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Methods, Techniques and Algorithms for Condition Based Maintenance of Railway Vehicles

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***Abstract* – Industrial Companies must avoid productivity losses due to low availability of equipment and machinery that cause high maintenance costs. In response to this concern, Companies try improving their maintenance policies over the years. Increasing the effectiveness of maintenance implies switching from simply reacting to machinery breakdowns (corrective maintenance - CM), to executing time-based preventive maintenance (PM). Today's emphasis is on the ability of detecting early degradation through condition based maintenance (CBM) practices. Each policy offers a different level of performances, and it requires a different amount of data for its actuation.**

This paper analyses methods to implement CBM for a fleet of locomotives. It presents the description of the Automatic Vehicle Inspection System (AVIS), to deliver a revolutionary integrated solution that could become a game changer in the rolling stock maintenance industry. A Company can implement a Condition-Based Maintenance solution with the usage of the AVIS System and a data conditioning and analysis software like OSIsoft PI System. The paper also highlights the reasons for choosing this type of maintenance policy and for using the PI System to collect operations and manufacturing data.

The results have been achieved making use at the same time of the PI System (that manages the database) and Matlab (that manages data) applied to the fleet of railway vehicles. The possibilities with this system are endless, since with its flexibility, adding new features is very easy. Results show different aspects for a good maintenance policy: reliable and high quality measurements are important; a condition-based maintenance would provide longer life of the components compared to the current policy; at the end, a new maintenance policy would result in high savings for the Company.

I. INTRODUCTION

Maintenance represents an important cost during the life cycle of the railway vehicles and machineries in general. The target of such a Company is to guarantee a high Quality of Service (QoS) to passengers with a minimal cost of maintenance. The point is not to reduce the maintenance itself -in this case, the number of failures should increase- but to maximize its effectiveness.

Maintenance practices in the tactical and operational levels adopt different policies. Reactive maintenance policy allows performing the maintenance job only after the equipment failure. For this characteristic, this policy may lead to a long system down-time.

Scheduled Preventive Maintenance (PM) policy was introduced to improve system availability, reliability and safety decreasing unscheduled interventions. Normally, PM is based on some criteria that reflect the amount of work performed by the equipment. Examples are mileage, operating hours, total load, etc. If the equipment experience a steady workload during its lifetime, this policy is usually called time-based preventive maintenance. Such time-based PM focuses on optimizing the maintenance periods to minimize the overall maintenance cost. However, PM policy may suffer of excessive and premature interventions.

More recently, Condition-Based Maintenance (CBM), has been developed. It is a strategy that monitors the actual condition of the asset to decide what maintenance needs to be done. CBM dictates that maintenance should only be carried out when signs of decreasing performance or upcoming failure are detected by means of specific indicators. The acquisition of these indicators may require non-invasive measurements, visual inspection, performance data and scheduled tests. Condition data can be gathered at given intervals, or continuously (as it happens with sensorized machines). Condition based maintenance can be applied either to mission critical and to non-mission critical assets [1,2].

The goal of condition based maintenance is to spot upcoming equipment failure so maintenance can be proactively scheduled when it is needed – and not before.

Asset conditions need to trigger maintenance within a long enough time lapse before failure, so work can be finished before the asset fails or performance falls below the optimal level.

This paper presents an approach to the CBM for the wheels of railway vehicles. The idea is to get raw data from an automatic system that collects all the significant data of the wheels while the train is running.

On the basis of such data it is possible to know if it is necessary to profile again the wheels or to change them or to continue with the same set of these wheels until the next stop at the depot for maintenance.

The railway vehicles has to stop every six months for maintenance at the depot. It is important to identify is the wheels are still able to run until the next stop. For such a reason a continuous monitoring of the wheels it is useful for detecting upcoming problems.

This paper presents the results of the analysis performed on the data collected automatically by an automatic system (AVIS). The aim of the data analysis is to discover the proper maintenance for the wheels of each train according to the real wear-out.

It is the first time that an automatic system is installed in a railway for the continuous monitoring of a vehicle and then the use of such data for CBM purposes.

The activities performed defined first of all a framework for collect, organizing and preparing the data coming from the AVIS system ready for an analysis with Matlab.

Then, Matlab uses a Knowledge Discover approach for defining a benchmark and rules for the proper maintenance on the wheels.

II. AUTOMATIC VEHICLE INSPECTION SYSTEM (AVIS)

The AVIS system as proposed by Bombardier is a complete system that measures, analyzes monitors, establishes trends and automatically generates work orders for the maintenance crew. It also generates alarms and permits data trending for long-term engineering investigations.

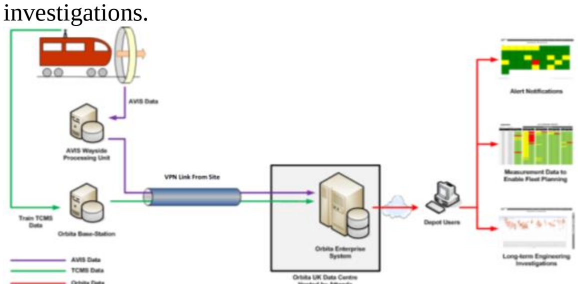

Figure 1 The AVIS Block Diagram

AVIS operates when the train runs through it at reduced speed (8 km/hour) and does not require the intervention of maintenance technicians. The automatic inspection can be performed when the locomotive enters/exits the depot. Data are gathered, sorted, stored, analyzed and work orders are generated automatically.

The system:

- Performs measurements on the train using lasers, thermal and optical imaging technologies;
- Processes the raw data to determine equipment condition;
- Automatically records key train components condition;
- Automatically raises a work order to enable rectification on condition.

AVIS is composed of:

- The Vehicle Equipment Measuring System (VEMS), which is the measuring apparatus where sensors, lasers and cameras collect live train data. It is housed in a dedicated structure and/or buried in and around the tracks.
- The Bombardier ORBIFLO Software which applies decision support algorithms on the VEMS event data for triggering maintenance alerts; it performs state detection, health status assessment, prognostic assessment.
- The Maximo© Asset Management Software that automatically generates work orders to the maintenance crew and passes environment data (such as mileage and configuration) to the VEMS.
- A Dynamic Planning System which provides a general visual overview for all work planned on a vehicle, and permits resource and material optimized allocation.

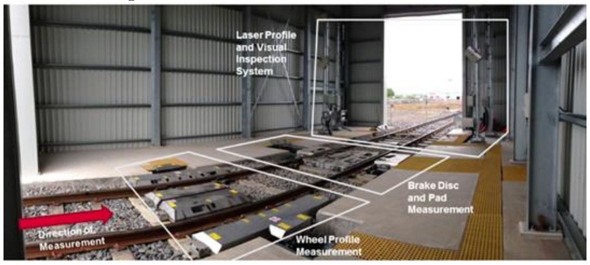

Figure 2 Vehicle Equipment Measuring System (VEMS)

III. VEHICLE EQUIPMENT MEASURING SYSTEM (VEMS)

The VEMS is a modular system and it is configured depending on the train design and operational needs (refer to Figure 2). It can contain the following modules:

- An axle end temperature monitoring system: This system measures every axle end temperature, issuing alerts when there is a variance from the average size;
- A brake pad monitoring system: This system issues an alert if a brake pad is missing, and measures every brake pad thickness, calculate brake pad wear rate and predict when

replacement is due;

- A brake disc monitoring system: This system measures the brake disk thickness, disk profile and maximum wear depth, providing alerts if something is out of parameters;
- A wheel profile monitoring system: This system measures the wheel profile and assess condition in comparison to several key markers (flange height, thread hollow, etc.);
- A pantograph wear monitoring system: This assesses the carbon strip profile, the maximum wear depth and localized chip size. A similar measuring system can be implemented for collector shoes;
- A wheel damage monitoring system: This measures flat spots on wheels and report the damage condition of a wheel by a system of thresholds, to determine when it must be sent for wheel re-profiling;
- A visual image capture system: This powerful system, through laser scanning and optical imaging, captures many data points of the train exterior, permitting verification of any deviation from the vehicle profile or previous vehicle condition. When required, it is possible to measure the car height, coupler height, to detect missing or displaced elements, open equipment boxes, foreign bodies, etc. It also detects and assesses damper leakage conditions and vehicle contamination (oil leakage, impact damage, graffiti, etc.).

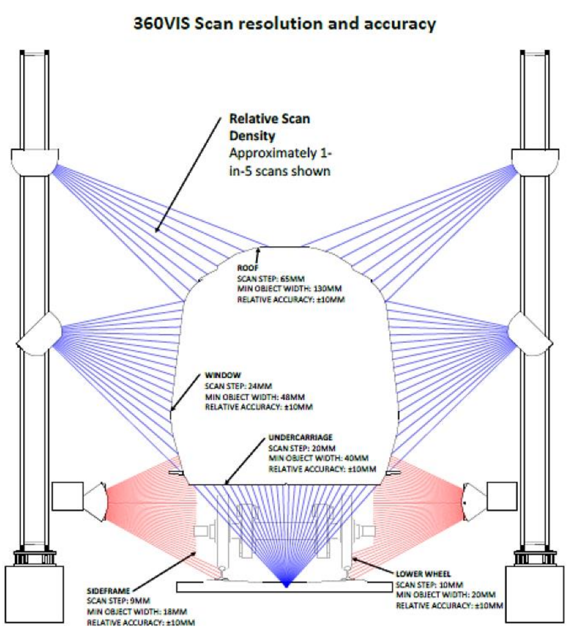

Figure 3 Visual Image Capture System

WPMS measures the structural data of the wheels with the accuracies in Table I.

Table I: Accuracy and performance of VEMS

	Accuracy	Availability
WPMS		Better than 95%
Profile (relative)	± 0.2mm	
Flange Thickness	± 0.3mm	
Flange Height	± 0.3mm	
Rim Thickness	± 0.5mm	
Tread Hollowness	± 0.3mm	
Back to Back	± 0.5mm	
Diameter	± 1.5 mm	

Measured data are automatically referred to the train under test and to the specific axle of the train.

IV. REFERENCE DATA FOR WHEELS

A boogie is a structure underneath a train to which axles (and, hence, wheels) are attached through bearings (refer to Figure 4).

Boogies serve a number of purposes:

- Support of the rail vehicle body.
- Stability on both straight and curved track.
- Ensuring ride comfort by absorbing vibration and minimizing the impact of centrifugal forces when the train runs on curves at high speed.
- Minimizing generation of track irregularities and rail abrasion

Usually, two boogies are fitted to each carriage, wagon or locomotive, one at each end.

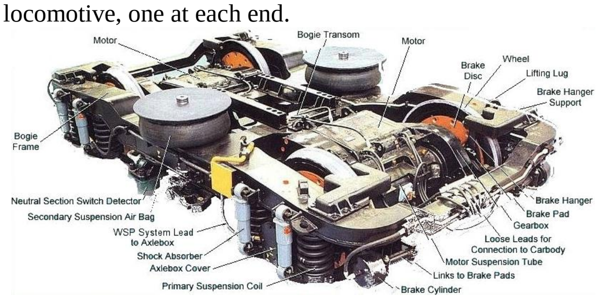

Figure 4 Boogie parts

Key components of a boogie include:

- The boogie frame: this can be of inside frame type where the main frame and bearings are between the wheels, or (more commonly) of outside frame type where the main frame and bearings are outside the wheels.
- Suspension to absorb shocks between the boogie frame and the rail vehicle body: Common types are coil springs, or rubber airbags.
- At least two wheelsets, composed of an axle with bearings and a wheel at each end
- Axle box suspensions absorb shocks between the axle bearings and the bogie frame. The axle box suspension usually consists of a spring between

the bogie frame and axle bearings to permit up-and-down movement, and sliders to prevent lateral movement. A more modern design uses solid rubber springs.

- Brake equipment: brake shoes that are pressed against the tread of the wheel, or disc brakes and pads.

In powered vehicles, some form of transmission, usually electrically powered traction motors or a hydraulically powered torque converter.

For our study, the main components are the wheels, whose functions are:

- Supporting the weight of the vehicle;
- Providing longitudinal forces for traction and braking;
- Providing adequate lateral forces to control of the trajectory of the vehicle:
  - Free Guide: stability in the corners is ensured from transversal adherence - case of the tire road.
  - Bound Guide: stability in the corners is ensured from the action on the wheel (especially on wheel flange) case of railway wheel.

The wheels will be used in two different circumstances that will bring to a wear out: curves and tangent track.

Wheel and rail profiles are critical to system performance. In straight track, lower conicity increases the critical hunting speed. In contrast, in curved track, higher conicity enables wheelsets to achieve a lateral position near the free rolling position at small values of lateral shift.

These two objectives should be achieved by controlling both wheel and rail profiles.

The reference standard for wheels' tread profile is DIN EN 5573 1995-06 [5].

Designation and meaning of the main variables are reported in Figure 5:

- AR distance between the inner wheel rim or wheel flange faces
- D Wheel diameter
- Sd Flange thickness
- Sh Flange height
- SR Track gauge
- qR transverse dimension at the wheel flange edge
- y, z Coordinates
- Δy, Δz Coordinate shift

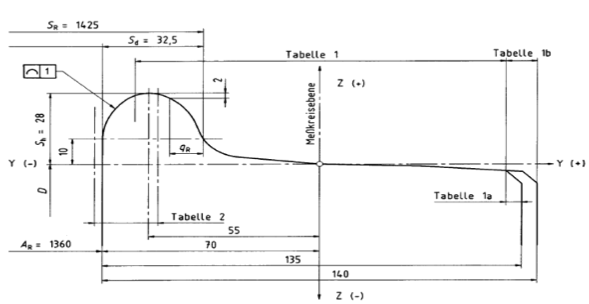

Figure 5: Wheel profile

Then, the normative defines the limits of the wheel profile variables for each type of wheel.

The variables can go beyond these limits because of the wear phenomenon over time of the wheels. Moreover, rails and wheels have their rate of wear accelerated by atmospheric corrosion, but wheels have also to be re-profiled at intervals and the metal removed in this operation is often greater than that removed by wear [4].

V. DATA ANALYSIS FRAMEWORK

The data are in a csv format, the system exports the data every time a train passes through the AVIS portal.

It is necessary to have a framework that allows to collect, organize and manage the data for the preliminary operations required before conducting the data extrapolation in Matlab.

The selected framework for the pre-processing and organizing the data is PI by OsiSoft [3].

The PI system is in charge of a main feature: the creation of the database for the Matlab analysis and the visualization of the results in a sort of operator graphical interface.

Therefore, we created the following System (Figure 6) composed by two different computers:

1. Server machine, which has the responsibility to run: PI Interface, PI Data Archive and PI Asset Framework (within there is PI AF Analyses);
2. User machine, where visualization and analyses software run: Matlab (for the development of algorithms), PI Processbook and PI Datalink (for the visualization).

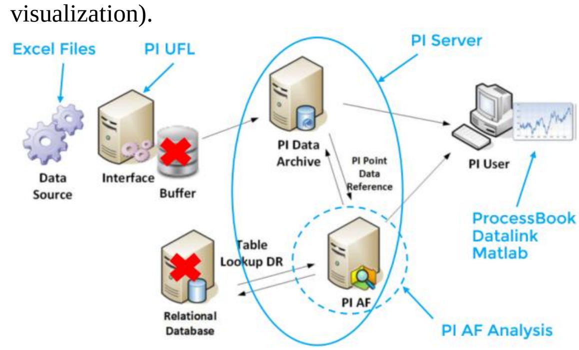

Figure 6: Architecture of the analysis system

The different parts of the system are:

- Import of the data in the PI systems through the PI UFL interface
- Archive of the data into the database, which is the PI server
- A connection between the database in the PI Server to Matlab for performing the analysis on the data
- The PI Process book responsible for the visualization of the results and the export in

tables or other formats and interface with the higher level management system (such as the Maximo system for the management of the maintenance assets)

VI. RESULTS OF DATA ANALYSIS

The study uses the data of the wheels of a British fleet composed by 302 trains measured and collected by AVIS. Measurements on each vehicle include 16 wheels (8 right wheels – RHS and 8 left wheels – LHS).

The aim of the study is to identify a signature of the wheels, to identify a marker for the re-profiling or replacement of a wheel and to define if it is possible to improve the actual cyclic maintenance.

The analysis considers the following wheel parameters (available from the database):

- Diameter of the wheel
- Flange Height
- Flange Thickness
- Difference between the right wheel's diameter and the left one
- Tread Hollowness

Firstly, in order to understand the "standard" behavior of a wheel, we need to study a "standard" trend of its parameters. A "standard" behavior could be associated with the Signature of a parameter of the wheel.

Figure 7 shows the Diameter, Flange Height and Flange Thickness trends of a single wheel, however, four important characteristics can be observed:

- o The Diameter always decrease during the life of the train;
- o The Diameter has negative step, which matches to a reprofiling of the wheel;
- o The Diameter has positive step, which matches to a replacement of the wheel;
- o Flange Height and Flange Thickness always decrease after a generic event (that could be a reprofiling or a replacement).

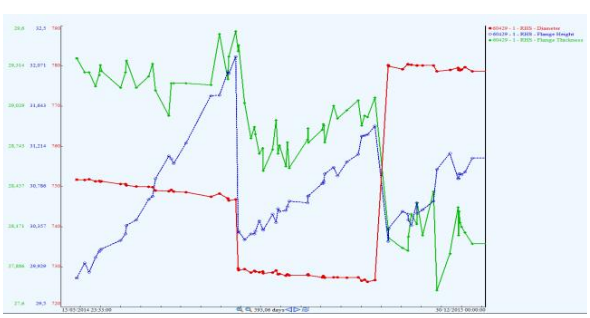

Figure 7: Example signature of the Diameter, Flange Height and Flange Thickness

From the data analysis, it is clear that the behavior of the flange thickness is not monotonic, and its behavior is not an useful indicator of the wear-out. It is useful as indicator that a change in the wheel happened: a reprofiling or a replacement. In the analysis, this parameter is used as confirmation that the generic event on the wheel happened.

For the main indicator of the wheels, a regression of the data is done. For each parameter, an upper and lower limit are defined.

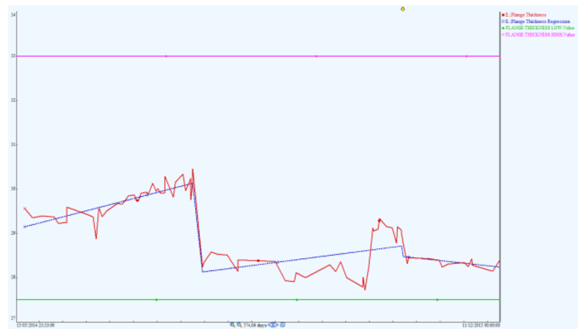

Figure 8: Flange Thickness (red line), its linear regression (blue line) and its limits (green and pink lines)

The first analysis on the database shows that the actual maintenance policy is based on a cyclic approach: a reprofiling is made every 200 days, while the replacement is every 630 days.

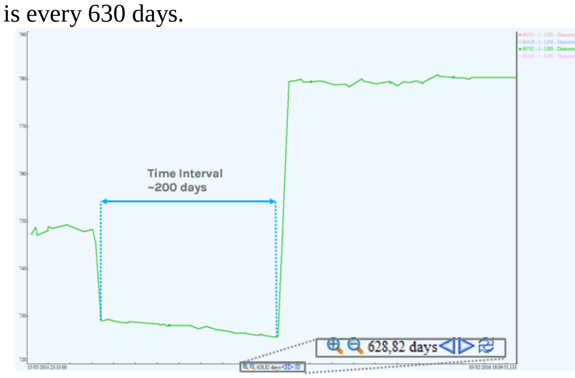

Figure 9: Identification of the cyclic maintenance intervals for reprofiling and replacement

It was possible to identify the wear-out curve for each parameter of each single vehicle. The curve is based on the actual "history" of that specific wheel on that vehicle.

Considering the wear-out curves it was possible to find out a correlation between the parameters:

- o The consumption depends on the physical position of the wheel on the vehicle (refer to Figure 10);
- o There is an increase of the duration of the interval when the wheel is at the end of its life (refer to Figure 11)

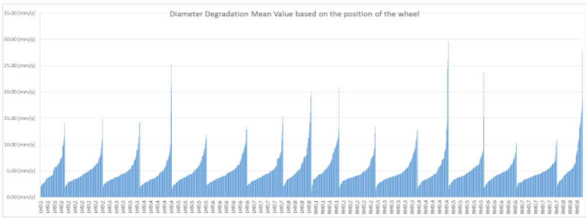

Figure 10: Increase of the lifespan at the end of the life

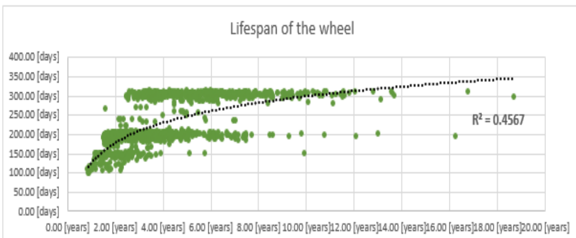

Figure 11: Increase of the lifespan at the end of the life

After the identification of the signature and the correlation between the different parameters, the two selected parameters for the identification of the behavior are:

- Lifespan of the wheel: it is the estimation of the life duration (in years) of the wheel. This parameter has been determined using the following formula:

$$Lifespan = \frac{TI}{365} * \frac{D_{max} - D_{min} - {(TI * D_{degr})}/{365}}{{(TI * D_{degr})}/{365} - \Delta D}$$

Where:
TI = Time Interval Mean Value;
Dmax = upper limit of the diameter (the wheel is restored to this diameter after a replacement);
Dmin = lower limit (we assumed this value from the trends);
Ddegr = Diameter Degradation Mean Value;
D = Diameter millimeter difference Mean Value.

- Error Mean Value: it is the difference (in days) between the estimated dates of the maintenance, using CBM (which is obtained from Matlab through the intersection of the parameters' regression and their limits), and the date of the cyclic maintenance.

Considering the parameters above mentioned, the final results are reported in Table II:

Table II: Final results obtained for CBM policy

Average Lifespan of the wheels with PM	5.22 [years]
Estimated Lifespan with CBM	5.54 [years]
Improvement	**6%**

VII. CONCLUSIONS

The paper presents the first use of data of the new system AVIS used for the measurement of the main parameters of a railway vehicle.

The focus was on the main parameters and measures from the vehicle wheels, that are an important voice in the overall maintenance for the vehicle.

It is possible to reprofile the wheel when some of its parameters are out or near the limits, while it is necessary to change them when the diameter is under a certain value.

The first step was to define a framework for the analysis of the data and to build up a Matlab tool for the processing. For the pre-condition and graphical display PI by Osisoft was used

After the preparation of the framework and the definition of the algorithms in Matlab, a study on the historical series (302 trains of the British fleet over one year) showed the important parameters for identifying the wear-out of a wheel: the diameter consumption and the flange height.

From this data, the cyclic maintenance was defined and the cyclic intervention period identified.

Starting from this data, an analysis on how it should be done the maintenance on the wheels referred to the real consumption shows an increasing of the lifespan of about 6%. This means that it is possible to have an extension of the lifespan of about six months.

The activities are still on progress and the next steps are increasing the evaluation considering a larger period of time and different fleets.

On the basis of the new results from the extended analysis, it will be possible to define an optimal maintenance policy and scheduling of the depot stops.

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