A novel integrated system for the inspection of train wheels capable of detecting both the wear level and other local defect on the wheel tread

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1 Introduction

The wheel-rail contact has a significant influence on aspects such as vehicle dynamics or noise emissions. It also plays an important role in the stability of the rolling stock and its safety. Wheel geometry and wheel profile greatly affect the dynamic behaviour of the vehicle. Small variations in the wheel profile have a significant influence on the geometry of the wheel-rail contact, completely changing the dynamic behaviour and the safety against derailment. Maintaining the good condition of the wheels of railway vehicles will allow optimal contact between the vehicle and the track, which translates into safe operation of the rolling stock.

Currently, the inspection of railway wheels is carried out in the workshop using visual means and manual equipment (gauges), and although there are on-track automatic railway wheel inspection systems on the market that analyse the condition of the wheels during normal operation, these systems have not managed to become a common practice adopted by railway operators due to their extremely high acquisition cost and because they are based on single technologies that are not able to detect all possible pathologies of different nature existing in the wheels (profile wear, punctual defects or overheating).

At present, approximately 20% of track maintenance investment, i.e. 897 million euros from public funds, is spent on repairing damage caused by the poor condition of train wheels [1], [2]. However, this is because small changes in the condition of wheels (even those that are not visually detectable) cause enormous damage to the railway infrastructure [3].

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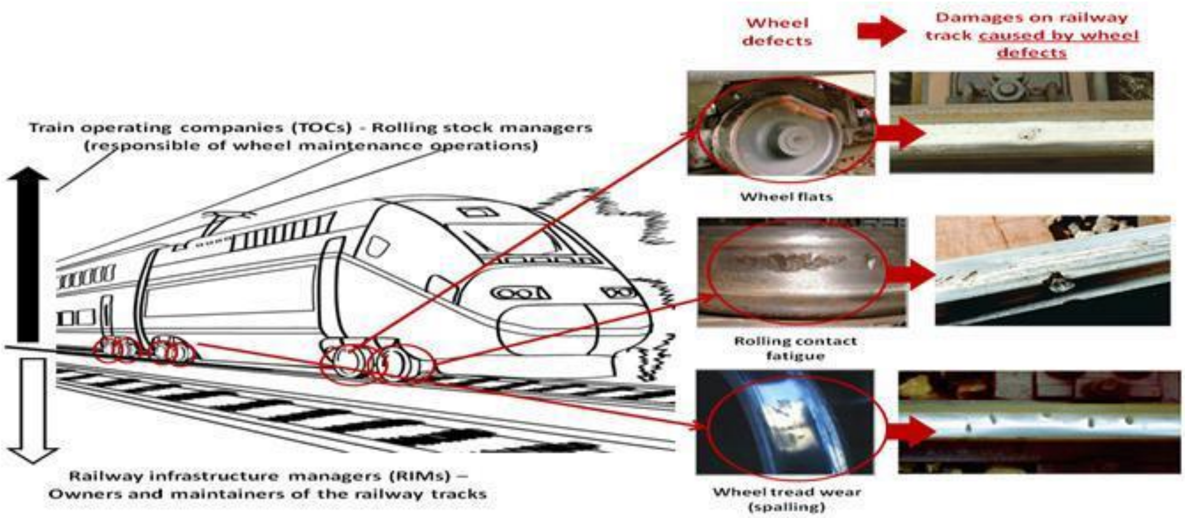

Figure 1. Deterioration of train wheels causes damage to the railway track.

The deterioration of railway wheels is caused by the loads and stresses to which they are subjected during vehicle operation, with the following deterioration mechanisms occurring [4]:

(a) uniform wear along the tread of the wheels.

(b) spot defects in the tread that progress to abrupt fractures in the wheel and/or loss of material at the periphery.

(c) thermal fatigue causing alignment defects and chipping associated with an abnormal increase in tread and bearing temperatures.

The general objective of this work is to develop a system that will allow the integral inspection of railway wheels during normal train operation by means of sensor technology implemented non-intrusively in the railway infrastructure. This system combines thermographic cameras, laser profilometers and accelerometers to carry out a comprehensive diagnosis of railway wheels during normal train operation.

2 Methods

The methodology for carrying out the system consists of developing, firstly, the hardware elements and, secondly, developing the deterioration model to be able to carry out predictive maintenance of the trains.

Figure 2 shows how the data collected by the three main hardware subsystems are used as input to the deterioration model to perform train diagnosis and to generate predictive maintenance of trains.

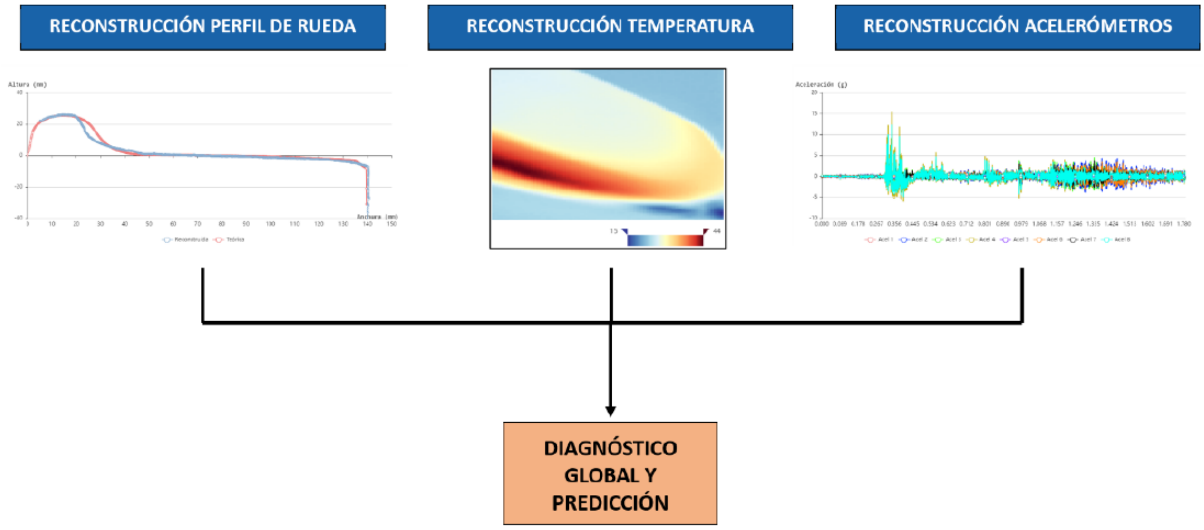

Figure 2. Scheme of the global diagnostic tool.

2.1 Measurement hardware subsystems

Each of the subsystems that make up the system is developed independently and, once developed, they are combined. Thus, there are three main subsystems: i) Wheel profile measurement subsystem; ii) Point defect detection subsystem; and iii) Temperature measurement subsystem.

The wheel profile measurement subsystem consists of two high-resolution 2D laser profilometers (one on each side) that will capture the wheel profile of the vehicle, delivering the data in the form of a point cloud. Wheel profiles will be calculated through the point clouds captured by the profilometers, interpolating the different curves that make up a wheel profile to subsequently measure the main wear parameters (width, height, and flange slope).

The point defect detection subsystem uses eight accelerometers (four on each side) on the rail, spaced far enough apart to cover the entire perimeter of the wheel and, by means of a deep learning algorithm (LSTM Neural Network), it is possible to detect up to 6 defects in the wheel tread: flat wheel, shattering, scaling, chipping and polygonalisation (periodic and stochastic).

Figure 3. Photograph of the profilometer and thermal camera on the support.

The image of the **¡Error! No se encuentra el origen de la referencia.** shows the support structure of both the profilometer and the thermal camera, made of structural aluminium elements with the possibility of dimensional adjustment in the axes of each sensor.

Finally, the temperature measurement subsystem will have two thermographic cameras (one on each side of the rail), the tread and bearing temperature will be obtained through further processing using image segmentation techniques. In addition, an ambient temperature sensor is incorporated to correct the measurements in case they are affected by seasonality and time of day.

2.2 Integration of the damage evolution and global deterioration model in the system.

To understand the steering and lift forces governing the dynamics of railway vehicles, it is necessary to know under what conditions they are generated in the wheel-rail contact. At the wheel-rail interface, because of the contact force, which is mainly normal, a deformation appears on the contact surfaces, which gives rise to the contact area. The interaction forces between the wheel and rail bodies result in a stress distribution. By integrating these stresses, the normal force and the tensile force can be obtained, which are the cause of the wear phenomenon between the two bodies [5].

From the measurement taken from the rolling stock, an integrated algorithm is developed that allows the overall diagnosis of the rolling stock based on material wear to predict a specific failure in the vehicle.

The deterioration model consists of three distinct phases: the local contact model, the wear assessment, and the profile update. The local contact model is based on the local Hertz theory and the simplified Kalker FASTSIM algorithm, starting from the global contact variables. Thus, contact variables such as contact pressures are evaluated and the contact area is divided into adhesion area and sliding area.

The most widely used wear law is the University of Sheffield Wear Law (USFD), which is based on experimental data obtained under laboratory conditions on a double disc machine and expresses the wear rate as the material lost (μg) per distance travelled (m) per unit area (mm2) [6]. The wear rate $T\gamma$ divided by the contact area A, known as the $T\gamma/A$ index, is used for wear estimation. This coefficient provides information on the amount of energy dissipated by friction per unit area.

Depending on the wear mechanisms occurring at the wheel-rail contact, three regimes are distinguished, with different associated wear rates according to Table 1.

- Soft (K1). In this first regime the wear rate increases linearly with the energy dissipated.
- Severe (K2). The wear rate remains constant. Wear is controlled by the tangential stress which remains saturated by the friction coefficient.
- Catastrophic (K3). The wear rate increases greatly, being proportional to the increase in dissipated energy.

Regime	Wear Rate (Ty/A) (N/mm^2)	Material Loss (WR) (µg/m rolled/mm^2)
Soft (K_1)	Ty/A < 10.4	5.3 Ty/A
Severe (K_2)	10.4 < Ty/A ≤ 77.2	55
Catastrophic (K_3)	77.2 < Ty/A	55.0 + 61.9 (Ty/A - 77.2)

Table 1. USFD attrition rates.

Figure 9 plots the measured wear values against the three identified wear regimes, so that a value of the Tγ/A index corresponds unambiguously to a point on the material loss graph.

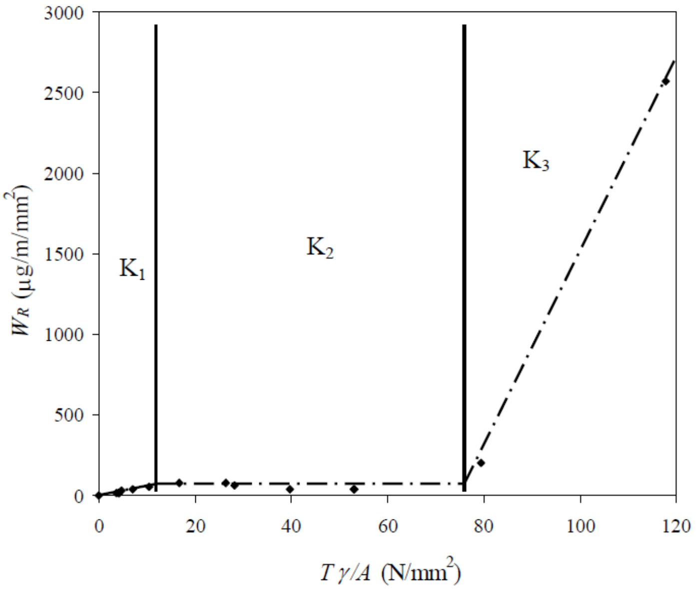

Figure 4. Attrition rates and regimes identified according to USFD law.

This law of attrition can be applied both globally and locally:

- Global. The index Tγ/A is obtained from the tangential forces and the pseudo-slips, including the spin moment, according to the Equation 1.

$$\frac{T\gamma}{A} = \frac{\left|F_x v_x + F_y v_y + M_{spin}\varphi\right|}{A}$$

Equation 1

- Local. The index Tγ/A represents the product of the tangential stresses (T/A) by the dimensionless slip values (γ) is obtained through the absolute slips at the contact, according to the Equation 2.

$$\frac{T\gamma}{A} = \left|p_x(x,y)\gamma_x(x,y) + p_y(x,y)\gamma_y(x,y)\right|$$

Equation 2

In this way, depending on the value of the Tγ/A index calculated globally or locally, the corresponding value of the wear rate WR (wear rate) for the contact area is obtained according to Table 3.

3 First laboratory tests and results

The laboratory testing phase was carried out in the Machado workshop facilities, belonging to Ferrocarriles de la Generalitat Valenciana (FGV), located in the city of Valencia (Spain). These facilities contain what is necessary to carry out tests in a controlled environment. Measuring equipment was placed on one of the rails, as shown in Figure 5.

Figure 5. Test set-up.

Several static measurements were taken with 10 mm increments between them to evaluate the measurement error in one of the wheel parameters, in this case the flange height. Data collection is shown in Figure 6, and after reference system change processing, combined in Figure 7, and evaluation of results in Table 2.

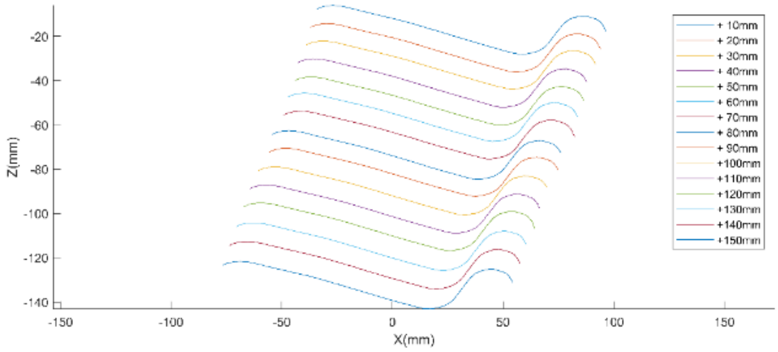

Figure 6. Profiles obtained at distances of +10 to +150mm.

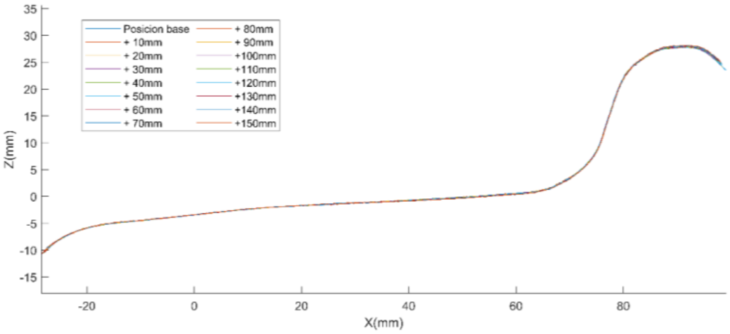

Figure 7. Profiles superimposed on the base for distances from +10 to +150 mm.

Position	Error (mm)	Error (%) Flange height = 29.5mm
+ 10mm	0.0139	0.0470
+ 20mm	-0.0222	0.0751
+ 30mm	-0.0805	0.2727
+ 40mm	-0.0491	0.1663
+ 50mm	-0.0613	0.2077
+ 60mm	0.0069	0.0234
+ 70mm	0.0322	0.1092
+ 80mm	0.0477	0.1617
+ 90mm	0.0672	0.2276
+100mm	0.1044	0.3540
+110mm	0.1372	0.4649
+120mm	0.1855	0.6289
+130mm	0.2627	0.8905
+140mm	0.3032	1.0279
+150mm	0.3363	1.1398

Table 2. Errors for flange height = 29.5mm.

4 Conclusions and future work

Initial laboratory tests have validated the laser profilometer system using a single measuring head and temperature and vibration data have been collected. The next tests will evaluate the rolling stock deterioration algorithm according to the methodology outlined above.

The usefulness of this diagnostic is that continuous records of the wheel profile and its defects can be evaluated in an overall dynamic assessment framework of the vehicle, thus allowing the identification of accelerated deterioration mechanisms due to problems in the rolling stock itself or in the way it is operated, as well as predicting the evolution of deterioration to adopt predictive wheel maintenance techniques.

The set of data collected by the proposed system constitutes a global diagnostic tool that makes it possible to find the trend in the evolution of wear over time, as well as to predict, considering all the factors incorporated in the algorithm, whether the rolling conditions will be adequate to guarantee the safety of the journey. This methodology can be implemented when sufficient records are available to achieve an adequate correlation between the records and the predictive extrapolation.

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