Analysis of Rail Degradation – Study Case of Portuguese Railway Network

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ABSTRACT

Railway Infrastructure Managers are faced with the need to increase railway productivity and efficiency, related to the transportation of people and goods. These changes have a high impact on rail component degradation, especially on rails, requiring a different set of maintenance and renewal measures. Rail degradation mechanisms are related to the head wear and defects caused by the wheel-rail interaction. Several models and contributions concerning the analysis of rail degradation are presented in this paper and were recently completed. The last one is an analysis of rail degradation in the Portuguese Railway Network, including the evolution of rail wear rates, depending on curve radii or cants and the presence of defects. It was verified that the renewed lines with rail UIC60 have lower wear rates and a minor presence of defects than non-renewed lines with rail UIC54. Moreover, in spite of the spread in results, the wear parameters have higher wear rates for minor radii and major cants.

1 – Introduction

Presently Infrastructure Managers are faced with the need of railways being prepared for the increase of productivity and efficiency related to the transportation of people and goods, resulting in increased traffic density, axle load, accumulated tonnages and train speed.

These changes contribute to a major degradation of rail components, especially rails, since these are the elements involved in direct interaction between vehicles and the line, requiring measures in terms of maintenance and renewal. These kind of interventions are essential to guarantee the operational conditions provided by railways on one hand, and to avoid accidents due to its degradation on the other hand. Rail degradation mechanisms are related to the head wear and defects caused by the wheel-rail interaction. Because of this it is important to do a study about the rail degradation in the Portuguese Railway Network (PRN) using these parameters.

The main aims of this paper are:

- Study rail degradation mechanisms;
- Identify the factors that cause rail degradation mechanisms and the way to oppose them;
- Study rail degradation models;
- Develop a study case for the Portuguese Railway Network, enclosing the analysis of rail wear and defects;
- Support a future decision support tool of maintenance and renewal of rails.

The rest of this paper is organized as follows: section II provides an overview of rail degradation and maintenance activities. A brief presentation of some rail degradation models and contributions related to recent years is presented in section III. Section IV provides the analysis of rail wear in the PRN, including the study of the following parameters: vertical wear, side gauge wear and head loss percentage, by rail type and depending on the layout of lines (curve and tangent track). Section V is about the analysis of the presence of defects on rails also for the entire PRN and the conclusions are presented in Section VI.

2 – Rail Degradation and Maintenance Activities

The wheels transmit vertical, lateral and longitudinal loads that can be static, dynamic or thermodynamic. These loads promote rail degradation and it is possible to make a distinction between continuous degradation, by examining wear, and point degradation, by examining the appearance of rail defects.

Wear is the loss of material from the contacting surface due to rail-wheel interaction. Rail operators currently use executive judgement and take decisions based on experience and historical data to mitigate wear. Rail wear depends on train speed and weight, axle load, rail-wheel material type, size and profile, track construction, bogie type and characteristics, track curvature, traffic type, lubrication, rail grinding as well as weather and environmental conditions (Reddy, 2007). The wheel-rail contact has a huge influence on the wear experienced by both. When the surfaces are worn, this contact changes due to the change of geometries. This leads to an inefficient transmission of loads.

Cannon et al., (2003) divided rail defects into three broad groups:

- Defects originating from rail manufacture (for example: tache ovale and internal cracks or fissures);
- Defects originating from damage caused inappropriate handling, rail installation and use (for example: the wheel burn defect and transversal or horizontal fissures on welds);
- Defects caused by the exhaustion of the rail steel's inherent resistance to fatigue damage. Many forms of Rolling Contact Fatigue (RCF) are within this group (for example: head checks and squats).

After a sufficient number of repeated stress cycles, a crack forms. If stress cycles continue, the crack will continue to propagate. The crack development process consists of three phases: crack initiation, crack propagation and rail break (Ishida, et al., 2003). Rail break is the final result of the crack development process. The first two phases of crack development are critical as it is during these phases that the crack should be detected by the inspection techniques and subsequently rectified, using suitable maintenance or replacement measures.

The more common inspection technique to measure rail profiles is one that uses the MINIPROF system (Esveld, 2001). This system allows the comparison between the measured profile and a reference unworn rail profile, and gives some wear parameters such as the vertical wear, the side gauge wear and the head loss percentage. Ultrasonic rail inspection and visual inspection are the common methods to check for rail defects.

In order not to affect normal operations, the processes that minimize the impact of the degradation mechanisms mentioned above are tamping, lubrication and grinding.

Tamping is a process whereby the ballast under the sleepers is compacted to provide proper load bearing (IHHA, 2001).

Lubrication, which should be applied to the rail gauge face in curves and to wheel flanges, has been accepted as an effective solution to reduce rail and wheel wear and noise. There are three methods of lubrication that can be used: track-side (way-side), Onboard and Hi-rail. In the way-side lubrication system, grease is applied to track when the lubricator is activated either mechanically or electronically by passing wheels. For the on board lubrication system, the lubricator is mounted on the locomotive and the lubricant is applied using a spray system to the locomotive wheel flanges. Hi-rail lubrication systems use a specially designed mobile truck for grease application from the nozzle, as a thin bead along the rail gauge face (Pandey, et al., 2000 in Reddy, 2007). According to (Diamond and Wolf, 2002 in Reddy, 2007), excessive lubrication leaves residue behind that builds up on the rails and wheels, resulting in a potential environmental hazard, and reduces also friction more than required which increases the train´s braking distance, elevating the risk of railway accidents.

Grinding is a process which allows the removal of surface metal from the rail head. Grinding is done by a series of rotary abrasive grinding stones or discs mounted at different angles on a rail car to give the rail head its required profile (Lichtberger, 2005). This is the appropriate process to avoid the initiation and the propagation of rail defects. Rail grinding could have two approaches, corrective and preventive. Corrective grinding requires deep and infrequent cuts whereas preventive grinding requires thin but more frequent cuts (Kalousek, et al., 1989).

Rail infrastructure owners around the world make decisions regarding grinding and lubrication frequency based on inspections (which has also a decision process associated with it), accumulated tonnage and traffic density (Reddy, 2007). This slow and costly process has a high associated operational risk between interventions, therefore finding an optimal interval to maximize the rail life cycle and minimize costs and risks has been an important challenge to rail players.

3 – Rail Degradation Models

During the last years, several models and contributions have been created to analyse rail degradation, with the main objectives being the assessment of rail life cycle and the decision-making about maintenance and renewal of rails. These studies were developed using collected data from inspections, track curvature, accumulated tonnage, traffic density, speed, axle loads, etc. The first model was proposed by the Office of Research and Experiment (ORE) in 1988, which analysed the impact of increasing axle loads from 20 to 22,5 tonnes on freight wagons and their effect on rail fatigue, rail geometry deterioration and costs. According to the report, a parameter designated track degradation index (E) is given by the following equation (ORE, 1988 in Larsson, 2004):

$$E = k \times T^{\alpha} \times p^{\beta} \qquad (1)$$

Where k is a constant related to specific track, T is the total accumulated tonnage since the track is new and p is the axle load. The exponents α and β are suggested to be:

- Rail, internal fatigue and welds: $\alpha = 1$; $\beta = 3$;
- Rail, surface defects: $\alpha = 3$; $\beta = 3{,}5$;
- Other components in superstructure: $\alpha = 3$; $\beta = 3$;
- Track settlement: $= 1$; $\beta = 3$.

Variation of α between 1 and 3 means a large uncertainty, which has led to a straight tonnage dependency when calculating costs for rail replacement and for costs are not separately defined (ORE, 1988 in Larsson, 2004). Nevertheless, this model was the base for some models and contributions presented in the following years that accounted for higher axle loads. This was due to the industry tendency of the need to increase productivity, and allow higher axle loads. Of these studies the contribution of Martland et al (1994), the model proposed by Zhang et al (2000), the contribution of Zarembski (2000) and the model proposed by Larsson (2004) stand out.

However, recent studies produced by Zhao et al (2006) and Reddy and Chattopadhyay (2007) approached the optimization of rail life cycle cost (LCC) based on degradation. The first one was based on the calculation of hazard rates of different rail failures, according to the studies of Wiseman, 1990 in Zhao et al, 2006, and respective occurrence, followed by the forecast of failures and defects during a period of time which depends on the number of inspections performed. Then, the LCC is achieved by the sum of inspection cost, costs of repairs, accidents and renewal cost. The application of the model in a tangent track with a 1 km section and an annual tonnage of 10 MGT showed that the rail economic life was 308 MGT and the minimal LCC was around 954 €/MGT/km. The second one is more complex and resulted in the integration of other models relative to rail degradation, which aim was to obtain an economical assessment regarding different inspection and grinding intervals and different strategies of lubrication. The results of the model are shown in Figures 1 and 2.

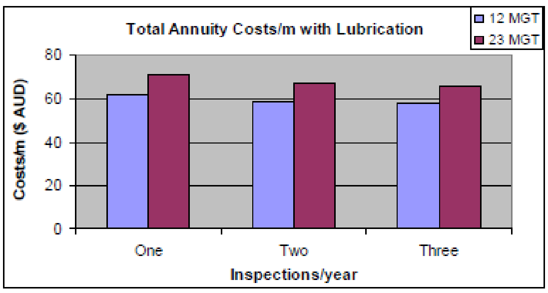

Figure 1 – Total annual costs /m of 0-300 m curve radius for 12 or 23 MGT grinding intervals with lubrication *(Reddy, 2007)*

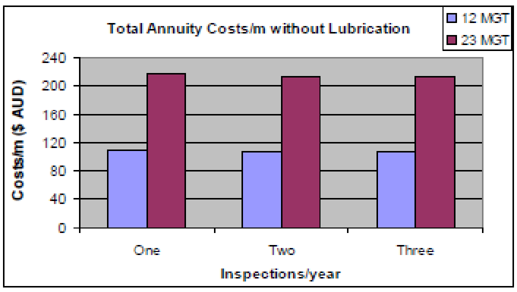

Figure 2 – Total annual costs /m of 0-300 m curve radius for 12 or 23 MGT grinding intervals without lubrication *(Reddy, 2007)*

Through its analysis, it is possible to prove the difference in costs related to lubrication of curves with a radius less than 300 m, and to see that two or three inspections per year with 12 MGT grinding intervals and lubrication are the most economical options. These results are achieved through the consideration of high renewal costs and risks of rail break and derailment, which emphasize the importance of maximizing the rail life cycle.

4 – Analysis of Rail Wear in Portuguese Railway Network

This section discusses rail wear evolution analysis, according to historical data of inspections made using the inspection vehicle EM-120 of REFER, for curve with a radius of less than 1000 m of PRN. The methodology followed in this section is described in Figure 3.

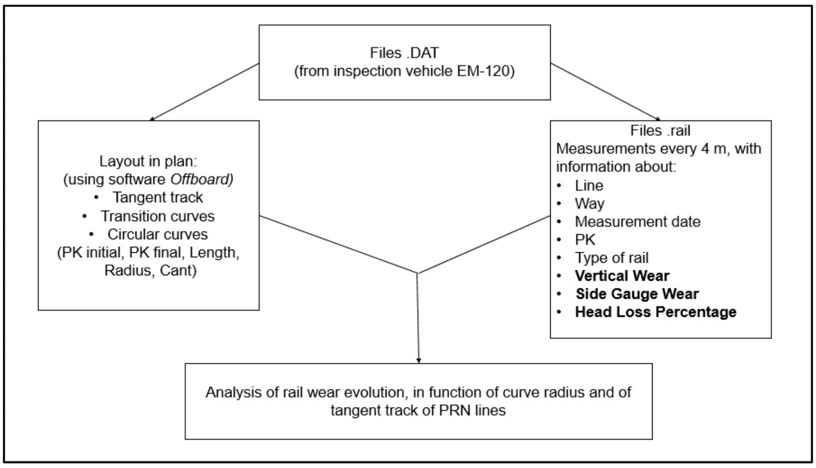

Figure 3 – Methodology followed to analysis of evolution of rail wear

The final output of this methodology was the average of parameter measurements in bolt (vertical wear, side gauge wear and head loss percentage) for every analysed curve. A total of 587 curves with UIC54-type rail and a total of 256 curves with UIC60-type rail were studied, all of which in lines of the entire PRN. The results are shown in Table 1, as a percentage of coherent results. A coherent result is one that has a positive variation of each average wear parameters for subsequent years.

Table 1 – Percentage of coherent results for the analysed curves of PRN

Wear parameters	**Left rail**		**Right rail**	
	UIC54	**UIC60**	**UIC54**	**UIC60**
Vertical wear	60%	76%	56%	78%
Side gauge wear	27%	32%	28%	37%
Head loss percentage	51%	61%	51%	59%

The analysis of Table 1 shows that vertical wear is the parameter with more percentage of coherent results, followed by head loss percentage and the parameter with least coherent results is the side gauge wear. It is also possible to see that curves with UIC60 type of rail have better results than the ones with UIC54. Comparing left and right rail, it is not possible to make an accurate analysis. Future analysis should consider the lower (inner) and the higher (outer) rails.

The Norte Line is the line with the most measurement data, which allows the study of wear parameters for every analysis year (2002 to 2011), for the analysed curves. Furthermore, the line has renewed sections with UIC60 rail type and non-renewed sections with UIC54, which allows the comparison between their wear rates. After analysing the evolution of vertical and side gauge wear in curves, for sections with UIC54 and UIC60 rail type, a considerable number of incoherent results were observed, especially for consecutive years. The period of time with more coherent results is 2007-2009, after the maintenance done by the infrastructure manager to the inspection vehicle. The evolution of vertical wear in lower (inner) rails of the curves analysed for both types of rails are presented in Figures 4 and 5.

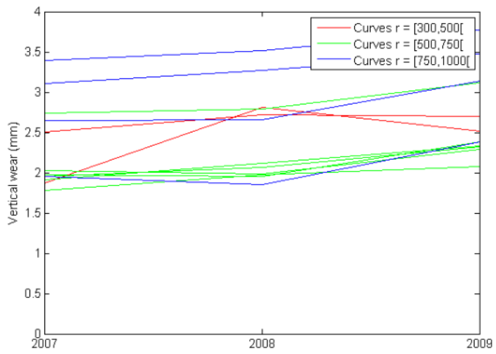

Figure 4 – Evolution of vertical wear in lower UIC54 rails of curves of Norte Line in the period 2007-2009, in mm

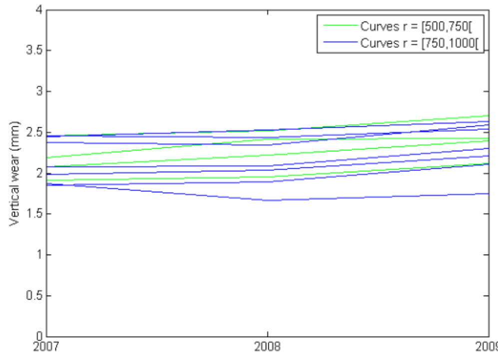

Figure 5 – Evolution of vertical wear in lower UIC60 rails of curves of Norte Line in the period 2007-2009, in mm

The analysis of figures above shows that vertical wear rates of curves with UIC54 are higher than the rates of curves with UIC60 rail type. Moreover, the wear verified in absolute terms in non-renewed sections (with UIC54) is also higher than the wear of renewed sections (with UIC60) because of the longer life service of the first ones and probably due to their worse properties compared with those of UIC60. The results verified for the higher rails are very similar to the results presented above for lower rails.

Figures 6 and 7 allow the comparison between vertical wear of different segments of curves and the following tangent track, after the transition curve, with UIC60 rail type.

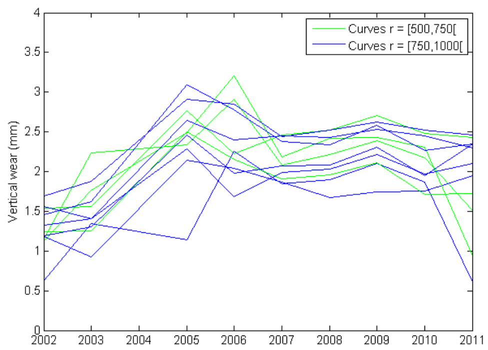

Figure 7 – Evolution of vertical wear in lower UIC60 rails of curves of Norte Line in the period 2002-2011, in mm

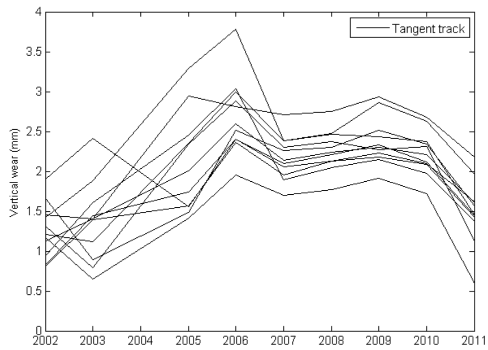

Figure 6 – Evolution of vertical wear in right UIC60 rails of tangent track of Norte Line in the period 2002-2011, in mm

Figures 6 and 7 show that there are a homogeneous vertical wear in the analysed sections, which means that this parameter is independent of track curvature. In fact, this is in accordance with what has been reported in the past by INNOTRACK (2009), the British (Tolley, 1992) and Dutch (Esveld, 2001) railway systems. However, the same does not happen with side gauge wear. The wear verified in the high (outer) rail in curves is bigger than in the low (inner) rail, which is almost nil, and the one verified in both rails of tangent track. The side wear of high rail is due to the permanent contact in curves between wheel flanges and the inner face of rails. This contact is not verified in the tangent track in a constant way because of the gap between the two elements mentioned.

In this analysis, the lines of PRN that have higher percentage of coherent results are the Leixões and Sintra Lines. Although this lines have similar results, the sample from the Sintra line is double than of the Leixões Line. Some results obtained on this line will be presented, considering the traffic. Figures 8 and 9 are related to head loss percentage rate per accumulated tonnage in function of curve radius less than 1000 m belonging to the Sintra Line.

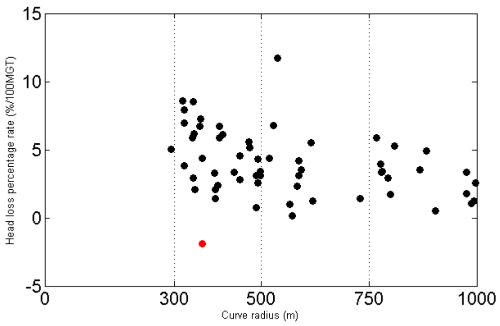

Figure 8 – Head loss percentage rate in higher UIC60 rails of curves of Sintra Line, in function of curve radius (m)

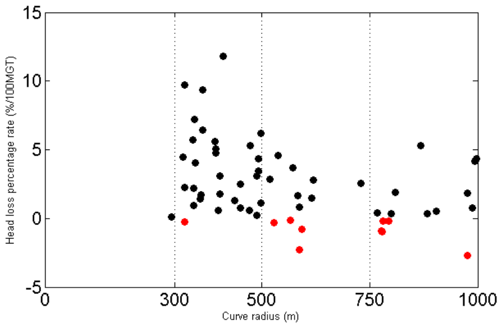

Figure 9 – Head loss percentage rate in lower UIC60 rails of curves of Sintra Line, in function of curve radius (m)

It is important to accentuate that the results shown in red are related to incoherent results (negative rates). In spite of the spread observed in results, it is possible to prove that the head loss percentage have higher rates for minor radii, for both rails of curves.

Another important layout parameter that is supposed to interfere in wear rates is cant. Thus, a similar study was performed to analyse the influence of curve cants in wear rates of both rails (the higher and the lower), and the results obtained were presented in Figures 10 and 11.

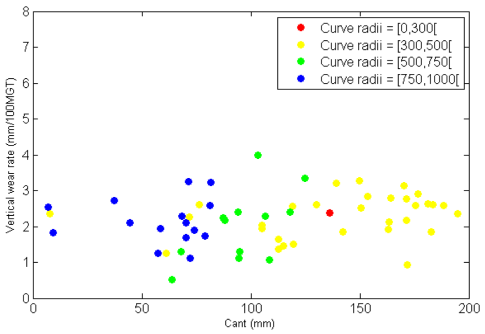

Figure 10 – Vertical wear rate in higher UIC60 rails of curves of Sintra Line, in function of cant (mm)

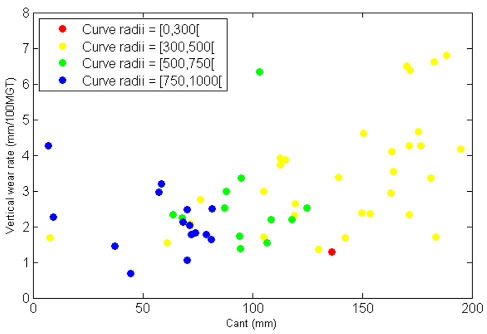

Figure 11 – Vertical wear rate in lower UIC60 rails of curves of Sintra Line, in function of cant (mm)

Figures 10 and 11 show that the vertical wear rate, verified in both rails of curves, is different. It is higher for the low (inner) rails, especially for high cants. Considering that for a conventional line the superior limit for cant is around 160-180 mm, there are some curves in this line, with curve radii between 300 and 500 m, with excess cant. In the majority of this curves, it is possible to prove that the vertical wear rate (mm/100MGT) in low rails is double or higher than the rate verified in high rails, which is a consequence of a non-homogeneous distribution of loads by passing trains.

An analysis of the errors associated with measurements was performed, and it was verified that the average deviation for vertical wear for both rails in curves is equal to the inspection equipment resolution (0,1 mm), despite the spread in results. Nevertheless, in tangent track this average deviation becomes higher, around 0,24/0,25 mm. In relation to side wear of high rails belonging to the analysed curves, the average deviation is around 0,5 mm, which is higher than the equipment resolution. Because of that the incongruities obtained in results cannot only be explained by this factor. Equipment calibration analysis was performed by manually comparing obtained results to rail settlement profiles. Unfortunately, with this procedure, the coherence of the results did not improve.

5 – Analysis of the Presence of Defects in Portuguese Railway Network

As mentioned previously, defects are detected by ultrasonic line inspections. These kinds of inspections allow rail defect identification and characterization, according to the following parameters: line and section where it is present, PK, rail (left or right), inspection date, type of rail, rail year of manufacture, type of alignment, type of defect, length of defect and type of measurement approach. Records were analysed between 2000 and 2012. The global analysis includes: the study of the prevalence of each type of defect in absolute terms and depending on the type of rail, type of alignment and type of measurement approach. Finally, a comparison was made between obtained results in PRN and records of other Railways Administrations around the world.

The global analysis made showed that the more representative types of defects in PRN in the analysed period are:

- Transverse fissure aluminothermic weld (31%);
- Vertical longitudinal fissure (23%);
- Horizontal fissure (9%);
- Squat (7%);
- Transverse fissure (6%).

Together, these types of defects represent 76% of the entire records obtained. It was verified that the majority of defects were present in continuously welded rail (66%) and only 31% were detected in short rail. In relation to the type of alignment, most defects were detected in tangent track (57%), followed by curves (40%). The 3% surplus were classified as “not set”.

The analysis related to the distribution of each type of defect per type of rail showed that 64% of defects were present in UIC54, 4% in UIC60, 13% in lighter rails than UIC54 and there were 18% of defects that were not associated with a type of rail.

Another analysis was related to the classification of defects per type of measurement approach. Thus, each defect could be classified as “Keep rail under inspection”, “Keep cracked rail under inspection”, “Remove the rail” and “Immediate removal of the rail”, from least to most severe.

It is important to state that the measurement approach “Keep rail under inspection” has only records for 2011 and 2012. This is due to a change in detection equipment made by the Portuguese infrastructure manager in 2011. This change was very positive because allowed the detection of more type of defects, like “Squats” and “Transverse fissure electric weld” which were not detected until this date. Furthermore, the introduction of a new type of measurement approach related to a detection of defects during an initial stage of cracking formation allows a better accompaniment of its development.

Figure 12 is about the distribution of classified records as “Remove the rail” during the analysed period of time. It is important to note that only the records whose first detection was classified as “Remove the rail” and the records which were detected previously in a less severe type of measure were considered.

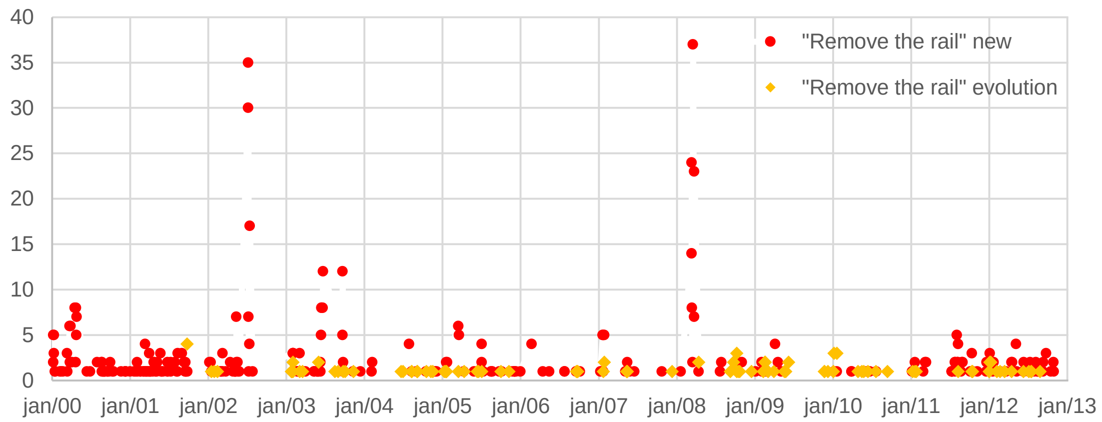

Figure 12 – Distribution of records classified as “Remove the rail” per year

Figure 12 shows the prevalence of records classified as “Remove the rail” in the first detection. It is condition that is preferable to avoid because it is very important to detect all defect types at its initial stage of development. This allows defect monitoring in the early stages and rail removal in later stages, when the risk of rail break is not high.

A comparison was made between the more representative types of defects of different railways, according to data presented in (Sawley & Reiff, 2000).

Table 2 shows the most common type of defects for the analysed railways.

Table 2 – Most common type of defects for different railways (adapted from Sawley & Reiff, 2000)

Railway	Four types of defects by percentage of railway total			
	First	**Second**	**Third**	**Fourth**
RailTrack (UK) (1999)	Squats (21,7%)	Vertical / transverse (20,1%)	Horizontal / longitudinal (12,5%)	Bolt holes (9,6%)
SNCF (France) (1999)	Squats (23,4%)	Internal fatigue (11,5%)	Shells (8,4%)	Thermite welds (4,7%)
HSPC[1] (1999)	Thermite welds (31,5%)	Wheel burns (17,2%)	Horizontal split webs (13,3%)	Bolt holes (11,3%)
NS (Netherlands) (1997)	Insulated joints (59,4%)	Transverse defects (18%)	Thermite welds (15,0%)	Shells, head checks (5,2%)
EJR (Japan)	Sheels and squats (63,9%)	Head flaws (15,8%)	Transverse cracks (6,7%)	Rail end cracks (6,1%)
DB (Germany) (1996)	Thermite welds (29%)	Sudden fracture (18%)	Shells, head checks (16%)	Electric bonds (4%)
Banverket (Sweden) (1998)	Transverse fracture (55,1%)	Welded joint (32,7%)	Horizontal defect (6,1%)	Vertical split (2%)
Spoornet (South Africa)	Thermite welds (59,2%)	Flash welds (17,7%)	Head / web horizontal (16,1%)	Rail head transverse (7,1%)
HH1[2] (1999)	Vertical split heads (34,7%)	Thermite welds (20,3%)	Detail fractures (13,1%)	Bolt holes (12,2%)
HH2[3] (1999)	Transverse defects (23,6%)	Thermite welds (15,5%)	Wheel burns (13,2%)	Shells (9,6%)
REFER (2000 to 2012)	Transverse fissure aluminothermic weld (31%)	Vertical longitudinal fissure (23%)	Horizontal fissure (9%)	Squats (7%)

Table 2 shows that generally the more frequent types of defects of the analysed railways are common to all, differing only by the representativeness of each one. Thus, RCF damage (squats, shells and head checks), aluminothermic weld defects and transverse fissures are the types of defects more frequent in the analysed railway networks, including the Portuguese.

Beyond this analysis it was also possible to compare the number of removed defects for each railway during the last two decades. The results are presented in Figure 13.

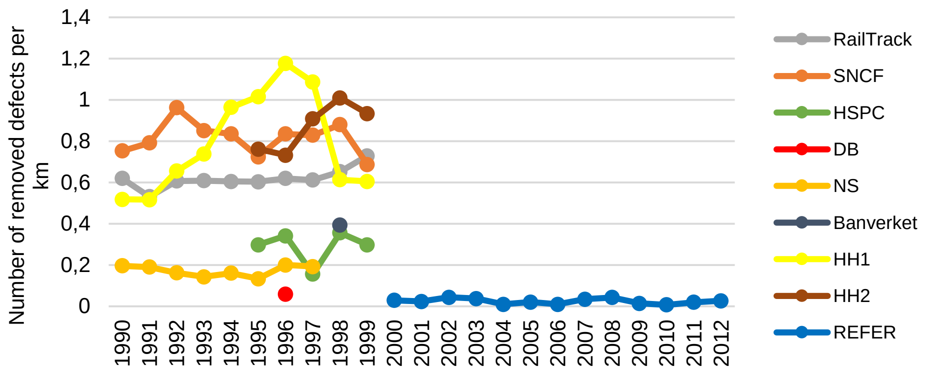

Figure 13 – Records of removed defects per km of the analysed Railways, adapted from *(Sawley & Reiff, 2000)*

[1] North American high-speed passenger corridor
[2] North American heavy haul 1
[3] North American heavy haul 2

It is important to refer that the REFER rates are related to the total number of defects classified as “Remove the rail” or “Immediate removal of the rail” for each year, because it isn’t possible to know with accuracy the number of defects effectively removed from the network. Figure 13 demonstrates the low number of removed defects per km in the PRN, with close rates to DB. The railway networks with higher rates are the ones dedicated to heavy haul, and SNCF.

6 – Conclusions

The study of rail degradation has gained particular interest to railway administrations in recent years. In fact, the need to have railways be prepared for the increase of productivity and efficiency of the railway system has contributed to a major degradation of rail components, especially rails. This study presented some rail degradation models and contributions made during the recent years and the analysis of rail degradation in the PRN.

It was verified that the renewed lines with rail UIC60 have lower wear rates and a minor presence of defects than non-renewed lines with rail UIC54. Moreover, in spite of the spread in results, the wear parameters have higher wear rates for minor radii and major cants.

It was also proved that the change in the defect detection equipment made in 2011 was positive because of the introduction of a new preventive measurement approach named “Keep rail under inspection”, which allows the accompaniment since an early stage of cracking formation. Furthermore, it is essential to invert the number of records classified as “Remove the rail” in the first detection verified in most of the analysed years.

Acknowledgment

The author would like to thank the support and collaboration of REFER, E.P.E. This work was developed as part of the FCT research project MODURAIL ref. PTDC/SEN-TRA/112975/2009.

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Notes:

s.n. – Unknown publisher;

s.l. – Unknown place of publication.