# Methodology for the monitoring, control and warning of defects for preventive maintenance of rails

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## Abstract

The preventive maintenance of rails is necessary for safe, successful and economical railway performance and operations. Rolling contact fatigue (RCF) is one of the main issues that concern the head of the railway. Progressively, RCF defects can propagate inside the material with the risk of damaging the rail, and thus they need to be monitored, categorized, evaluated, and treated through a comprehensive maintenance system. In a previous work with the Athens Metro, an innovative monitoring system was developed based on the capability of non-destructive techniques, such as IR thermography, to inspect and identify defects at early stages and reveal the activated paths of fracture (Moropoulou A., Avdelidis N., et al. Thermosense XXVII, 5782, 371-378, 2005). In the present work with the Athens Piraeus Electric Railways S.A. this system is further integrated into a complete system consisting of three components. The surveillance component identifies the rail defects and includes non-destructive techniques, such as visual inspection, infra-red thermography, ultrasonics, fiber optics microscopy, and ACFM. The data management component receives information from the various defect identification techniques, categorizes them and stores them for further use. The defect warning component uses risk indices such as defect level indices, defect extent indices, and risk threshold values, in order to evaluate the significance of the observed defects. All three components are part of a decision making system that monitors the development of defects, warns for significant threats and schedules rail maintenance.
*Keywords: preventive rail maintenance, rail defect management, risk indices.*

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# 1 Introduction

The preventive maintenance of rails, one of the most critical components of a railway system, is necessary for safe, successful and economical railway performance and operations. The rail distributes the forces from the train to the track bed and together with the tread and flange of the wheel allows for the movement of the train. The forces exerted on a rail include the vertical load and the directional and frictional components as the train moves.

The interaction between the wheels and the steel rail, and in particular the wheel - rail interface, has been the subject of intense research since it controls the initiation and development of defects. In order to be effective, a preventive maintenance system has to take into account the decay mechanisms and be able to reveal the extent of rail damage, so that the appropriate remedy measures can be taken. The overall process is termed "Rail Defect Management" (RDM) and it will be described below.

# 2 Rail defects

The wear resistance of rails is mainly controlled by hardness. However, the wear resistance is also dependent on the stresses the rails are subjected to that include bending and shear stresses, contact stresses, thermal stresses, and residual stresses. These stresses control the development of defects in rails, eventually leading to failure Cannon et al. [1]. Bending stresses act either vertically (vertical load of the vehicle), or laterally (dynamic and directional forces). The vertical bending stresses are mainly compressive in the rail head and tensile in the rail base. Contact stresses originate from the wheel load, traction, braking and steering actions. Thermal stresses originate from the welding process, during the connection of rail sections to create a continuously welded rail, whereas, residual stresses originate from the manufacturing processes.

## 2.1 Rolling contact fatigue

Various types of failures in steel rails exist that originate from various internal and intrinsic and extrinsic factors [1]. Such failures are generally categorized as: (a) *Manufacturing defects: they originate from the manufacturing process of the rail; (b) Inappropriate handling, installation and use: defects originating from out-of-specifications installation of rails, unexpected scratches and wheelburn defects; (c) Decrease of the metal's resistance to fatigue: They include the most common rail defects such as head checks and squats.*

A well designed railway system can minimize the effect of the first two types of defects. The defects due to the decrease of the metal's resistance to fatigue cannot be avoided, and the railway system can only either delay their occurrence or minimize their effect on safe operations. The term "Rolling Contact Fatigue" (RCF) refers to the fatigue of the metal of the rail due to the application of repeated and of high-values vertical and tangential stresses, and describes the initiation and development of rail defects.

When the wheel comes in contact with the rail head, both are deformed and they effectively create two "waves" at the leading and trailing edges of the wheel-rail interface, that travel along the wheel as the later moves on the rail head. Böhmer et al. [2] have shown that these deformed areas as well as the area below the wheel-rail interface are subjected to a complex stress distribution that shears a surface layer, the depth of which depends on the history and remainder properties of the metal.

The shearing of the surface layer of the rail initiates microscopic cracks. The application of repeated loadings has the effect of these microscopic cracks developing further and propagating under small angles through the plastically deformed surface layers [3]. This occurs down to a certain depth (~ 5mm) that depends on the loading pattern and the material used, until steel exhibits its isotropic properties. Generally, these microcracks develop in a direction parallel to the running direction of the vehicle.

### 2.2 Classification of defects

Classification of defects is typically performed by use of a catalogue of defects, such as the *UIC (2002) Handbook of rail defects - UIC Code 712R (4th Edn.)*. Many types of RCF related failures exist, of which the two main ones are "head checks" and "squats" [1]. "Head checks" are defined as low angle microcracks with the same direction as the running direction of the vehicle that develop near the gauge corner of the rail and correspond to repeated plastic deformation beyond the plastic shakedown limit. A large number of head checks in a limited area may lead to spalling, or in most extreme cases, propagation of the microcracks in a transverse direction, leading to rail fracture. "Squats" are identified as a broadening of the wheel-rail contact band and occur on the surface of the rail head.

## 3 Monitoring of rail defects

The detection of rail defects is an active research field and a wide range of non-destructive techniques have been employed with varying success. A simple method of detecting defects in track is the visual inspection carried out by track maintenance staff. Often this is the only method used by some railway operators, due to limited financial resources. However, advanced systems using CCD cameras and laser profilometers, linked to digital video recorders are fielded by modern operators, enhancing the capabilities of the method.

Ultrasonic defect detection has been widely used for the past forty years to reveal surface breakings and internal defects. Unfortunately, despite the advent of wheel array probes with multiple transducers operating at different frequencies and angles, often, small surface breaking defects cannot be reliably detected. Vehicle based ultrasonic test systems operate typically at 40-70 km $h^{-1}$, although the average speed is often much lower when manual verification is required, further limiting the effectiveness of the method for large rail networks.

Other methods to detect defects that are currently used or under development include eddy current testing, electromagnetic acoustic transducers, radiography, ground penetrating radar, laser generation and reception of ultrasonic waves, alternating current potential drop (ACPD), alternating current field measurement (ACFM), and impedance spectroscopy [1, 4].

In a previous work funded by the Athens Metro, an innovative monitoring system was developed based on the capability of non-destructive techniques such as infrared thermography and fibre optics microscopy to inspect and identify defects at early stages and reveal the activated paths of fracture [5, 6].

## 4 Preventive maintenance system for Athens Piraeus Electric Railways S.A

The Athens Piraeus Electric Railways S.A. (ISAP), has been operating a Metro line in Athens, Greece for the past 136 years. Over 400,000 passengers use the specific line daily, amounting to over 80 millions annually. The company owns 25.6 km of double rail tracks, using K39, S49, UIC54 and UIC60 rails with wooden and full-body prestressed concrete sleepers type B70. ISAP is currently initiating a significant infrastructure upgrade that will include the complete replacement of older types rails and sleepers. As part of this modernization plan, ISAP has funded a research program with the National Technical University of Athens, School of Chem. Eng., Lab. of Materials Science and Eng., to provide specifications and methodology for the development of system for monitoring, control and warning of defects for the preventive maintenance of rails [4].

### 4.1 Rail defect management

Rail defects cause significant costs to railway operators. These include [1]: (a) inspection costs - depending on the frequency of inspection; (b) maintenance costs - rail replacements, weld repair, use of lubricants; (c) pre-emptive treatments - rail reprofiling to hinder crack growth; (d) derailments; (e) indirect costs - loss of business confidence and customer support due to safety issues or unnecessary delays. As a result, railway companies try to minimize these costs through regular maintenance of the rails and through appropriate remedial actions when defects are detected.

Rail Defect Management (RDM) is the overall process that aims to identify, classify, assess and remedy defects before they lead to rail failures, and to minimize and if possible avoid rail defects [1]. In order to accomplish these objectives an effective RDM structure consists of two basic stages:

1. Rail inspection which includes (a) detection of defects with non-destructive techniques; (b) classification of defects; (c) decay mapping, to evaluate the extent and rate of development of wear; (d) study of decay mechanisms
2. Treatment of decay problems which includes (a) risk assessment; (b) assessment of intervention necessity; (c) application of limitations; (d) intervention - lubrication / rail reprofiling / rail replacement

### 4.2 Surveillance system

Detection of defects, especially at their early stages, plays a crucial role in an effective RDM. A wide range of non-destructive techniques, as mentioned above, are typically employed to identify rail defects. These techniques are either used as independent systems, or as subsystems of an integrated surveillance system mounted on a special vehicle or train. The selection to use non-destructive techniques independently or integrated in a complex surveillance system depends heavily on the available human and financial resources, and the needs of each railway company. For ISAP, with the rather limited rail network, a modular surveillance system is specified that consists of up to seven subsystems, each of which can be integrated gradually as the needs arise, as experience is gained, and as financial resources allow.

Specifically, the visual inspection (VI) subsystem can consist of up to one high-speed CCD camera and two laser profilometers per rail, the digital signal of which will be sent to a digital video recorder and an LCD. The infrared thermography (IRT) subsystem will consist of a 8-14 μm IR camera, with at least 320x256 pixels resolution and better than 0.08°C thermal sensitivity. The IRT subsystem should be supplemented by a fully developed thermal imaging and analysis software, a digital video recorder, portable PC, and a thermal excitation source for use during the night.

A fiber optics microscopy (FOM) subsystem can be used in conjunction with the IRT and VI subsystems, to aid in the in-situ identification and the acquisition of high resolution micrographs of defects for further analysis. It can consist of a walking stick configuration employing a CCD camera with at least 1024x768 pixels resolution and zoom lenses 25x-200x with autoscale feature.

Due to its importance and extensive experience in railway applications, an ultrasonic testing (US) subsystem is included that will be portable (optionally vehicle-mounted if desired). The US subsystem will consist of a UT wheel array probe operating at 2-20 MHz, offering A-scan, B-scan and C-scan capabilities. Similarly, an ACFM subsystem can be included based on international experience with the technique. It will also have a walking stick configuration with an option for vehicle mount, and will consist of an array of 8 pairs of Bx/Bz coils, at 50 kHz. Both subsystems can be linked to the same operator's station.

The above surveillance subsystems will be supplemented by a number of support subsystems. Specifically, a precision positioning / navigation (PPN) subsystem is considered necessary for decay mapping, since its capabilities control the resolution with which the development of defects with time can be monitored. Advanced PPN subsystems can include inertial navigation systems (INS), linked to DGPS, event triggers, and to the main train position control unit. Preferred position accuracy is less than 1m. A rail cleaning subsystem consisting of brushes, heating units and blowers will also permit all-weather operations.

All subsystems briefly described above can be either used independently (portable) or preferable mounted on a special vehicle. This can either be a truck able to travel on rails or an appropriately modified train. ISAP will initially field a selected number of surveillance subsystems independently and once experience is gained the company will upgrade to more expensive options. An ISO container with three operator's stations, mounted on a truck with detachable mounting for an array of surveillance subsystems has been proposed to ISAP for future use.

### 4.3 Data management system

As described above, the defect detection techniques can be used independently, and this is typically the case with the majority of railway operators that do not have the ability to procure comprehensive integrated rail defect detection vehicles (e.g. specialized trains). For most Metro lines, such as ISAP, to resort to such expensive solutions is not a viable option. In fact, a great improvement in the effectiveness of the available surveillance subsystems can be achieved by their gradual or partial integration into a data management system, which with an open architecture can be developed to any required level of complexity.

The basic features of such a data management system should include:

- Ethernet network
- Integration of surveillance subsystems into a local network with standard analog, digital or serial input/output units
- Development of a specialized database
- Computer/server which can be configured either (a) for in-situ, real time data acquisition / data storing, and in-situ or remote, near real time data processing; or (b) for in-situ, real time data acquisition / data storing, and post-processing of data at the technical base. The use of GSM Railway mobile communication networks can be a valuable tool.

### 4.4 Defect warning system

Non-destructive detection of rail defects and storage of the acquired data are important capabilities for a maintenance system of a railway company, but if they are not combined with an expert rail defect warning system (ERDWS) their effectiveness is limited. The lack of an ERDWS essentially restricts the preventive maintenance system only to knowledge of the extent of rail decay. Any remedy actions are made through traditional decision making procedures involving past experience of the technical staff and available resources. As a result, rails are often replaced either too early or too late. In contrast, an ERDWS supports all stages of preventive maintenance after the rail decay has been identified, which are described below.

#### 4.4.1 Archiving and classification of rail defects

Once detected, classification of rail defects should follow the general guidelines of standard defect classification catalogues such as the *UIC (2002) Handbook of rail defects - UIC Code 712R (4th Edn.)*. Archiving of each defect in a database should include further information, such as a unique identification number of the defect, type of defect (4-digit number), date of detection, exact location relative to a reference system, detection technique, link to relevant images/micrographs/thermographs/data, environmental data (temperature of the environment, temperature of rail, relative humidity), rail identification number, and any other notes made by the maintenance operators or the train drivers. The database should be sufficient large to store all available information and should be accessible by the in-situ operators (e.g. through GSM-R)

### 4.4.2 Defect level indices

The term "defect level index" refers to the evaluation of the state of a rail section or part thereof and corresponds to the worst (most dangerous) value of every observed type of defect. Specifically, appropriate software will search through the database to reveal all observed types present on a specific rail section or part thereof, and for a specific date. Then, the observed defects will be grouped in defect categories (e.g. according to UIC code 712R) and relevant defect level indices will be calculated. Table 1 shows a selection of defect level indices that can be defined to describe defects observed on the head of a rail. The numerical index $i$ is the unique identification of each observed defect.

Table 1: Typical defect level indices for defects on the rail head.

| Index | Description |
|---|---|
| $L_i^{trans-head}$ | Length of transverse crack of the head [111, 211, 100, 200] |
| $L_i^{horiz-head}$ | Length of horizontal crack of the head [112, 212] |
| $L_i^{long-head}$ | Length of longitudinal, vertical crack of the head [113, 213] |
| $L_i^{corrugation}$ | Length of corrugations [2201, 2202] |
| $\lambda_i^{corrugation}$ | Wavelength of corrugations [2201, 2202] |
| $D_i^{trans-head}$ | Depth of transverse crack of the head [111, 211, 100, 200] |
| $W_i^{horiz-head}$ | Width of horizontal crack of the head [112, 212] |
| $D_i^{long-head}$ | Depth of longitudinal, vertical crack of the head [113, 213] |
| $A_i^{surf-defect}$ | Area of surface defect [121, 221] |
| $A_i^{shell-run}$ | Area of shelling of running surface [2221, 122] |
| $A_i^{shell-gauge}$ | Area of gauge corner shelling [2222] |
| $A_i^{crush}$ | Area of crushing [123, 223] |
| $A_i^{burn}$ | Area of wheel burns [125, 2251, 2252] |
| $A_i^{uneven}$ | Area of local unevenness [124, 224] |
| $A_i^{corrugation}$ | Area of corrugations [2201, 2202] |

### 4.4.3 Defect extent indices

Although the defect level indices reveal the most dangerous situations for each type of defects, it is often desirable to know the extent of decay of the rail. The term "defect extent index" is used to describe the percentage of occurrence of each type of defect relative to a rail section or part thereof. If the reference system is a rail section, then the defect extent indices reveal the total percentage of occurrence of each type of defect for a given rail section length, $l_{rail}$. If the reference system is a specific part of a rail, with a length $l_x$, then the defect extent indices correspond to the "concentration" of each type of defect in the given rail part, usually of different value than those for the whole rail section. Table 2 shows a selection of typical defect extent indices defined for a rail section, $l_{rail}$. Similar defect extent indices can be defined for other rail defect types.

Table 2: Typical defect extent indices for defects on the rail head.

| Index | Description |
|---|---|
| $L_{spec-rail}^{trans-head}$ | Specific length of transverse cracks of the head *[111, 211, 100, 200]* $= \sum_{i=1}^{n} \left( \frac{length\ trans\ crack\ i}{rail\ width} \right)$ where $n$ is the total number of transverse cracks of the head for the given rail length $l_{rail}$ |
| $P_{mean-rail}^{trans-head}$ | Mean percentage of transverse crack of the head *[111,211,100,200]* $= \sum_{i=1}^{n} (area\ trans\ crack\ i) \cdot 100 \big/ (area\ rail\ cross-section)$ where $n$ is the total number of transverse cracks of the head for the given rail length $l_{rail}$ |
| $P_{mean-rail}^{shell-run}$ | Mean percentage of shelling of running surface) *[2221, 122]* $= \frac{\sum_{i=1}^{n} (area\ shelling\ i\ at\ running\ surface) \cdot 100}{area\ rail\ head}$ where $n$ is the total number of shelling defects at the running surface for the given rail length $l_{rail}$ |

### 4.4.4 Risk assessment

Assessment of the risk of rail failure for the observed defects will be done automatically by a software that will use the defect level indices and defect extent indices and compare them to corresponding values from a risk threshold table. The latter will contain the threshold values for each index, which will be defined experimentally by "calibration" curves that correlate the probability of failure as a function of the observed defect index.

As an example, Figure 1 shows the relevance of the threshold values for the defect level index $D_i^{trans\text{-}head}$, the depth of a transverse crack $i$ at the head of a rail.

The left curve corresponds to the tensile strength of a rail as a function of the depth of a transverse crack on the rail head. The right curve corresponds to the probability of failure of the rail as a function of the depth of a transverse crack *i* at the head of the rail. If two probabilities are selected to define the desired ranges of risk of failure (see horizontal dashed lines), Three “regions of risk state” can be calculated by the interception of the respective horizontal lines with the probability of failure curve, thus providing the corresponding threshold values. Similarly, threshold values can be defined for all other indices.

Once the threshold values are defined, the defect level indices for each classified defect and the defect extent indices for a specific rail section or part thereof will be compared to the threshold values and the worst case will correspond to the risk state of each individual rail section or part thereof.

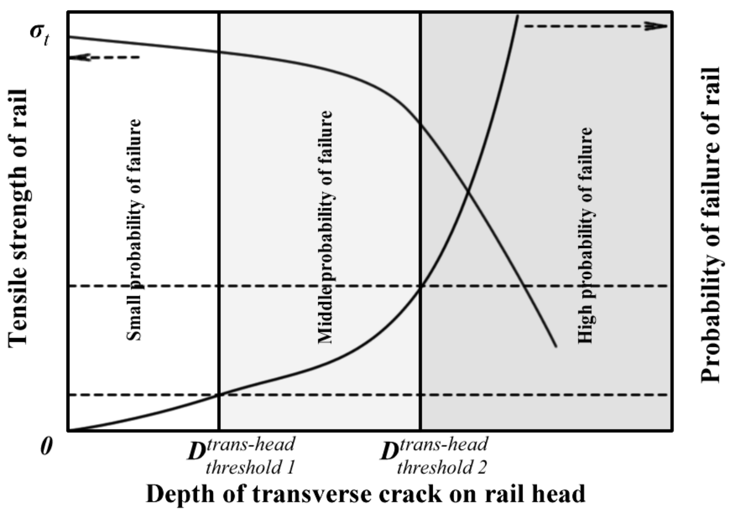


Figure 1: Schematic representation of the calculation of threshold values for the defect level index $D_i^{trans\text{-}head}$ and the definition of risk regions.

### 4.4.5 Scheduling of maintenance

The next stage, after the risk assessment, is to schedule rail maintenance. Often, although an intervention is justified due to the risk of failure involved, the final scheduling of maintenance has to take into account other factors such as, safety issues, intervention costs, cost of alternative options, remaining life of rail, schedule of train routes, existing know-how, availability of maintenance tools and materials, etc. In some cases, especially at low probabilities of failure, limitations to traffic and/or loads are imposed, until more permanent measures are taken to treat the problem. Thus, the ERDWS should be able to provide effective guidelines for scheduling of a preventive maintenance and for corrective actions. The final decisions can be made by the technical staff.

## 5 Conclusions

In the present work, the methodology for the development of a modular system for the monitoring, control and warning of defects for preventive maintenance of rails has been presented, that includes a surveillance component, a data management component and a defect warning component that uses risk indices. All three components are part of a decision making system that monitors the development of defects, warns for significant threats and schedules rail maintenance.

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