Wheel/Rail Condition Monitoring to Support Rolling Stock Maintenance Actions

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Summary: Wheel/rail guidance is made possible by the shapes of wheel and rail profiles. For train operators to increase revenue and decrease cost for railway infrastructure owners they must monitor the conditions of the assets.

The Iron Ore Line in northern Sweden has two different monitoring systems installed to monitor conditions of all passing vehicles. The wheel/rail force measurement are made in a curve to see the how the vehicle negotiate the curve, and the wheel profile measurements are done on tangent track not far away. The vehicles investigated are iron ore wagons from LKAB mining company with an axle load of 30 tonnes and a loaded top speed of 60 km/h.

This study uses the condition from either wheel wear or wheel/rail forces as decision-making support for maintenance actions. A correlation between forces and wheel wear will make it possible to use this kind of force measurement stations at more places than just profile stations. This correlation will help to obtain maintenance limits for the operators to use on their rolling stock.

1. INTRODUCTION

Railways use the low resistance of movement between wheel and rail to create an energy efficient mode of transport. The most important element in the dynamics of a railway vehicle is the interaction between the wheel and the rail [1]. Keeping wheels and vehicles in an acceptable condition is therefore a major concern for both railway operators and infrastructure owners. A wheel impacting on a railroad track can cause extensive damage, the ultimate form of which is rail break.

Traditional inspection techniques used in the railway industry, such as drive-by inspections, are not as accurate and reliable as more rigorous and quantitative inspection methods [2]. Wayside detection systems provide a means of monitoring the condition of vehicles, ensuring that they are in a serviceable condition [3]. How track-friendly a vehicle is depends not only on its design, speed and axle load, but also on its maintenance condition [4]. Wayside monitoring stations are used to identify wheel profiles and wheel/rail forces [5].

Condition monitoring aims to record the current (real-time) condition of a system [1]. Automated condition monitoring technology includes wayside detection systems capable of monitoring the condition of railway wagon components over time to facilitate preventive maintenance [6]. By identifying these defects at an early stage and performing maintenance before component failure, railroads can reduce the likelihood of equipment-caused derailments and in-service failures and take advantage of lower-cost predictive maintenance strategies. The lifetime of railway wheels and rails is limited by wear and rolling contact fatigue both of which are deterioration phenomena [7].

Imperfections on the wheel tread can have a detrimental influence on both track and vehicle components [8]. Several different types of out-of-roundness may be present in railway wheels [9]. Examples of these wheel tread imperfections include wheel flats or tread material loss due to rolling contact fatigue cracks. Wheel flats are amongst the most common local surface defects of railway wheels [10]. The repetitive high impact forces involved cause a rapid deterioration of both, rolling and fixed railway structures.
The wear at the wheel/rail interface is an important problem for railways. The evolution of the profile shape as a result of wear has a strong effect on the vehicle's dynamics and its running stability, leading to performance variations both in negotiating curves and in straight track. [11]

The objective of this paper is to collect and combine data from both wheel/rail forces and automatic wheel profile measurements. This combined data can then determine improved maintenance limits on wheel profile wear, greatly benefiting condition monitoring.

2. WAYSIDE CONDITION MONITORING

The technique of detecting specific faults on rolling stock by interrogation sensors placed along the sides of tracks is referred to as wayside detection [3]. The condition monitoring of wheels enables scheduled maintenance of each vehicle.

Wheel condition has historically been managed by identifying and removing wheels from service when they exceed a vertical impact load threshold [12]. These thresholds are typically based on when a wheel/rail impact is presumed to cause sufficient stress on the track structure. Wayside detection sites are able to send reports on all passing vehicles, not only those exceeding the safety limits.

2.1 Wheel profile measurements

Wheel profile is critical to the railway vehicle's dynamic behaviour, stability and ride comfort; also important are the rate of wear and rolling resistance of the wheel and rail [3, 13]. The shape of the profile has a relationship to the prevention of derailment and the material properties of heavily worn wheels. It is not uncommon for wheels on both sides of a wheel axle to degrade differently despite having the same axle load and initiating tread defect [12]. Automatic wheel profile monitoring technology uses high speed cameras and lasers to capture the wheel tread profile of each rolling stock wheel as it passes [14]. The equipment monitors wheel profiles against a maintenance standard for detection of worn wheels.

2.2 Wheel/rail force measurements

Force measurement detectors make it possible for vehicles with defective wheels, which are likely to cause damage to the permanent railway structures, to be identified and removed from service immediately [15]. Out-of-round wheels can be detected using a wheel impact monitor [16]. These wayside detection systems are available commercially and report impact as either a force at the wheel/rail interface or a relative measure of the defect.

Vertical impact loads between wheel and rail resulting from surface anomalies such as wheel flats have been used to create mathematical models of wheel-rail impact behaviour [17]. Systems that solely measure the axle load of wheel flats are mostly placed on a tangent track with no gradient or a negligible gradient where trains do not accelerate or brake [18].

When measuring the lateral forces, it is best to perform measurements in narrow curves where the vehicles show their steering ability. For an illustration of lateral and vertical forces, see Fig. 1(b), and for bogie/wheel placement in a curve, see Fig. 1(a). Lateral forces are the result of poor steering bogie and train speeds outside the track design and of longitudinal buff and draft forces transmitted through train action and coupler angularity [19].

2.3 Maintenance decision support

To mitigate the risk of failure, condition monitoring, which performs incipient fault detection, is routinely applied to railway assets. The general aim is to move from reactive/routine based maintenance to a condition based or even predictive maintenance regime. This has been achieved in the railway industry, see Fig. 2 for an example. However, the identification of proper measurements is a challenge; not all failure modes are detectable using condition monitoring systems. Therefore, wheel condition monitoring using lateral forces to detect an impending wheel fault/failure seems feasible.

Once the main physical parameter to be monitored has been identified, a second challenge arises, namely, integrating data from multiple heterogeneous information systems. This is an area of consider- able interest for large scale systems such as railways. The integration and interoperability of systems enables decision makers, such

![Figure 1: Wheel position and force definition for a bogie in a curve](image)

![Figure 2: Flow chart for condition-based maintenance system](image)
as maintainers, to make informed decisions based on the status of the assets. In particular, in situations where the deteriorating status of an asset is detected and a failure occurs due to wear, replacement of the asset, the wheels in this case, can be scheduled in an accurate way to maximize the dependability of the rolling stock.

3. CASE DESCRIPTION

The only existing heavy haul line in Europe, is the Iron Ore Line (Malmbanan), which stretches 500 km from Luleå in Sweden to Narvik in Norway, see Fig. 3(a). The line's mixed traffic includes both passenger and freight trains. The iron-ore freight trains consist of two IORE locomotives accompanied by 68 wagons with a maximum length of 750 meters and a total train weight of 8 500 metric tonnes, see Fig. 3(b).

In 2010, the LKAB mining company transported 26 MGT (million gross tonne) from its mines in Kiruna and Malmberget; of these, 6 MGT were shipped from Luleå harbour. The trains operate in harsh conditions, including snow in the winter and extreme temperatures ranging from -40°C to +25°C.

The iron ore wagons pass both of the measurement stations up to three times a day. The data are only collected from the wagons when they are traveling loaded towards Luleå.

In Fig. 4 is the set-up of a wagon with wheel, axle and bogie designation; as shown, the two wagons are always connected at the A-end with a steel rod. This means that our two wagons travel as a pair with one wagon having its B-end first and the other its A-end.

3.1 Wheel profile measurement station

Outside Luleå a profile measuring station was installed in October 2011 and configured for data collection and transfer during the winter and spring of 2012. This study collects wheel profiles of all passing vehicles to see if they can be used by infrastructure managers and train operators.

The measurement system consists of four separate boxes, one on either side of each rail, see Fig. 5. These boxes contain a laser, a high-speed camera, and an electronic control system. Before a train passes the boxes, the first wheel triggers a sensor 200 meters before; the protection cover opens and the laser beam starts to shine: when the next wheel passes, the camera takes a picture of the laser beam projected onto the surface of the wheel. Heating elements have been installed to make measurements possible during the cold and snow of winter.

3.2 Wheel/rail force measurement station

In a research station outside Luleå, the wheel/rail forces are measured, both lateral and vertical, in a curve with 484 m radius for speeds up to 100 km/h [18, 20]. Due to the hostile environment of railroads, there is a weather proofing shield on top of the strain gauges, see Fig. 6(a).
The measurement system consists of several strain gauges sensors micro-welded to the web of the rail, as indicated in Fig. 6(b). There is only one measurement point on each rail. The measured forces are vertical and lateral, see Fig. 1(b), with the positive lateral force outwards in the curve. Mainly iron-ore trains with an axle load of 30 metric tonnes and a speed of 60 km/h are monitored [18].

3.3 Maintenance decisions

The intended life length of an iron ore wagon wheel between rewheeling is at least 800 000 km of running distance. Reprofiling for wheel profile wear is done today between 120 and 150 000 km of running distance, due to material fatigue. The wheel profile is checked each time the wagon is stopped for maintenance, usually two or three times per year. The wheels might be pulled out early due to wheel damage detected either by monitoring systems or visual inspections. Yearly travel distance for these wagons is 160 000 km.

4. RESULTS AND DISCUSSIONS

In this study two wagons, 73 and 74 paired with 74 traveling first, traveling from the mine in Gällivare to the harbor in Luleå. They were followed from the end of March 2012 to the beginning of May 2012. This corresponds to an assumed distance of 428 km or 29 960 tonnes-km per day and about 22 000 km of total travel distance. The data presented are flange heights from the profile measurement station and lateral forces from the wheel/rail force measurement station. The data for these two wagons are always with wagon 74 traveling with B-end first, see Fig. 4 for an explanation. The limits describing when to pull a wheel from service appear in Table 1.

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<th>Safety limit</th>
<th>Maintenance limit</th>
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<td>36 mm</td>
<td>34 mm</td>
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The data collected and shown are for the flange height of the wheel; this corresponds well to the profile wear of the wheel from an earlier study on the same fleet of vehicle, see Ref. [20, 21]. The earlier study concluded that the leading axle was the best source of data for condition monitoring using wheel/rail forces. The right wheel in the travel direction will be designated as high-rail for both profile and force measurements. The study made no measurements between 9 000 km and 20 000 km.

4.1 WHEEL PROFILE WEAR DATA

Data from the profile measurement station were collected as the two wagons passed the station in the specified configuration described earlier. The first measurements, shown in Fig. 7, are relatively close while there is about another month until the last is from the end of the period. In Fig. 7(a) are the two wheels from the leading axle of the leading bogie of the first wagon in the pair. The other, Fig. 7(b), is from the leading axle of the leading bogie in the second wagon.
Moderate wear regime is assumed due to the linearity of the measured wear, also indicated in Ref. [22]. There is a decrease in flange wear because the measurements are not made on the same part of each wheel, and each one might be worn a little differently. The whole wheel circumference is assumed to have this measured profile.

From both graphs in Fig. 7, we see that the wear for the high-rail is greater at both the start and end of the test even if the wear rate is approximately the same. This could be an indication that something happened prior to the start of this study. The wear pattern is as expected between the beginning and end of the period. In condition monitoring, then, the wheel must be measured frequently.

4.2 Wheel/rail forces data

Data from the force measurement station are processed and analyzed as vehicles pass. In Fig. 8 all collected passings of the specified configuration of the two wagons are shown. The same axles are shown as in Fig. 7. As seen in earlier studies on the same vehicle fleet [20, 21], the lateral forces need to be separated on a position within the bogie. The dotted lines in the graphs are "best-fit" lines, showing the trend for that wheel.

Both leading high-rail wheels (Fig. 8(a)) are slowly increasing in lateral force, even when those on the second wagon have a lower rate of increase. In Fig. 8(b) both wheels have a slight decrease in lateral force. This information show that the axles are pushing outwards in the curve with a greater force, indicating a worn wheel profile.

4.3 Relation between wear and forces

The data from the low-rail wheels from Fig. 7 and 8 are shown in Fig. 9. The flange heights for both wheels in Fig. 9(a) are presented as a linear wear pattern line to remove some of the uncertainty that result from measuring on different points of the circumference. In Fig. 9(b) the lateral force and flange height are plotted to find any relationship.

The wear rates for both wheels in Fig. 9(a) are increasing almost linearly which is expected in the modern wear regime. In Fig. 9(b) there is a cluster of points for each wheel with some outliers. For the first wagon, the cluster is narrower, but there are two significant outliers. The second wagon has a larger cluster with two outliers in close proximity. Moisture and lubrication on the track is a problem when trying to compare different measurements, since forces on a dry day can drop up to 50% if it starts to rain. This shows the difficulty of relating the data from lateral force to those of wheel wear. To make predictions or find relationships, we need a larger data sample both in time and wagon population.

5 CONCLUSIONS

From the preceding measurements and presented data, we conclude the following:

![Figure 8: Lateral wheel/rail force data from selected wheel axles](image)

![Figure 9: Relation data from selected low-rail wheels](image)
The trending possibilities for the wheel profile are excellent and need to be used to their full potential. In this study the wheels have only traveled a small portion of what they would normally do in a year, which is about 160,000 km. While our measurement period is short, however, it shows the linearity of the wheel wear that is assumed in the moderate wear regime. By extending the study, it will be possible to see at what point the wear becomes severe. This information will be useful for maintenance planning and decision making.

Using the wheel/rail force data collected for this paper in decision-making support is difficult since the data have not been collected for a long enough period. According to earlier findings [20, 21], the condition data collected at this interface say little about the wheel profile, but they do show the condition of the wheel in general, as well as how the bogie is performing. These data are very useful for the train operator to make maintenance decisions for the wagon. The maintainers need to keep in mind that there are different lateral force signatures for the different wheel positions within the bogie.

With a linear wear pattern and lateral forces, it would be very easy for maintainers to make decisions on when to pull out wheels and wagons for maintenance. In this case, we assume linear wear for the flange height, but the lateral forces can change greatly between two passings. From Fig. 9(b) we see that determining limits or thresholds for trending analysis to support decision makers is a real possibility.

The maintenance limit used on flange height for these wagons is valid. At this point, there is no maintenance limit on lateral wheel/rail forces, but with a better understanding of any connection and with a larger data set available on the wheel/rail force, there will be a possibility to use this as well.

6. FUTURE WORK

When there is moisture on the track the forces are lower and this need a further study to confirm sizes and occurrences. From experienced personnel there is a view that there is larger lateral forces with larger flange height. This will also need a further investigation and also the occurrence of high forces from wheels with new profiles, which should correspond to bad bogie steering.

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