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Reliability and measurement accuracy of a condition monitoring system in an extreme climate: A case study of automatic laser scanning of wheel profiles

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Abstract
The Iron Ore Line (Malmbanan) is a 473 km long track section located in northern Sweden and has been in operation since 1903. This track section stretches through two countries, namely Sweden and Norway, and the main part of the track runs on the Swedish side, where the owner is the Swedish Government and the infrastructure manager is Trafikverket (the Swedish Transport Administration). The ore trains are owned and managed by the freight operator and mining company LKAB. Due to the high axle load exerted by transportation of the iron ore, 30 tonnes, and the high demand for a constant flow of ore and pellets, the track and wagons must be monitored and maintained on a regular basis. The condition of the wagon wheel is one of the most important aspects in this connection, and here the wheel profile plays an important role. For this reason an automatic laser-based wheel profile monitoring system (WPMS) has been installed on this line using a system lifecycle approach that is based on the reliability, availability, maintainability and safety (RAMS) approach for railways. The system was prepared and installed and is being operated in a collaborative project between the freight operator and infrastructure manager. The measurements are used to diagnose the condition of the wheels, and to further optimize their maintenance. This paper presents a study of the concepts and ideas of the WPMS, and the selection, installation and validation of the equipment using a system lifecycle approach that is based on RAMS for railways. Results from the profile measurements and validation are shown. The system's reliability during performance in extreme climate conditions, with severe cold and large quantities of snow, is presented. Then the benefits, perceived challenges and acquired knowledge of the system are discussed, and an improved V-model for the lifecycle approach is presented.

Keywords
Condition monitoring, wheel profile, lifecycle, laser scanning, extreme climate, wheel maintenance

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Introduction

The Iron Ore Line (Malmbanan) has been in operation for over 100 years; it was originally constructed for an axle load of 14 tonnes but has been gradually upgraded to withstand a load of 30 tonnes. The length of a normal iron ore train is 750 m, the number of wagons is 68 and the gross train weight is 8520 tonnes.[1] The line supports a mixed traffic flow that has a large range of speeds and consists of passenger and cargo traffic together with the iron ore transports.

The Iron Ore Line has the largest predicted traffic increase of all railway lines in Sweden, with a predicted growth of 136% between 2006 and 2050 due to the expansion of the mining industry in the north of Sweden.[2] To meet this demand for increased

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capacity, the asset manager must think in new ways and add more intelligence to the infrastructure, e.g. through automatic asset monitoring. In the words of Ollier[3]: '[Effective] asset management and the use of intelligent infrastructure are key factors in delivering the railway of the future'.

For a railway system, the rail/wheel contact is an important factor, in which the wheel and rail profiles play a significant role. The rail profile is measured using measurement cars or handheld MiniProf instruments. Due to the high axle load exerted by the iron ore transports and the high demand for a constant flow of ore and pellets, the track and wagons must be monitored and maintained on a regular basis.

The condition of the profile of the wagon wheel is one of the most important aspects in this connection. Traditionally, the wheel profile is measured manually using the MiniProf equipment. This is a tedious and time-consuming task and there is a need to increase the inspection frequency and automate the measurement procedure for the wheel profile in order to track wheel deterioration and remove defective wagons from service. The operator can benefit from this by using the information to optimize the wagon maintenance intervals[4] and reduce the risk of failing wagons causing delays in the delivery chain. The infrastructure manager can also use the information from a wheel profile monitoring system (WPMS) for management purposes, for reducing maintenance costs or even for preventing failures of and damage to the track.[5–7] Information on the wheel profile can also give information about any rail degradation process and therefore increase the quality of maintenance activities.[8]

Condition monitoring can be categorized into: analysis, process monitoring, performance monitoring, functional testing and inspection.[9] The WPMS can be categorized under periodic inspection. There are numerous wheel condition monitoring systems installed along the Swedish railway network, focusing on warnings and alarms about wheel failures such as wheel flats and other types of out-of-roundness behaviour. Automatic measurement of the wheel profile is still an area where little research has been conducted in Sweden. There are still uncertainties regarding the availability and robustness of an automated WPMS installed in areas with an extreme climate characterized by low temperatures and large amounts of snow. There is also a need to examine the possibility of reducing the failure-driven capacity consumption on a line by analysing the information from an automated wayside WPMS.

A workflow to find the parameters for a wheel that is to be monitored has already been proposed.[9] The purpose of the present paper is not to find the condition monitoring parameters, but rather to show how an already defined standard for railways can be used for a lifecycle approach to condition monitoring.

This paper also describes an adaptation of the lifecycle process in the EN-50126 standard (reliability, availability, maintainability and safety (RAMS) for railways) for an automated WPMS dealing with the following components of that process: the system concept and idea, system requirement, system selection, installation and system validation. Moreover, the paper presents results from initial performance tests performed during the first year and the experience gained from the collaboration setup within the installation and operation project for the WPMS.

WPMS

The Swedish railway system is well developed and utilizes equipment for condition-based maintenance of the rolling stock and the track. To inspect the rolling stock there are wayside detector stations for the detection of hot boxes, hot/cold wheels, damaged wheels, overloaded cars, unbalanced loads, contact wire lift, and pantograph and wheel-rail forces.[10]

Figure 1 shows a diagram of wheel monitoring systems for the railway where wheel profile monitoring is included. The WPMS consists of four separate units (A, B, C and D), one on each side of each rail, see Figure 2.

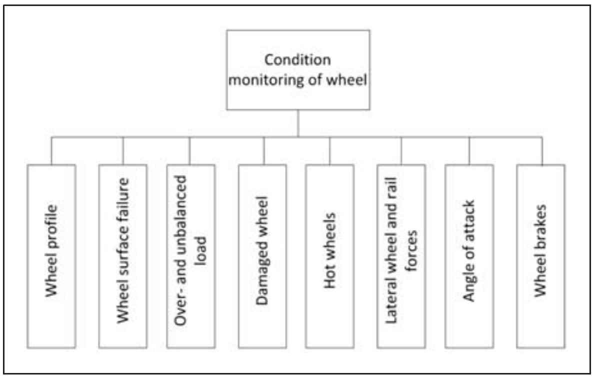

Figure 1. Condition monitoring of the wheels on rolling stock.

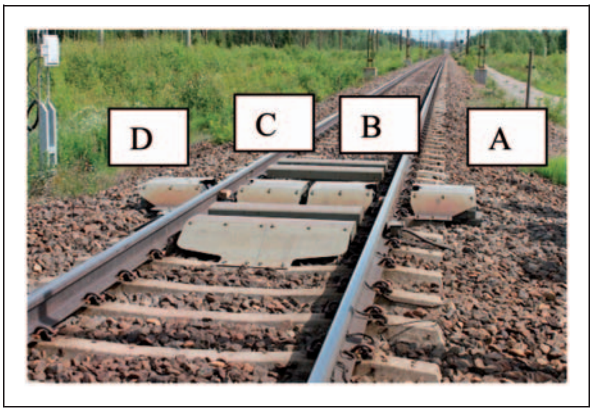

Figure 2. WPMS system located on the Iron Ore Line in northern Sweden.

These units contain a laser, a high-speed camera and an electronic control system. When a train passes the units, the wheel triggers a sensor and the protection cover opens, the laser beam starts to shine, and then the camera takes pictures of the laser beam projected onto the surface of the passing wheels. These pictures are saved and an algorithm transforms the pictures of the wheel profiles to a *xy*-coordinate system. The coordinates can be shown using software and can be compared with the nominal wheel profile. This system can automatically measure and monitor the wagon wheel profiles at speeds up to 130 km/h.

The lifecycle of the WPMS

The present project required collaboration between the infrastructure manager and the main operator of the track. The infrastructure manager's commitment was to equip the site with the infrastructure needed for the installation. The operator's commitments were to purchase the WPMS and arrange and perform the installation of the measurement equipment together with the supplier. When the measurements started, the operator was responsible for any required spare parts and the infrastructure manager for the operation and maintenance of the equipment. See Figure 3 for the system lifecycle based on the V-model in EN-50126.[11]

The whole system lifecycle consists of 14 different stages, and the V-model used in this project is an adapted version of this, especially adjusted to fit this application. This paper will focus on the following steps: concept and idea, system requirement, system selection, installation and system validation. The other steps will be treated in another paper. The core team in the work performed in the different stages is the expert group, which consists of people from the infrastructure manager and the rolling stock operator, as well as a measurement expert from the railway sector. This group developed the selection criteria.

Concept and idea

'Concept and idea' is the first step in the lifecycle process in the EN-50126 standard, and in this step one starts to define the basic concepts and ideas that underpin the system. Here the infrastructure manager and the rolling stock operator formulate the objectives of the project. The objectives come from the expert group and the company organization and are set based on the company's maintenance goals. The infrastructure manager has the following maintenance goal: 'Maintenance is carried out in order for traffic to be able to operate as the quality of service objectives imply, both now and in the future'.[10]

The objectives were summarized as follows and they constitute the concepts and ideas of the WPMS.

1. To gain more capacity for the busy Iron Ore Line, by decreasing the failure-driven capacity consumption.
2. To find the maintenance limits for wheels in order to decrease the costs for the wheels and the rail.
3. To investigate whether there are correlations between actual wheel profiles and different failures, for instance, the out-of-roundness level and failures caused by high lateral wheel forces.

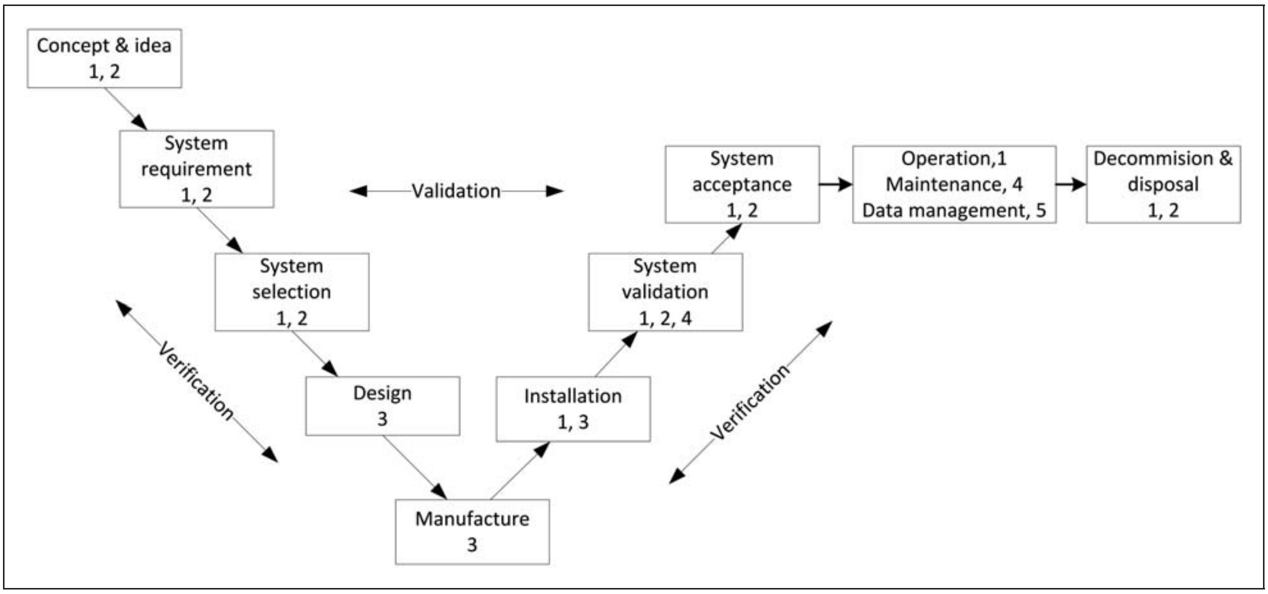

Figure 3. V-model representation of the lifecycle of the WPMS (adapted from EN-50126).
1-Infrastructure manager, 2-Train operator, 3-Supplier/manufacturer, 4-Equipment maintenance company, 5-Data management organization.

4. To increase the effectiveness and efficiency in the railway system by using condition monitoring of wheel profiles.

These objectives are broken down into system requirements in the following section.

System requirements

This section describes the selection process for the WPMS.

Commercial WPMS

The first criterion was that only commercial WPMSs were to be considered. It was deemed important to use a system that was already in operation, one of the advantages being that a large amount of operating information and references would be available. Spare parts would be available and a system for advice and support would already be in operation.

Suggestions for commercial WPMSs were found in a report by Brickle et al.[5], where 12 systems for this purpose were presented, see Table 1. The aim of the report by Brickle et al. was to: 'identify and evaluate systems that monitor various features and aspects relating to wheel set condition, and to make recommendations for integrating these systems into a comprehensive condition monitoring regime'.

General requirements

The following criteria were considered as the general requirements for this step of the evaluation process for the WPMS: system features, reporting capabilities, user-friendliness, availability, accuracy, performance, installation, deployment, speed requirements, maintenance and support. An investigation based on these criteria had already been conducted, resulting in the 12 different suppliers listed in Table 1.

Screening

By screening the candidate companies, the number of suppliers was reduced. In this step we sent a questionnaire to those companies whose existence we could establish. The screening criterion was that, if a company replied to the questionnaire that we had sent to them, then that company would be considered as a candidate supplier. If, on the other hand, no answer was received from a supplier, then that supplier would no longer be considered as a candidate supplier. After this screening five suppliers remained.

Special requirements

The special criteria set for the WPMS were the following: climate-resistance, measurement accuracy, photographing speed, vehicle identification, ease of calibration, maintainability and ease of installation. Some of these criteria have already been mentioned.

Climate. The climate in northern Sweden is extreme and is characterized by cold winters, large quantities of snow and snowstorms, but the summer can be fairly warm. The temperature can vary to a great extent for the same line; for example, for the stretch from Boden to Gällivare the temperature can vary by almost 70 °C. That same section can have a maximum precipitation of 43 mm of rain in a day.[12] The average snow depth in the winter is usually around 60 cm, but there are large local variations. The WPMS must have a high level of reliability, especially during the winter, when the wear rate is considerably higher than during the summer.[4] The system has to work in extreme conditions, with a temperature range between +30 °C and −40 °C and with large quantities of snow.

Measurement accuracy. The accuracy must be as high as possible.

Photographing speed. The WPMS has to operate at line speed and photograph wheels moving at speeds in the range 50–120 km/h, since the traffic speed is in this range.

Vehicle identification. The WPMS must be able to interact with the Automatic Vehicle Identification system and to match data sent from the tag reader to the WPMS with wheels and wagons.

Table 1. Suppliers of WPMSs that can be found on the open market.[5]

System	Company	System	Company
FactIS WPM	Lynxrail/TTCI	Wheel Profile Measurement System	MRX Technologies
Treadview	Deltarail	Trackside Measurement System	Mer Mec
Wheelspec	ImageMap	Multirail Wheel Profile Diagnostics	Schenck Process
WheelCheck	Tecnogamma	Laser Measurement System	GHH Radsatz
Argus	Hegenscheidt MFD	WheelScan	KLD Labs
Model 2000 EVA	Talgo	Wheelview	Beenavision

Calibration. The system must either be easy to calibrate or not need any calibration. It is an advantage if the system emits an alarm, through self-inspection, indicating when it is time for calibration of the equipment.

Maintainability. The system has to be easy to maintain and the time required for maintenance has to be as short as possible. Good maintenance support must be provided, with a short delay.

Installation. Disturbance of the traffic cannot be accepted, either for preparation of the site or for installation. The installation has to take place in the empty slots in the timetable.

Summary. These main requirements, together with the requirement of commercial availability, had to be met by the WPMS, and a survey was sent to each of the companies. Five suppliers were able to answer the survey, and these five remained in the evaluation process (see the summary in Table 2).

Table 2 had enough precision to allow the selection of two systems for deeper scrutiny.

System selection

The evaluation was performed by an expert group consisting of personnel from the infrastructure manager and the operator, together with a railway consultant. The most important requirements were high measurement speed and an easy installation of the equipment that did not entail any disturbance in the flow of traffic. Of course, the system had to be able to survive and work properly in a cold climate, but this was impossible to verify, other than by checking how many systems each supplier had in operation in a cold climate. This assessment of the systems was qualitative and not quantitative.

The most important features of the WPMS, as previously mentioned, included good speed performance and climate-resistance and only three systems possessed these features, namely systems A, E and F. The requirement for measurement accuracy was set as 'the highest possible accuracy' and, since one of these three systems had a significantly lower accuracy, two systems remained and both showed the same performance in this respect, namely systems E and F. The next step was to invite the competing companies supplying these two systems to provide more detailed technical information and discuss business issues. After individual meetings with each supplier, one was found to more adequately meet our requirements and system F was thus selected.

Installation and validation

The selection process ended with the conclusion that one supplier fulfilled the requirements in the most preferable way. This supplier was awarded the contract to deliver the WPMS.

Preparation and installation

The installation of the WPMS was carried out in the autumn of 2011 by the supplier, and before the installation, the site was prepared by the infrastructure manager. The Investment Department of Trafikverket was responsible for organizing the preparation of the site, and the actual work involved was carried out by contractors.

Performance test

The performance test consisted of two parts, a test of the measurement accuracy of the system and a test of the winter performance. The measurement accuracy test involved the comparison of measured values obtained from the measurement station with values obtained with handheld measurement equipment. The purpose of the winter performance test was to investigate how the system survived a winter climate, by determining the number of faults that were due to the low temperatures and the number of useful measurements in conditions characterized by snow and low temperatures.

Measurement accuracy. When the test of the measurement accuracy of the equipment was passed, the supplier received the whole payment for the system. This performance test was carried out on 32 wheels and

Table 2. Performance of the five WPMSs left after the screening process.

Company	No. of systems in operation	Min. speed (km/h)	Max. speed (km/h)	Radial accuracy +/− (mm)	Cold climate operation	Calibration	Vehicle identification	Maintainability	Estimated installation time
A	12	5	120	1.5–2.0	Yes	No	Yes	Yes	No stop
B	12	0	40	0.2–0.5	No	Yes	Yes	Yes	4 h stop
C	11	0	30	0.2–0.5	No	Yes	Yes	Yes	10 h stop
E	5	0	130	0.25	Yes	Yes	Yes	Yes	No stop
F	7	0	130	0.5	Yes	Yes	Yes	Yes	No stop

four different wagons moving through the site in November 2011. Then 16 of these wheelsets (on wagons 4011, 4012, 4019 and 4020) were measured manually with a MiniProf instrument and the results were compared with the pictures generated from the measurement equipment. Figure 4 shows the profile of one wagon and one locomotive wheel of the iron ore train taken with the WPMS. The measurement parameters were the flange height, flange thickness and flange slope. The hollow wear of the tread was not presented since the measured value was zero in most of the cases.

The measurement of the wheels was performed in random places on the wheel, which means that the WPMS and the MiniProf instrument did not use the same measurement points. The compared measurements made by the WPMS and the MiniProf instrument showed good agreement with each other; see Figure 5 for measured data. Some measurement parameters show a large deviation, for instance, wagon 4020 and wheel 3 have a deviation for the flange slope of 0.77 mm. Wheel 1 on wagon 4012 was excluded due to a problem when performing the measurements with the MiniProf instrument.

A boxplot diagram shows that these measurements have a different behaviour, the flange height is closer to zero and has a smaller spread compared with the others. The flange slope has the largest spread and all the measurements have a positive weight, see Figure 6. The reason why the flange thickness has a large spread is the combination of the two cameras (camera A and B see Figure 2) used when capturing the flange thickness. The reason for the flange slope having a spread in the plot may be due to the measurement reference of the slope having an accuracy problem or the fact that there is one large difference in the wheel circumference.

Table 3 shows the mean and standard deviations for all the measurements except those for wheel 1 on wagon 4012, which were wrong due to the problem with the MiniProf measurements. The grouping information obtained using Tukey's method shows that the flange height error belongs to group A, the flange thickness error belongs to groups A and B, and the

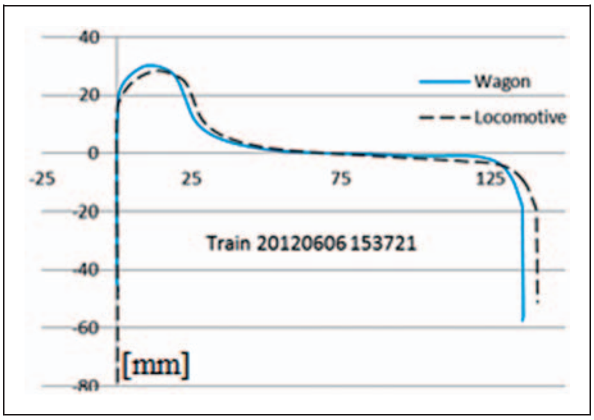

Figure 4. Measurement data from the WPMS, wheel profiles of one wheel of the iron ore train.

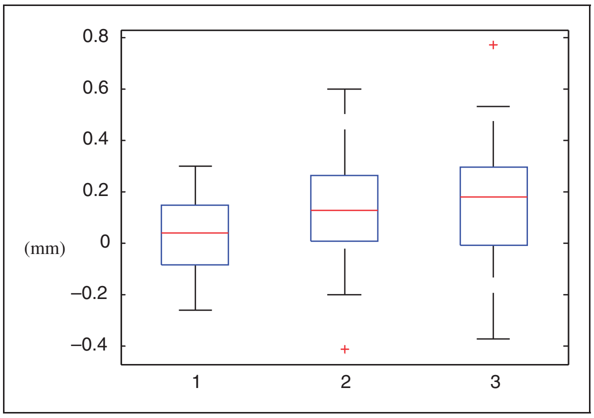

Figure 6. Boxplot of the measurement errors for the flange height (1), flange thickness (2) and flange slope (3).

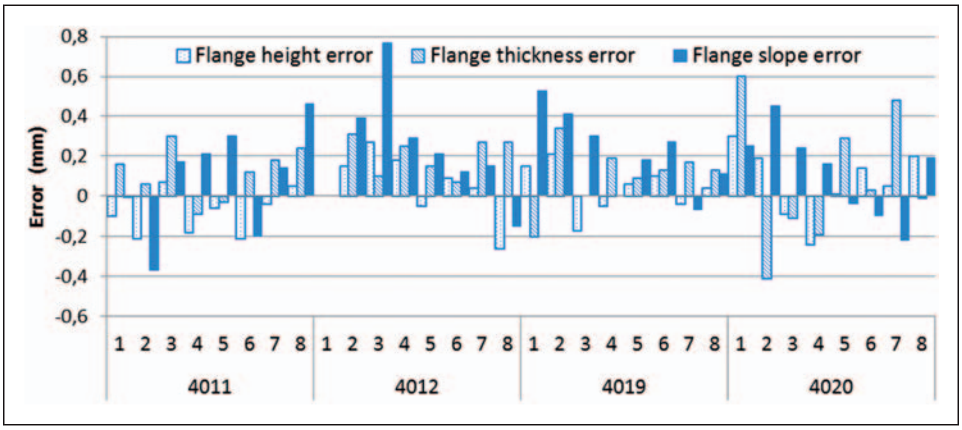

Figure 5. The errors of all the wagons and wheels that were measured, 4011–4020 are the wagon numbers and 1–8 are the wheel numbers.

flange slope error belongs to group B. This can be interpreted to mean that the errors in the flange height and flange slope values do not have the same behaviour, which is consistent with Figure 6. The Anderson–Darling goodness-of-fit test shows that all these three measurements belong to a normal distribution.

A wheel profile is not constant around the whole wheel; there is an average variation of 0.131 mm for the flange height (affecting the circumference) and of 0.145 mm for the flange thickness.[13] The accuracy of the MiniProf measurement equipment is ±9 μm.[14] These variations and the accuracy of the measurement equipment have to be taken into account, see Table 4.

Winter performance. The winter performance test was divided into two blocks: the first concerned the measurement reliability and the second the system reliability. The measurement reliability for the winter season depended, to a great extent, on the snow smoke and the snow on the equipment. The system reliability depended more on whether the equipment worked in a cold climate and whether the components were damaged or degraded due to the extreme conditions.

Table 3. Performance test of the WPMS: accuracy of the system compared with that of the MiniProf handheld measurement tool.

	Measurement error		
Statistics	Flange height	Flange thickness	Flange slope
Mean (mm)	0.02	0.13	0.17
SD (mm)	0.15	0.20	0.24

Table 4. Performance test including the variation of the circumference of the wheel: accuracy of the system compared with that of the MiniProf handheld measurement tool.

	Measurement error		
Statistics	Flange height	Flange thickness	Flange slope
Mean (mm)	0.151	0.275	0.315

Measurement reliability. For the winter month of April, around 45% of the data were useful, while the rest of the data were not usable, since the WPMS was unable to take pictures of the wheels. This can be compared with the month of May where 90% of the data were useful, see Figure 7.

The reason for this big difference may be snow smoke under the passing train and the system thus having problems photographing the wheel profile. There are two main reasons for the amount of missing data, the first reason being snowfall and snow blowing up due to passing trains, the second being failures of the measurement system due to mechanical and software problems. In this connection one can mention the fact that the last heavy snowfall for this season was between 4 and 5 May 2012, during which period there was a low percentage of useful data.

The failures in the system during this period concerned an axle sensor, which malfunctioned until 8 May 2012, and problems with the communication between the camera and the computer which was remedied on 5 May 2012. After that the snow melted, the failures ended and the information from the system was useful, see Figure 7 after 8 May 2012.

Figure 8 shows two trains from the same day with different process rates; one train has a process rate of 97% and the other has a process rate of 6%.

The low process rate for some trains can be attributed to at least two reasons. The first is the hunting motion of the train, resulting in the wheel drifting too much to one side and the laser beam being projected onto a wrong position, with too small a spread of the laser, or in the flange shadowing a part of the laser beam. A comparison of Figure 8(a) and Figure 8(b)

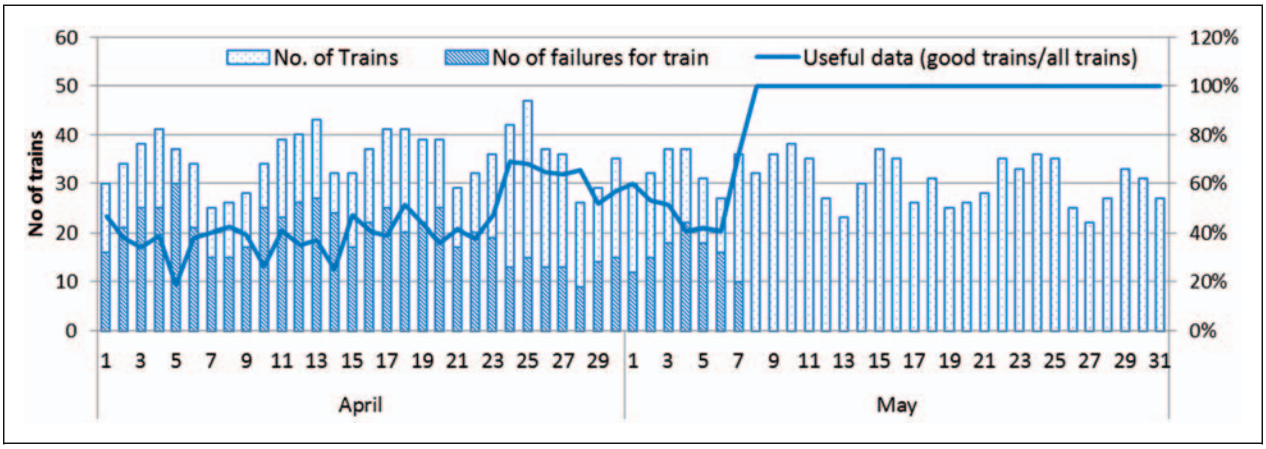

Figure 7. Measurement data from the WPMS for the months of April and May for the first year (2012).

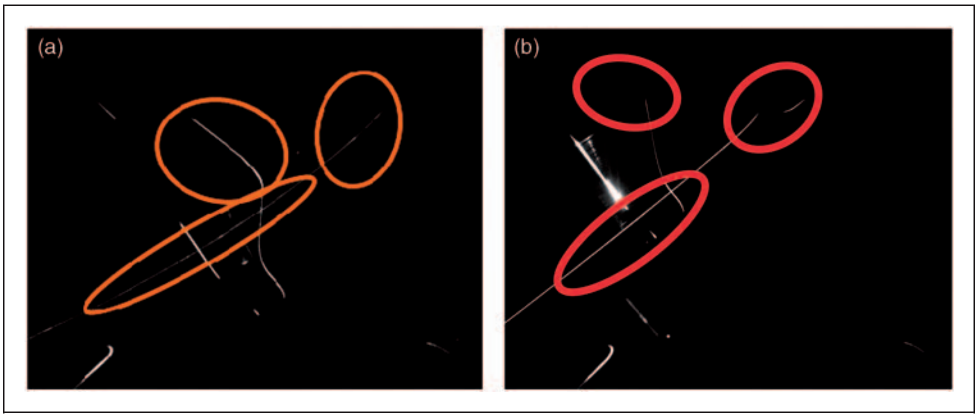

Figure 8. Two pictures from camera A for different trains on the same day but had different process rates. (a) Iron ore train with a process rate of 97%, train no. 26500 from 9 November 2013 at 19:14:48 and (b) iron ore train with a process rate of 6%, train no. 26494 from 9 November 2013 at 16:39:41.

Figure 9. Failed sensor belonging to the wheel profile monitoring system (photo by Dan Larsson).

shows that the laser beams in the rotation direction are different. In Figure 8(a) the laser beam is on the wheel tread whereas in Figure 8(b) the laser beam is on the wheel flange root. The second reason for a low process rate is the velocity of the passing train, since trains with a velocity lower than 40 km/h show a process rate of less than 40%. The reason for this is that there is no adaptive algorithm that takes into account the time between passing the sensor and taking a picture of the wheel profile. If the speed of the train is too low, the wheel is in the wrong position and this gives a wrong picture or no picture at all.

System reliability. At the beginning of the system's operation, there were problems with the router and the residual current switch. During the winter the system encountered problems with a failed sensor. The wheels piled up ice and snow on top of the sensor, and after a while the sensor broke due to the wheel load; the broken sensor is shown in Figure 9. This sensor triggers the start of the WPMS and is an important part of the system.

Moreover, a short-circuit in one of the rail heaters caused problems for the traffic and it took several days to detect this failure (for failures see Table 5). The router was replaced with another one, the residual current switch was removed, and these problems were thereby solved. The problem of the sensor breaking due to the snow and ice load could be eliminated by placing heaters close to the sensor to melt snow and ice. The short-circuiting problem was fixed with an insulating distance between the heater and the rail.

The system acceptance is a commercial issue and cannot be presented in this report.

Discussion

This form of cooperation between the infrastructure manager and the rolling stock operator creates the possibility to share the risk and costs involved when new technology is implemented and evaluated in the field. Moreover, both parties derive the same advantages from the investment without competition for data and information. Furthermore, both parties have the same incentive to enhance the capacity of the Iron Ore Line, through improving the maintenance quality of the rolling stock and the track assets to meet future demands.

The WPMS has already provided great benefit by triggering alarms indicating wheels that have exceeded the permissible range and has already enhanced the capacity on the track. The reliability of the winter performance was adequate for this equipment. Snow and other running-in problems were reasons for incomplete measurements during the first winter. Hopefully, the improvements made in the system will increase the reliability of the WPMS during the coming winter season.

The presented work will lead to the implementation of additional activities and research.

1. Integration of the information from the WPMS in the computerized maintenance management system. (This integration has already been started by the operator.)

Table 5. Problems encountered during the installation and almost 2 years of operation of the WPMS.

Problem	Component	Reason	Improvement
No connection	Router	Faulty router	New router
Current turned off	Residual current switch (RCS)	Humidity	Removal of the RCS
Short-circuit	Heater	Humidity/cold	Insulating distance
Failed	Axle detector	Ice and snow	Heater/new type of detector
Failed	Current converter for one laser	Unknown	No improvement

2. More research is needed to design models for interpreting and predicting the results from wheel profile monitoring, as a foundation for maintenance decisions.
3. Research should be conducted to determine the number of bad wheels running on the track and what benefits the infrastructure manager can gain in terms of capacity enhancement and cost reduction if this number can be minimized.
4. Further research should focus on the economic threshold for rolling stock wheels to extend the useful service life of railway assets.
5. Further research should be conducted to investigate how this system can work together with already existing systems for monitoring rolling stock.
6. Further research should be performed to investigate whether the wheel/rail interface optimum is dependent on the wheel and rail profile and whether there is a degradation model for the rail that represents this condition.

Suggestions for capacity enhancement when the WPMS is in use are as follows.

1. Wheel maintenance should be better planned due to the monitoring of wheel profiles.
2. Bad wheels should be selected for removal from the railway.

Conclusions

There is a great variety of wayside condition monitoring equipment in use on railways. This paper shows that the lifecycle approach in EN-50126 can be used to introduce new condition monitoring systems that suit railway applications and also function in extreme climates. This paper presents the deployment of the important steps in the lifecycle approach: concept and idea, system requirement, system selection, installation and system validation.

The accuracy of the laser-based WPMS compared with the MiniProf measurement equipment corresponded to a deviation of less than 0.2 mm for the flange height, 0.3 mm for the flange thickness and 0.32 mm for the flange slope, when the test included the variation of the circumference.[13] This accuracy is probably good enough to make it possible to use the wheel profiles to plan the maintenance process.

The goodness-of-fit test shows that all three measurements (the errors in the flange height, flange thickness and flange slope) belong to a normal distribution, and that the errors in the flange height error and flange slope do not have the same behaviour. The speed of the train influences the process rate in such a way that speeds under 40 km/h have low process rates. The reliability of the measurements made in the month of April 2012 was around 45%, basically due to failures of system components. The reliability increased to around 90% when the snow melted, as shown by the data at the end of May 2012. The system reliability was disturbed by problems and failures in components such as the router, the residual current switch, the heater for melting snow, the axle counter and the current converter for the laser.

The infrastructure manager and the rolling stock operator both have potential benefits to reap from the newly installed WPMS. The new maintenance principles and concepts resulting from the information obtained from the equipment are as follows:

- the introduction of a proactive type of inspections of rolling stock in the Swedish railway network;
- a better status check of the wheels for the rolling stock fleet;
- less expensive and time-consuming manual inspection of wheels;
- information for the maintenance organization for planning the re-profiling of wheels;
- use of the information obtained to develop maintenance principles for wheels;
- probably of higher safety on the track;
- in the long run, less capacity consumption due to wheel failures.

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