Optimization of in-service UT inspections intervals based on wheelset loads monitoring – SMARTSET®

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Abstract

NDT inspection, in particular UT inspection of railway axles, represents a fundamental part of the preventive maintenance plan for a vehicle, both from the point of view of safety (that always needs to be enhanced) and also from the point of view of cost and technology.

A main parameter that has to be set in the maintenance plan is the periodicity of inspection, that has to be low enough in order that, if a crack was present in the component at the previous inspection but too small to be detected, it will be possible detect it in a next inspection before a final failure takes place. Intervals are usually defined based on the previous service experience but not by a numerical approach, whose aim is to predict how a prospective crack would tend to propagate under the vehicle loading conditions; that is mainly for the fact that real distribution of loads are unknown and crack propagation softwares are not commonly available (up to now, mostly limited to Universities and R&D Centers).

Lucchini RS has been investing in the last two decades in the development of a database of experimental crack propagation tests on full scale axles and in a model that simulates the propagation of a prospective crack in an axle based on the material properties and the loading conditions. In practice, even if on one side fracture mechanic properties were known, real loading conditions, when available, are limited to a few thousand km of tests performed during the vehicle homologation (typically carried out for testing dynamic behavior) and so not representative of the actual service life.

The innovative solution “Smartset” presented in this paper provides the first opportunity to rail operators to monitor in long term bending and torsion loads in a few representative axles of a trainset. This is made by a miniaturized intelligent sensor that is imbedded in the axle and periodically communicates through a radio connection the load data to an onboard data concentrator.

“Smartset”, that in the future can be integrated in a complete CBM\DMMS system of a vehicle, is presently available with its own onboard computer that receives and transmits the load data to a remote server. Here the data, in the form of Rainflow matrixes, are analyzed by the Lucchini RS Starcrack software, providing an UT inspection interval, optimized for the actual vehicle and operated service line.

The first application experience of Smartset, was made with the cooperation of Trenitalia by instrumenting a Bombardier E464 Locomotive, a very common loco in Italy widely used in regional passengers service. The paper describes details of this first project, and the opportunities for increasing the inspection intervals depending also on the actual region where the vehicle is operating, considering the variety of railway lines in Italy, from fairly straight in the plane regions to the winding lines in the mountain areas.

Keywords: CBM, load spectra, crack propagation, NDT, periodicity of inspection

1 Introduction

EU statistics on accidents happening every year on different means of transportation show that after airplane, railways is the safest in terms of number of fatalities per year per km [1]. Safety is often related to the technology and the reliability performance of the vehicle and to the quality of the maintenance and the inspections. Railway vehicle fleets being managed by a single maintenance organization have an effective chance to continuously improve the maintenance plans, taking advantage of the available long term return of experience from the service.

When it comes to sustainability, from the point of view of environment, railways are in an optimal position thanks’ to the electric power that eliminates direct emissions during service (in EU the electrified railway lines are presently in excess of 60% of the total EU network). On the other side, financial sustainability is often limited by both the high investments and management costs and the ticket prices that passengers are available to pay.

Cost savings, especially in the area of maintenance has become in the last years an opportunity where many railways are focusing by testing and introducing technologies that can on one side ensure and even improve safety through higher reliable standards and on the other can reduce labor work, unnecessary replacements of components, number and duration of train stops, increasing the overall fleet availability.

A term that has become very common in the recent years and that includes the above objectives, is CBM (Condition Based Maintenance). Maintenance operators are trying to install sensors on various components that are normally subjected to fixed periodic replacement and through new data communication technologies, performance parameters are continuously uploaded to the cloud where modern data science algorithms are applied to evaluate health\life indicators and their trends. In the following paragraph it's described how Lucchini RS approached CBM concept in the wheelset component.

2 Axle in service NDT

Wheelsets represent the most safety critical mechanical component in a train vehicle; at all times their integrity must be ensured from fatigue or corrosion fatigue cracks that may initiate for various reasons such as: impacts that damage the protective coating generating an indentation on the metal surface, or a painting failure were local corrosion may develop generating surface degradation including pits; in both cases the highly dynamic loads acting on the wheelsets can contribute first to the enucleation of small cracks, then to their propagation.

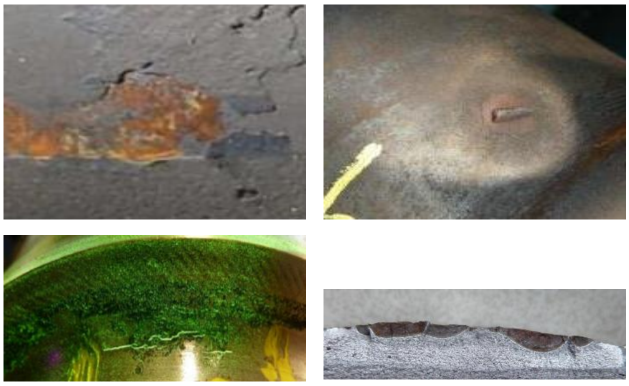

Figure 38: Cases of in-service damages on axles.

In order to prevent axle to break during operation, trains are often taken out from service for inspection with ultrasound probes that are capable to detect small cracks, with a relevant probability depending on the specific technique and the position along the axle. Ultra sound techniques have gone through a great technological development in the last two decades, in order to enable an efficient and automatic scan of the axle volume without having to dismount the wheelset from the vehicle. These are the cases of the rotating probe for inspecting solid axles from the head and bore probes that further improve defect detectability from the axle bore.

Figure 39: UT bore-probe inspecting an axle of a trainset in the depot.

In comparison to other maintenance activities, the interval between NDT inspections is normally relatively short: for high speed trains typically between 150.000 and 250.000 km.

The definition of inspection intervals for a new vehicle is normally defined by the manufacture; moreover, as defined by the European Directives the ECM (Entity in Charge of Maintenance) is responsible to define and apply the maintenance plan and to review or adapt it depending on the experience from the service; in particular inspection intervals are influenced by:

- trainset service conditions (that includes axle load, environmental conditions, kind of railway track, etc.)
- characteristic of the axle steel grade
- maximum stress levels on the axle in relation to the fatigue limit
- position of the axle most critical sections
- axle protection from corrosion and mechanical damage (both in terms of coating and protection by design of running gear\bogie).

Moreover the NDT method (manual, semi-automatic or automatic, through the bore or from the axle end) plays an important role in the inspection reliability and so in the definition of the inspection interval.

In any case it’s always important to combine the NDT inspections with other planned maintenance activities in order to minimize the time that the vehicle will remain out of service.

Taking into account the above principles, an NDT interval is defined by comparing the present with other former similar applications.

This approach needs a quite specific experience and competence and is normally performed in collaboration with NDT level 3 personnel and design experts. This process is quite difficult to be translated in a scientific and methodic approach, also because, from a practical point of view, detection of cracks during inspections is a very rare event and whenever it happens, the defective axles are immediately removed from service; for these reasons it is difficult to develop rules for defining an inspection interval based on the experience on how a crack generates and propagates in real service conditions.

Finally, it has to be considered that with such a process it is difficult for the train operators to adapt the inspection interval to the actual needs.

In a statistical approach the inspection interval for a safety critical component should ensure a probability of failure in the order of 10-7, meaning that one among 10 million axles in service, will fail during their entire life. The inputs to calculate this parameter are the propagation curve of a prospective crack in the axle and the crack probability of detection (POD) diagram for a defined NDT instrument used in service to inspect the axle integrity; an example is shown in Figure 3 [2], [3].

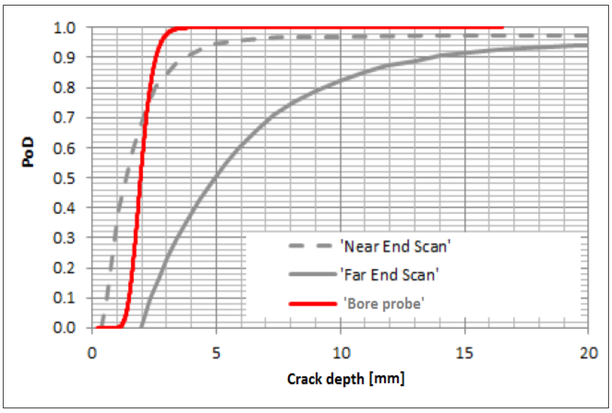

Figure 40: Example of POD curves.

The probability of failure for the remaining life of the component is:

$$PF = \prod_{i}^{n} POND_i$$

where n is the number of inspections performed on one axle during the propagation period, and PONDi the probability of non-detection (1-PODi) related to the crack size and shape during the inspection i. In this estimation the hypothesis is that a crack is existing; PF should be further multiplied by the probability that a small crack will actually generate due to one of the damages described at the beginning of this paragraph; this further probability may be estimated based on the return of experience, such as: how many small cracks or corrosion pits were found in a certain period.

3 Crack propagation software

The calculation of the crack propagation curve is dependent on the load spectrum acting on the axle section where the crack is placed and on the material crack propagation properties. The interaction of the crack propagation with the alternated variable stresses is modelled in the Lucchini RS Starcrack software developed with the support of the Politecnico di Milano [4], [5], [6], [7].

The algorithm was validated over 15 years of full-scale axle tests on a three-point rotating bending test rig (Figure 4). These type of tests are made on axles with a small elliptic notch placed at the basis of a transition and from which a real crack is generated to reach a depth of about 2 mm; specific techniques are adopted in the crack generation phase in order to limit as much as possible the plasticisation generated at the crack tip that would influence the following part of the test. Once the crack is generated, a variable loading test starts, reproducing a load spectrum representative of a long service distance in the order of 106 kilometres. During this second part of the test the crack length is monitored by a dedicated microscope installed on the test rig in order to monitor the surface crack evolution thus obtaining crack propagation curves used in the validation of the Starcrack® software. Figure 5 shows one of these cracks opened at the end of the test so that also parameters related to the crack shape evolution during the propagation are used to validate the model

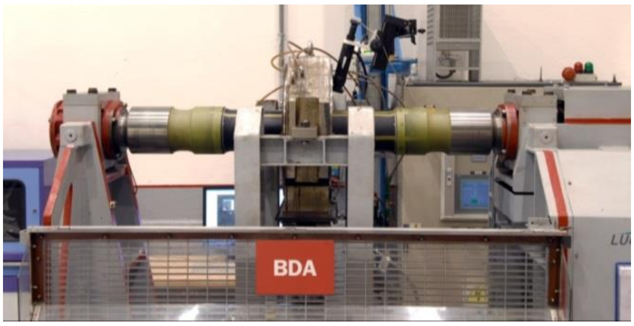

Figure 41: Three-point axle rotating bending test rig BDA installed at Lucchini RS. In the upper position there is a digital microscope, used to measure the crack length.

Figure 42: Large crack, opened after a propagation test. In the center outer area is the initial artificial notch.

Today this test is often used to verify, under a given service load spectrum, the propagation of a crack generated on a defined axle design; from this result, train manufacturers have a scientific base for setting the most suitable inspection intervals for the service.

In this process, the main uncertainty comes from the load spectrum, as it has to be representative of a long service life, considering the possible changes in the wheel/rail interaction (actual rail line, wheel tread wear or defects that may develop). In practice as load measurement campaigns are highly expensive, load spectra are typically based on short-term measurements made during the vehicle qualification tests for the service. The extrapolation of the measured data to an extended life spectrum is thus critical and it must take into account various safety margins, becoming probably much more severe than it would be in reality [8].

4 SMARTSET®

The difficulty in performing long-term measurements is normally due to the fact that the typical measuring setup, based on strain gauges and multi-channel telemetry data signal transmission, is expensive and requires an adaptation of the bogie/wheelset mechanics. Moreover data processing is carried out offline and is time consuming.

The idea behind the LucchiniRS SmartSet® patented solution was to develop a miniaturized and customized Telemetry electronic flexible PCB (printed circuit board) integrated onto the axle component, and designed to be fully autonomous and to function for a very long period (i.e. between two wheelsets main overhauling). The measuring sensor remains the strain gauge bridge that is reliable and cheap. The Telemetry electronic board has a dimension of about 45 mm and extends in the circumferential direction for about 140 mm as shown in Figure 6; directly connects two full strain gauge bridges and includes a processor which, for each strain gauge channel, applies in real time the rain-flow algorithm that estimates the amplitude and the main values of each consequent signal oscillation. The combination of amplitude and main values is continuously counted in a rain-flow matrix saved on the board memory.

The Telemetry electronic board also includes a radio module that has no need to be always active: when requested it can transmit the rain-flow matrix data to a PC installed under the car body frame and powered by the DC voltage of the vehicle battery. The telemetry board is sealed and fixed on the axle surface with specific resin and then completely covered by an anti-ballast impact protection coating (i.e. Lursak®).

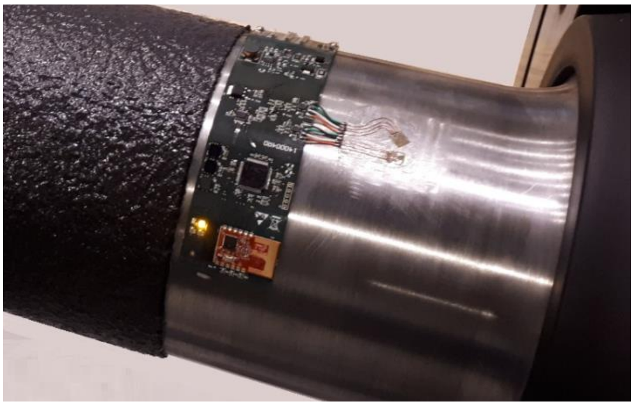

Figure 43: Flexible telemetry PCB installed on the axle before the final protection with specific resins.

The power supply for the telemetry system is provided through a specially developed electromagnetic inductive coupler. An inductive head (Figure 7), placed near to the axle surface, generates locally a high frequency electromagnetic field that induces electric current on a coil embedded under the protective coating; the coil power up the telemetry board. The inductive head can be fixed to the gearbox as shown in Figure 7 or to the bogie frame (in case of a trailer wheelset). The inductive head is power supplied by an inverter connected to the DC voltage of the vehicle battery. The inverter is developed in an IP67 box that can be installed under the car body frame.

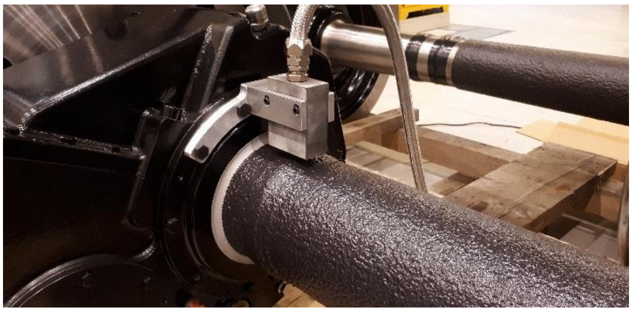

Figure 44: Inductive head connected to the gear box body; under the coating: the coil

Figure 8 provides a scheme of the SmartSet® system: the on-board PC receives the rainflow data from the instrumented axles and periodically transmits the data via GSM to a centralized database server that makes the data available on a web based dashboard that can be access by the railway operator.

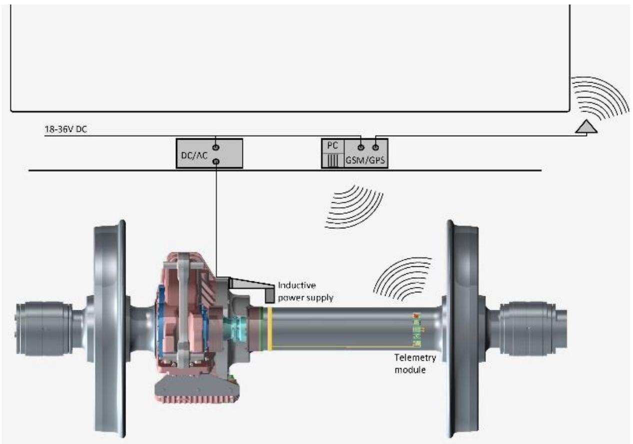

Figure 45: Installation scheme of SmartSet® system components.

The on-board PC also includes a GPS antenna that provides the possibility to distinguish load spectra from different rail line segments. For instance, a list of main stations can be defined together with the GPS coordinates, and the load spectrum will be saved each time the vehicle reaches the defined station, associating it to the actual line route. In this way, it will be possible to assess whether some rail lines are more severe than others for fatigue damaging.

Moreover the SmartSet® system has a special function that identifies overloads that are saved and associated to the geographical position where the over load took place.

As explained above, the SmartSet® telemetry board acquires 2 channels. Normally a channel measures the bending stress near to the most stressed area of the axle (typically at the body transition), while the other measures axle torsion.

The continuous monitoring of axle torsion is of particular interest in the case of motor wheelsets, as the related load spectrum will also include specific events, such as short-circuit effects from the motor or torsional wheelset resonances that may take place during acceleration on wet rails. Stress amplitude oscillations in resonant conditions, can increase rapidly to undefined high levels at frequencies around 70-80Hz. Such events are difficult to measure during the normal vehicle qualification tests, and in any case it is always doubtful whether the maximum levels can be reached during normal service if the measurement is made for a short time. In case a verification of torsion resonant conditions taking place on the motor wheelset is requested, it is necessary to carry out a long and expensive test campaign in which the critical conditions have to be recreated while measuring the torsion loads; these results are then used to perform a final validation of the axle design assessment.

5 SMARTSET PILOT PROJECT ON THE E464 LOCO

The first SmartSet® pilot project was on the Bombardier ETR464 loco (Figure 9), a common locomotive in Italy and part of the Trenitalia regional fleet; in Italy there about 700 in service starting from year 2000 that have accumulated a total of 1.2 109 km. Aim of Trenitalia was to compare the service loads of this loco in different Italian regions in order to evaluate the possibility to adjust the inspection plan based on the actual service.

Figure 46: The Bombardier E464 Loco from Trenitalia.

In the first period of the pilot project, the locomotive was making its service in the center of Italy, running on different service lines. During this period of about 8 months the bending stress spectra accumulated at different distances up to 85.000 km are reported in the diagrams of Figure 10; it's interesting to note that the most frequent load, corresponding to the straight running condition (that also equals the axle static load), remains constant during the time, indicating a good stability in the measurements. On the other side the maximum load tends to gradually increase as the probability of measuring higher loads in a longer period is higher.

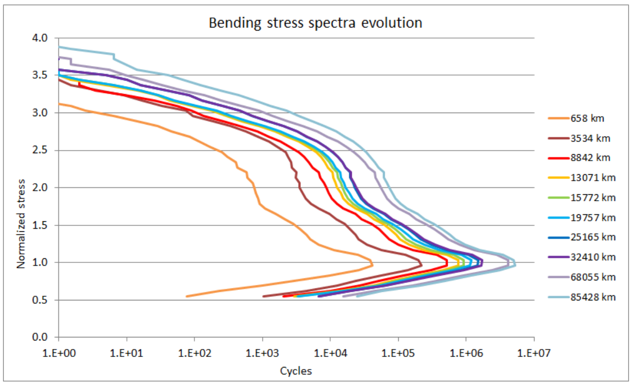

Figure 47: Evolution of the bending stress amplitude spectrum during a long period of service. Stresses are normalized to the static load.

A further analysis on the load spectra is to distinguish them for different railway lines characterized by different track severity. The lines selected for this analysis are represented in Figure 11:

- the orange line along the Adriatic coast (from Rimini to Termoli) is generally quite straight,

- the green line from Rome to Pescara passing through Sulmona (Appenninic line 1), that is even more severe due the the number of curves and altitude differences (from the sea level up to beyond 700 m).
- the blue line (more severe) running across the Appennini mountains from Ancona to Roma or to Florence (Appenninic line 2)

The load spectra, in terms of bending and torsion loads, distingushed for each line, are represented in Figure 12 and Figure 13 respectivelly. The red line in the two diagrams refers to the actual combination of all types of lines served by the loco in the area, representing the real whole service carried out by the loco during the same period.

The load spectra reported are normalized to the same total service distance, in order to make possible the comparison of the line severities. In evaluating the above spectra diagrams, it's important to notice that the cycle axis is in logaritmic scale, so that apparently small differences in the curves can result in relevant differences in terms of severity. The comparison confirms there is a higher distribution of cycles in the load range between 1.5 and 3 times the static load for the Appenninc lines compared to the Adriatic line; this is true both for the bending diagram (indicating more severe curves) and for the torsion diagram (indicating higher traction and braking load cycles).

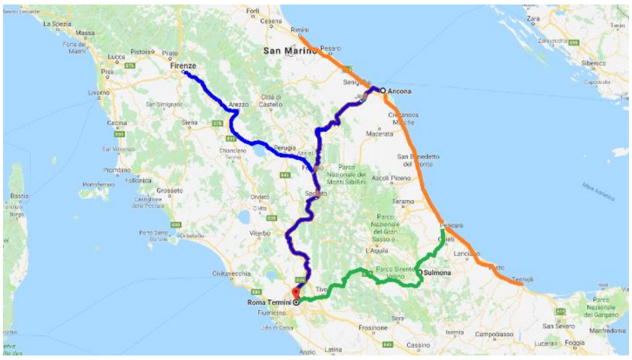

Figure 48: Map of the railway lines where the instrumented E46s4 Loco was in service.

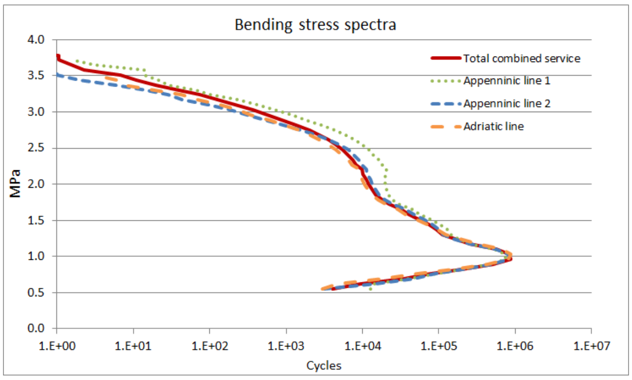

Figure 49: Bending stress amplitude spectra for different railway lines.

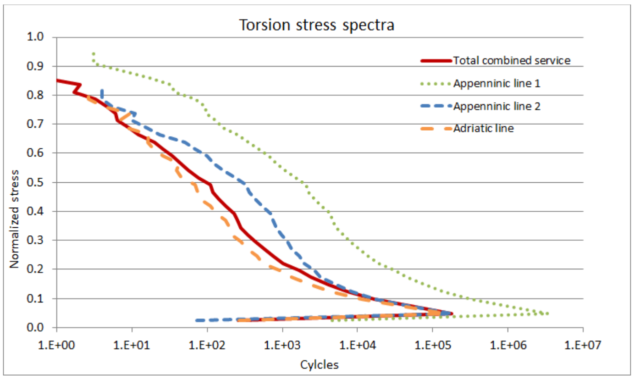

Figure 50: Torsion stress amplitude spectra for different railway lines.

A further step in the analysis is to evaluate the propagation of a prospective crack (semi-eliptic and 2 mm deep) under a variable loading sequence representative of the spectra defined above.

Figure 14 shows the propagation curves for the four load spectra where the distance is normalized by the propagation distance estimated for the reference combined service spectrum (the continuous red line in the diagram).

This representation clearly shows that the inspection interval in the case of the Adriatic line can be 20% larger than the combined service or the Appenninic line 2; on the other side, according to the simulation, the exclusive service on railway lines with a severity level like Appenninic line 1 would result in a shorter (about 50%) inspection interval than the combined service.

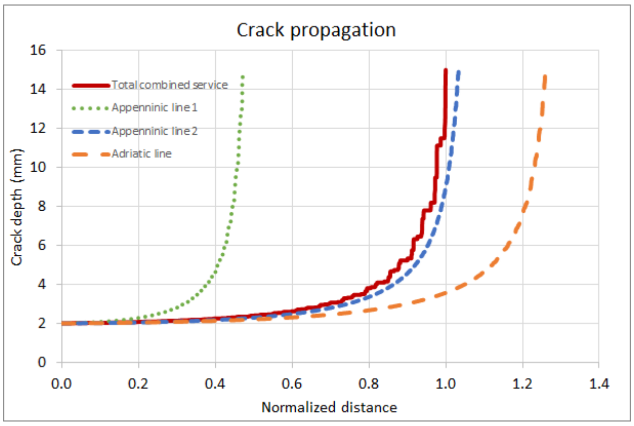

Figure 51: Crack propagation for different load spectra

The results confirm how sensitive the crack propagation is to the actual loading conditions. Therefore it's important (in terms of safety) and convenient (in term of maintenace costs) to have a precise evaluation of the real service load spectra, in order to calibrate on both the rolling stock and service the most suitable inspection interval.

For the test case used for this analysis, the very positive return of experience, is that no failures or NDT non-conformities were registered during the long period of service of this loco (since 2000, more than 1 billion km have been cumulated, with 679 E464 today in Trenitalia fleet) on all kind of railway lines, confirming the validity of the present NDT inspection plan also for the more severe conditions and providing an option to expand the intervals in the cases of the less severe lines.

6 Conclusions

The paper presents the SmartSet® solution as a key element to enable maintenance managers to schedule train stops for NDT inspection based on real service conditions of the vehicle, moving from a fixed to a dynamic interval. In most cases it is expected that SmartSet® will provide an opportunity to reduce part of the maintenance cost, increase vehicle availability and in general ensure a higher level of safety.

The description of the SmartSet® components shows how the system is easy to install also on existing vehicles with a low impact in terms of vehicle modifications.

The continuous monitored load data is always available at a remote data-base not only for optimizing the NDT intervals but also to enable track managers to compare the severity of different railway lines and, with a new development of the algorithm, also to identify the areas along the line where overloads occur more often. In general this type of monitoring will also provide the opportunity to monitor the track condition along the time and provide warnings to the infrastructure manager in case overloads are recorded in single points well identified with their GPS coordinates.

Depending on the characteristics of the wheelset and its bogie, the combined information of load histories and registered overloads might also be used as input data to develop a life indicator, not only for the axle but also for other components of the running gear.

Moreover for the vehicle and wheelset manufactures it’s a fundamental instrument for validating their assumptions in the design and in the definition of the maintenance plan.

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