test by conducting hardware integration of the Instrumented Wheelset system and other sensors. The authors would also like to thank Ghislain Boisvert, Roger Langelier and Carman from QNS&L for their contributions.

7 REFERENCES

Association of American Railroads (AAR), Manual standards and Recommended Practices. 2015. Design, Fabrication and Construction of Freight Cars, M-1001, Chapter 11. Service-Worthiness Tests and Analyses for New Freight Cars, Amended November 30, 2015.

- Bernal, E. Spiriyagin, M. & Cole, C. 2019. Onboard Condition Monitoring Sensors, Systems and Techniques for Freight Railway Vehicles: A Review, in *IEEE Sensors Journal*, vol. 19, no. 1, pp. 4-24, 1 Jan.1, 2019, doi: 10.1109/JSEN.2018.2875160.
- Clark, Dwright, Toth, Thomas, Dick, Matthew, and Maldonado, Rafael. "Eliminate Track Caused Derailments with V/TI Monitoring & Cluster Analysis," AREMA Conference, 2015.
- Huang, W. Magel, E. & Liu, Y. 2011. Stochastic Modelling Applied to Vehicle-Track Performance and Safety. IAVSD 2011: 22nd International Symposium on Dynamics of Vehicles on Roads and Tracks: 14-19 August 2011.
- International Heavy Haul Association, 2015. Guidelines to Best Practices - Management of the Wheel and Rail Interface, 450 page.
- International Union of Railways (UIC) 2019. Testing and approval of railway vehicles from the point of view of their dynamic behaviour - safety - track fatigue - ride quality, UIC 518 (E) 4th Edition.
- Liu, Y. Wahba, A. Magel, E. & Lamb, T. 2019. Monitoring and Managing Wheel – Rail Force by Using Instrumented Wheelset Technology in Revenue Operation at New York City Transit Subway. WCRR 2019.
- Liu, Y. Wahba, A. Oxelgren, E. & Sirois, D. 2020. Continuous Monitoring of Wheel/Rail Forces during in-Service Freight Operations Has Led to a Successful Performance-Based Track Maintenance Plan. AREMA Conference 2020.
- MTA/New York City Transit, KLD Labs, Brown, D.T. 2019. Plasser-American, National Research Council of Canada, "Integrated Wheel/Rail Characterization through Advanced Monitoring and Analytics," Federal Transit Administration Report No. 0145, 2019.
- Roney, M. Eadie, D.T. Oldknow, K. Sroba, P. Caldwell, R. & Santoro, M. Total Friction Management on Canadian Pacific, in: Proceedings of the 19th IHHA Conference in Shanghai.
- Schorr, R. 2015. Basics of Vehicle Truck and Suspension Systems and Fundamentals of Vehicle Steering and Stability. WRI Conference, Principals Course.
- Stock, R. Eadie, D. Oldknow, K. & Xia, P. 2015. Lateral forces as indicator for an efficient friction management implementation. AREMA 2015 Conference Proceedings
- Tableau Software 2021. Tableau Desktop and Server, Version 2021.3, <https://www.tableau.com/>.
- Thompson, C. Reichl, P. Zheng, D.Y. White, J. Ahmed, F. & Sethi, H. 2016. Predictive maintenance approaches based on continuous monitoring systems at Rio Tinto. Proceedings of CORE conference, Melbourne, Australia.
- Wolf, G. 2014. Truck Warp: The Causes and Cures. *The Journal of Wheel/Rail Interaction*, [Online] Available at: <http://interfacejournal.com/archives/1053> [Accessed 06 04 2022].
- Zarembski, A.M. 2020. Big Data Journey: From Collection to Analysis to Predictive Use. *Railway Age*, [Online] Available at: <https://www.railwayage.com/analytics/big-data-journey-from-collection-to-analysis-to-predictive-use/?RAchannel=home> [Accessed 06 04 2022].