A Technological Infrastructure for Implementing a Policy of Condition Based Maintenance for a Fleet of Railway Vehicles

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Abstract – Different policies exist to maintain a fleet of railway vehicles or machineries in general, e.g. cyclic, event driven, proactive, condition based. Each policy offers a different level of performances, and it requires a different amount of data for its actuation. As a general rule, the higher the diagnostic information, the more effective are the maintenance actions. Effectiveness of maintenance can be measured in terms of availability of each vehicle (or machine), and must be compared with its cost.

Increasing the effectiveness of maintenance implies creating a network for funneling information from the machineries to the central maintenance room where information is elaborated. Moreover, to increase the amount of information the machineries must be sensorised to monitor variables of interest for detecting incipient failures or need of repairing interventions. Such an infrastructure of sensors, data collection units, communication networks, and computers for data storing and sorting has a cost and a failure rate. Increasing the power of this infrastructure increases its cost and its failure rate, so it is mandatory for a Company to find an adequate equilibrium point between complexity and expected benefits.

This paper presents a roadmap for a Company that manages a fleet of vehicles (or machineries) towards the Condition Based Maintenance, that is the most efficient maintenance policy. The paper associates to each maintenance policy its benefits and its requirements in terms of infrastructure and costs. Using the proposed roadmap, a Company can decide its strategy and can schedule the investments in terms of technologies and skills. Bombardier Transportation Italy started this roadmap few years ago, for moving from a reactive maintenance policy to a proactive policy where some indicators are measured and monitored to optimize (and reduce) the maintenance interventions. The paper presents the first results achieved by means of an analytical tool developed together with the Dept. DITEN of the University of Genoa applied to the fleet of Bombardier locomotives in Europe. Even very simple statistical analysis on the data collected from the fleet of vehicles gave quite interesting and economically important results.

Index Terms—Railway vehicles, Condition Based Maintenance (CBM), Condition Monitoring, industrial communication

1 Introduction

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

For safety reasons, railway vehicles must stop for maintenance a fixed number of times per year or after a given number of kilometers according to national regulations and laws. An optimal maintenance policy should use these scheduled stops to actuate all the required maintenance actions, and not any un-necessary ones.

The most popular maintenance policy is today the “cyclic maintenance”, where maintenance is carried out within predetermined intervals without taking the equipment condition into account [1, 2, 3]. The period between service interventions is often based on expert knowledge about the equipment usage, its lifetime and its rate of deterioration [4].
Two of the main advantages of cyclic maintenance are the ease of programming the vehicle stops (hopefully during low traffic periods) and of budgeting the yearly costs for maintenance. On the other hand, with cyclic maintenance parts of the vehicle are likely to be replaced well before their end-of-life is reached. Since during scheduled stops a standardized set of checks is carried out, a high risk of unexpected failures remain. These failures require unplanned repair actions, which are more costly than planned service interventions. By sure, cyclic maintenance is far to be efficient in preventing failures and it can lead to unnecessary expenses [5].

In recent years, the interest in developing and improving policies more efficient than cyclic maintenance increased. Examples of these policies are the Condition Based Maintenance (CBM) and the Predictive Maintenance (PdM) [6]. Both these policies are based on the idea of maintaining equipment only when necessary [7]. For this purpose, various metrics (such as distance travelled, hours of operation, the number of times a door has been opened and closed, etc.), and sensor-based methods (such as oil analysis, vibration analysis, etc.) can be used to measure and monitor continuously the condition of the equipment [8]. CBM and PdM require an adequate technological framework for collecting and processing data useful for maintenance purposes. For railway vehicles, the framework can be split into two parts:

- “on-board” (the train): produces atomic data and cumulated info through sensors, data pre-processing equipment, and communication devices; 
- “off-board”: collect data from all the vehicles and implement the functions for data-mining and the algorithms for CBM and/or PdM.

Inside the train data comes from different sub-systems. The only functions implemented on-board are related to data collection and formatting, warning management, and remote communication. The maintenance policies and functions are concentrated in the off-board infrastructure that can be conveniently located in the manufacturer premises. The advantage of a centralized design is that data analysis and the scheduling of the maintenance stops can be based on a global view of the fleet. A holistic approach is mandatory to optimize the vehicles management.

A centralized architecture offers other important advantages, such as:

- use of the latest informatics techniques developed for web-based applications (e.g. Service Oriented Architecture);
- software maintenance and update is made once, on the central system,
- optimization of the hardware resources.

In Chapter II and III this paper gives an overview of the on-board system and of the off-board system available for Bombardier locomotives. Chapter IV defines the different maintenance policies that can be implemented, from the “remote maintenance” up to the “predictive maintenance”. Chapter V describes the roadmap towards better maintenance policies, focusing on the expected benefits of each policy and on the relevant infrastructural costs. Chapter VI reports the technologies used and the results achieved by Bombardier Transportation Italy after moving from a cyclic maintenance strategy towards a proactive strategy. A specific tool for analyzing the data from the locomotives and for identifying incipient failures was developed in cooperation with the Dept. of Electrical, Electronic, telecommunication and Naval Engineering of the University of Genoa.

2 The on-board infrastructure

Like Figure 1 shows, the train as a system is composed by a set of independent subsystems, each one dedicated to a specific function, and interconnected via the Multifunction Vehicle Bus (MVB). Each subsystem is largely autonomous, and produces basic diagnostic messages and warnings. All the diagnostic messages from the various sub-systems are collect on-board and cyclically transferred to the off-board servers. Each subsystem has a dedicated Train Control & Management System (TCMS) that collects data both for control purposes and for diagnostic. All the TCMSs communicate via the MVB. Cyclic data related to the process, such as temperatures, levels, positions, and so on are real-time transmitted for the management of the vehicle. When a TCMS detects an anomaly (defined internally in the control logic of the TCMS) it generates a standardized Diagnostic Data Set (DDS) that contains all the relevant data. All the DDSs generated by the TMCSs are stored in the On Board Database Server (ODBS) that contains the diagnostic logbook of the train during its operation. All diagnostic messages recorded by the diagnostic system are related also with the environmental data (e.g. line voltage, gear temperature, etc.) that were present when the recorded event happened. These environmental data can be set and configured by the manufacturer according to the vehicle characteristics. In addition to the DDS, the ODBS contains also counters of specific occurrences defined by the logic of the vehicle (e.g. number of switching of a relay).
Summarizing, ODBS contains five different categories of data:
- Diagnostic event (DDS): warnings generated by vehicle logic or by other electronic on-board devices characterized by a fault code, a start date/time, an end date/time and by a set of environmental data;
- Condition data (counters): variables that are used to estimate components lifetime. Counters may correspond to the total of executed operations (e.g. number of switch movements) or the increment of continuous variables (e.g. covered kilometers);
- Process data: set of process data samples collected in a defined time window. Process data are typically recorded to collect information for ex post analysis;
- CBM data: on-board measures and pre-elaborated data that may be used to characterize the operating status of a component/subsystem;
- Alarms: an alarm informs that a given subsystem of a particular vehicle is not working properly and needs to be checked. An alarm is generated when an operational rule is violated.

Fig.1 Infrastructure for Condition Based Maintenance

3 The off-board infrastructure

Data stored in the ODBS of all the vehicles are transmitted to the off-board system that runs statistic functions and possibly specific CBM algorithms (see Figure 1). A statistical approach to the maintenance has a meaning only when the data of an entire fleet of vehicles is considered. The off-board infrastructure is centered around a “Ground Server” that consists of a single redundant server, which filters, processes and aggregates the diagnostic data received from the ODBS of the entire fleet. The ground server makes the data available to remote users by a web based application, called “Maintenance Software Package”. It is a set of programs that support the maintenance staff to plan the maintenance workflow according to the information extracted from the data. A centralized off-board infrastructure that concentrates all the diagnostic data and functions into one “maintenance room” gives the possibility of controlling the following features:
- complete monitoring of the fleet
- execution of algorithms designed to identify and prevent faults and malfunctions
- automatic generation of alarms and support for the required communication with the Enterprise Resource Planning (ERP)
- extensive statistical reports
- expert technical support to the train drivers
- virtualization of the driver dashboard

On the other hand, the maintenance room can share real time data on the status of locomotives with the Regional Operation Room to reduce the consequences of failures that could lead to delays and blocking faults in the railway lines.
4 Maintenance policies

Over the time, the approach to the maintenance changed. The main goal is today the achievement of a predictive (also preventive) maintenance that should lead to more effective interventions. Predictive maintenance is often referred to as Condition Based Maintenance (CBM), since it is based on the information collected from the monitored equipment. CBM has one great advantage compared with any other policy; maintenance is carried out only when equipment really needs it or, in other words, when an equipment needs maintenance it is maintained. Consequently, with CBM no unnecessary intervention is carried out, like it happens with cyclic maintenance. CBM maximizes the efficiency of maintenance and minimizes its costs. To summarize, the main advantages of the CBM are:
- improved vehicle reliability,
- increased fleet operational availability,
- reduced maintenance costs.

The effectiveness of CBM depends on the depth of the diagnosis about the equipment health, and this depends on the technological infrastructure starting from the on-board sensors to the algorithms in the maintenance room.

A Company should implement a maintenance policy oriented to CBM through several steps, each one characterized by a deeper level of diagnosis (see Figure 2). We split the “maintenance roadmap” into four steps:
- **Reactive**: cyclic maintenance is carried out according to scheduled Maintenance Plans, instructions and feedbacks from the operators, problems during service;
- **Remote**: the maintenance staff can monitor the operating status of each vehicle through the real time acquisition of diagnostic warnings, environmental data, remote measuring;
- **Proactive**: the Maintenance Plan is updated according to the info collected from the vehicles that allows detecting hidden faults, anomalies, prompt alerts, etc.;
- **Predictive**: vehicle data together with maintenance processes and analytical tools make it possible to measure the residual life of components and to drive the maintenance actions.

Each maintenance profile should satisfy a set of enabling features, i.e.:
- Reactive: all the vehicles are “reactive ready”. Maintenance includes both scheduled cyclic interventions and repairs consequent to overhauls during the stops at the depot. In this case it is necessary to schedule the stops and the operation needed for each maintenance review;
- Remote: a live connection between the on-board diagnostic system and the off-board diagnostic system for the data transfer (GPRS or others) is required. The maintenance staff can access the ODBS from a web service (or similar);
- Proactive: dedicated resources monitor the data in the off-board maintenance center. On-board and/or off-board rules can trigger alarms that are validated by the maintenance staff in the maintenance center. In case of valid alarms, off-board staff informs the train driver about the possible immediate interventions or operational limitations;
- Predictive: the tripping of diagnostic triggers and the real-time analysis of process data allow calculating the residual life of the monitored components. Alarms are sent to the field operators. A process of feedback exists to update the system logic and functions.

The implementation of a “higher” or “stronger” maintenance profile leads to an improvement of the Key Performance Indicators (KPI) of the fleet. A Company should consider the decision to move a step towards a higher level in terms of costs and payback.

5 A roadmap towards CBM

Before programming a roadmap towards CBM, a Company should start with a clear definition of the present state of its maintenance process. Every further step requires a cost-benefit analysis that includes both the on-board and the off-board infrastructures.

5.1 Where we are

The maintenance process of a Company can be positioned in a plane where the axe of abscissa defines the off-board infrastructure, and the ordinates are the on-board equipment and functions. To achieve a pseudo-quantitative evaluation, we split each maintenance policy into three levels based on
the functions that are implemented. Such a classification is arbitrary, but complies with the experience and with the sequential steps to follow. The levels of the on-board system are:

- **Reactive**:
  - Level A: an overall diagnostic concept exists and it is implemented;
  - Level B: the diagnostic data are available in a unique database;
  - Level C: the environmental data are available in a unique database.

- **Remote**:
  - Level A: diagnostic alerts and data are transferred via a wireless modem;
  - Level B: environmental data are transferred via a wireless modem;
  - Level C: data are collected by a real time server (reasonably with a 30 min delay) that can be remotely accessed.

- **Proactive**:
  - Level A: a significant number of diagnostic signals have a consistent occurrence (it is clear why they appear);
  - Level B: a significant number of signals have a one to one relation with a failure mode;
  - Level C: it is possible to modify and update the diagnostic logic from remote.

- **Predictive**:
  - Level A: it is possible to activate cumulative counters (km, time, number of switches, etc.);
  - Level B: an overall predictive concept exists and is implemented, sensor included;
  - Level C: the vehicle is designed to support predictive functionalities and includes all the necessary features.

The levels for the off-board system are:

- **Reactive**:
  - Level A: an overall diagnostic concept exists and is documented;
  - Level B: the maintenance procedures are extensive and fully defined;
  - Level C: a friendly tool to visualize the data collected is available.

- **Remote**:
  - Level A: data are collected from a server without loss of info;
  - Level B: the server translates and publishes data in plain language. A web portal exists;
  - Level C: full data streaming or specific requests of sampled variables can be activated through the web portal. Data processing and plotting are available.

- **Proactive**:
  - Level A: a maintenance center exist, and is remotely accessible by engineers and depot technicians (with the proper access rights);
  - Level B: it is possible to elaborate automatic real-time routines (alerts) to identify patterns. A specific staff is dedicated to this task;
  - Level C: it is possible to open a work order (from the alerts) and to receive its feedback. System is prepared for that. Feedbacks are monitored.

- **Predictive**:
  - Level A: counters and other relevant performance indicators (e.g. residual life) are calculated and available to the maintenance staff;
  - Level B: performance indicators are statistically analyzed to detect anomalies. Analysis can be performed starting from the historical data of a single vehicle, or by cross referencing data of the whole fleet;
  - Level C: a stable and automatic process creates predictive work orders in the ERP of the customer. Feedbacks are monitored.

As an example of this classification, Figure 3 shows the today status of some Bombardier locomotives based on their diagnostic features. The higher level is achieved by the high-speed passenger train “Zefiro”. This diagram gives an immediate view of the status of the maintenance system, and allows a simple identification of the future evolution to achieve more efficient policies.
5.2 Benefits of maintenance policies

A higher maintenance policy leads to better performance of each single vehicle, and so of the entire fleet. Different Key Performance Indicators (KPI) have been defined to evaluate the vehicle and the fleet status and performance [10, 11, 12]. The most popular KPIs are:

- Mean Time To Repair (MTTR): it represents the mean time necessary for resolving a failure after it arises. It can be applied only to repairable components and/or sub-systems;
- Mean Time Between Failures (MTBF): a basic measure of reliability for repairable items. It represents the mean time during which all the parts of a sub-system perform within their specified limits, during a particular measurement interval under stated conditions;
- Quality: it is intended as the Quality of Service offered by the fleet, and it is a measure that includes two main factors: the availability and the safety that for the users become reliability and punctuality;
- Reliability: the ability of a subsystem to perform a required function under stated conditions for a stated period of time;
- Availability: is defined as the probability that a sub-system is ready to correctly perform its functions at time t, under specific working conditions;
- Life Cycle Cost (LCC): sum of all recurring and one-time (non-recurring) costs over the full life span or a specified period of the system. It includes purchase price, installation cost, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or its useful life.

An increase of one or more of the KPIs leads to a more efficient management of the fleet. Of course, the more the maintenance is structured and organized, the higher are the KPIs of the fleet. Moving from a maintenance policy to a higher level one should increase the main KPIs:

- From Reactive to Remote: it is possible to increase the KPIs related to the quality and to the organizational aspects of the maintenance strategies (MTTR and MTBF). For example, with remote maintenance it is possible deciding to replace or maintain parts that present an abnormal behavior compared with the similar parts of the entire fleet;
- From Remote to Proactive: the most affected KPIs are availability and reliability, since proactive maintenance makes it possible a real-time reaction to abnormal behavior detected through the analysis of the data. Special algorithms or rules applied to both real-time and historical data of the complete fleet can detect potential faults. New maintenance inspections and intervention can be scheduled during the depot stops;
- From Proactive to Predictive: well-proven real-time diagnostic algorithms are used to schedule only the interventions that are strictly necessary, before device failures. Such an approach reduces the Life Cycle Costs and increases the availability of the vehicles.

The increasing of performances, however, has a limit related to installed equipment and to the technological framework available. Figure 4 shows the typical increases on the KPIs moving from one maintenance policy to another.

![Figure 4: Estimate of the KPIs increase for different maintenance profiles in the Bombardier fleet](image)

Past experiences show that a very appealing increase of the KPIs around 15% is possible.

5.3 Technical and organizational framework

Each maintenance policy requires a different technological framework, composed by the infrastructure (on-board and off-board) and by the organization that manages the maintenance data and organizes the depot and the activities. The structure needed for the reactive policy is the base point for starting a roadmap towards the higher levels. Each maintenance profile requires the introduction of the technologies and the structures listed below:

- Remote:
  - Technological framework: all vehicles are equipped with an on-board GPRS modem, while the off-board facility is equipped with hosting and web server and interface for collecting data from the on-board systems;
  - Organizational framework: the people at the depot and in the maintenance center can access the data and can acquire data according to their needs;

- Proactive:
  - Technological framework: in addition to the maintenance server, data analysis tools are
available. Standardized maintenance reports are created;
- Organizational framework: there is a dedicated staff in the maintenance center for the off-line analysis of the collected data in order to detect and solve the main operational problem of the fleet;
- Predictive:
  - Technological framework: real time algorithms are used to detect abnormal functioning of devices or sub-systems and to compute their residual life. Self-diagnostic alerts are sent to the management tools for the automatic creation of work orders and feedbacks;
  - Organizational framework: experts are dedicated to develop advanced algorithms that, after validation and certification, run automatically.

The evolution of the on-board and off-board infrastructures must be coordinated with the parallel evolution of the human resources dedicated to maintenance. Pushing one of these aspects and leaving behind the others does not lead to any useful result.

6 A case history: Bombardier Transportation Italy

6.1 Where did we start from and where we want to arrive?

In the beginning of 2005 Bombardier Transportation Italy started an internal process for improving the quality of maintenance of its fleet of locomotives in Europe. The activity was started for two of the most popular locomotives: model E483 and model E186.

In the framework described in the previous chapters, both locomotors implemented a reactive maintenance policy, and precisely:
- E483:
  - on-board: reactive class B ⇒ the diagnostic data are available in a unique database
  - off-board: reactive class B ⇒ the maintenance procedures are extensive and fully defined
- E186
  - on-board: reactive class A ⇒ an overall diagnostic concept exists
  - off-board: reactive class B ⇒ the maintenance procedures are extensive and fully defined

Over the years, a continuous improvement of the on-board and off-board infrastructures allowed moving towards a remote maintenance policy of level C for both locomotors:
- on-board: remote class C ⇒ data are collected by a real time server that can be remotely accessed
- off-board: remote class C ⇒ full data access through the web portal

This transition from the original reactive status towards the new remote status is mainly related to the implementation of a new infrastructure for data management in the depots. In fact, the reactive status requires a specific data management infrastructure in the depots, a planned maintenance schedule, and a staff trained for prompt interventions on the vehicles, when required. These functions were achieved by means of a data-center that collects data from the vehicles and is accessible from the depots. This was the status at the beginning of 2013.

Today all the locomotives have a GPRS connection with cyclic real time data transfer to a wayside server. The train position, the vehicle diagnostic, and the environmental data of the whole fleet can be accessed via dedicated web applications. From the technological point of view this means that each vehicle has an on-board GPRS modem plus a SIM, while the off board system stores the database and should guarantee a connection to it by means of a web interface, so that it can be accessed remotely.

As Fig.5 shows, the on board infrastructure contains two new equipment, both connected to the MVB bus that is an Ethernet based communication system specific for railway applications:
- the diagnostic controller that contains the database, and
- the Ethernet gateway for the GPRS modem.

Each subsystem of the vehicle, such as the battery system or the main circuit breaker, has a proper controller that is connected to the MVB infrastructure. Each controller has an internal logical trigger, defined by the manufacturer of the subsystem, that creates the “diagnostic message” that is stored in the diagnostic database. In the diagnostic database, every diagnostic message is associated with the environmental parameters, such as voltage, current, position, etc., measured when the event happens and stored in a process storage system called “observer” (see Fig.6).

The two gateways create two different databases, one contains all the diagnostic messages and the other contains all the environmental data. The data control center in Vado Ligure downloads in real-time these two databases through the GPRS modem. The web portal MyBTFleet makes it possible accessing the databases to engineers and maintenance staff.
Diagnostic data are stored as records containing the following information:
- ID Number of the vehicle
- Date and hour of triggering from negative to positive of the diagnostic signal
- Date and hour of triggering from positive to negative of the diagnostic signal
- Name of the subsystem that generates the diagnostic message
- Message code: it is a four digit alphanumerical string that identifies the diagnostic message; for example in Fig.7, 21FF is the message related with “battery voltage: ON”

Each subsystem generates the diagnostic messages only when specific conditions are present, e.g. the vehicle speed is higher than a given value or the pantograph is in upper position.

Several environmental data are associated with each diagnostic message, like:
- line voltage
- line current
- total kilometers
- geographic position (from GPS)
- the transmission system in use for the communication between the vehicle and the control system; this allows identifying the country where the vehicle is operating.

6.2 Actions towards Proactive Maintenance
Bombardier Transportation decided to move from a maintenance policy “Remote – level C” to the higher policy “Proactive – level B” with the target of achieving the capacity of detecting event-based maintenance rules through an in-depth analysis of validated diagnostic data. The first action to achieve this result was the implementation of a system for the graphical display of the diagnostic data that are collected and stored in the database. The graphical visualization of data variations makes it easier for experts detecting periodic patterns or discovering functional correlations between different events. This type of man-made analysis is aimed at the discovery of rules that, after a process of validation, will be used for predictive maintenance.

A specific tool for the intelligent data sorting and visualization was created with Matlab. An example of a graphical output of this tool is presented in Figure 8. With this tool the maintenance staff can:
- select and show the variables that were active in a selected time interval
- sort single variables by their code
- calculate time-based KPIs, e.g. number of worked hours, number of hours with a speed > 3 km/h, etc., for single or grouped variables
- define statistics on the active signals; this means that for each active signal in a considered time interval it is possible to calculate the total number of hours in which the signal is active, the number of transitions from ON to OFF, the number of transitions from OFF to ON, etc.

Considering the database of maintenance data composed by “n” parameters for each of the “m”
vehicles like in Figure 9, it is possible to start two simple types of analysis:
- horizontal: considering the i-th parameter of all the vehicles of the fleet,
- vertical: considering the parameters of each vehicle independently from the other vehicles.
More complex techniques of data mining are possible, but the size of the database suggests a step-by-step approach; the monitored vehicles are about 150, and the considered parameters are about 500 for each vehicle, with a sampling time of 1 second (data transmission is only by exceptions).
For testing the validity of the tool for data extraction, we started with the analysis of one of the most critical components of electric locomotors: the Main Circuit Breaker (MCB) that is used for connecting the locomotive to the supply line. According to the supply voltage, the MCB may be either DC (in this case it is called “IR”) or AC (in this case “IP”). In both cases, MCB is an electro-mechanical equipment suffering both mechanical and electrical stresses. With a detailed analysis of the logs of the historical failures, it was selected a sub-set of data that are relevant for detecting abnormal operation of the MCB, namely:
- number of opening/closing operations of the IR/IP MCB (in normal operation, the MCB is operated after the switching off of the traction drives, that is with no current)
- number of MCB trips caused by the intervention of the overcurrent protective relay (the MCB opens the short circuit current of the supply system)
- speed > 3km/h
- pantograph status (open/close)
To search significant statistical relations, an analysis was carried out on the entire fleet of locomotors E186 for the year 2013 that means 55 vehicles monitored for about 11 months (a locomotive is in the depot for about 1 month a year). The KPIs (in fact two counters) used for classifying the locomotors are:
- KPI#1: total number of opening and closing of circuit breaker (off-load operation)
- KPI#2: total number of interventions of protective devices (high current operation)
The two KPIs are further split into two classes: operation with the train running (speed ≥ 3 km/h) or with still train (speed < 3 km/h). These two counters are compared with the reference values indicated by the manufacturers of the circuit breakers for major maintenance intervention after 2 and 8 years of operation. According to the average values, the number of operations after 2 years is 1.000 and after 8 years is 4.000. Fig.10 and Fig.11 show that the Main Circuit Breaker of all the locomotives are working less than expected (both AC and DC).

Following the concept of horizontal analysis, for every locomotive it was calculated the average value of the counters per month, together with its standard deviation. The maintenance history of all the vehicles with the counters significantly different from the average values was studied, and the following heuristic rule was identified:

IF (average number of operations per month > 3,5) AND (protection trips per month > 3,5) THEN (maintenance is required)

This rule has no false negative result, i.e. no vehicle with smaller counters experienced faults of the circuit breaker. On the other hand, the rule has a number of false positive errors of about 33%. It means that 33 out of 100 circuit breakers with high counters should not require maintenance. Since the number of breakers with high values of the counters is about 30% of the total, the effectiveness of the heuristic rule gives the following results:

- number of maintenance interventions per year
  . with remote maintenance 55
  . with proactive rules 15
  of which necessary 10 and un-necessary 5
Considering that 10 breakers must be maintained, the number of un-necessary interventions is reduced from 45 to 5 (practically, one order of magnitude).
6.3 Future steps
The first very simple results of a CBM strategy are extremely positive, and lead to a significant reduction of un-necessary maintenance interventions. The activity is now aimed at the improvement of the KPIs for circuit breakers, looking for correlations with environmental parameters, and at the research of similar rules for the other critical subsystems of locomotive. The investigation is now upon the compressors and the battery storage system. The research of the rules and their validation is carried out using the entire fleet of vehicles E186 and E483 over the last 3 years.

7 Conclusions
The policy for maintenance has a central impact on the overall performance of a fleet of vehicles during their life cycle, and it represents an important cost. To maximize the results, a Company that controls a fleet of vehicles should follow a clear roadmap for setting the required targets and the necessary technological framework. The roadmap proposed in this paper defines four main maintenance profiles (or policies), each one with increasing levels of diagnostic capacity and, as a result, higher efficiency.
Each profile of maintenance requires a technological infrastructure both on-board of the vehicles, and off-board. Diagnostic and environmental data are collected on-board and transferred to an off-board infrastructure that stores the data and makes them available to the maintenance staff. Sophisticated software tools for data sorting and analysis are mandatory for finding heuristic rules able to identify the maintenance requirements of equipment.

The roadmap proposed in the paper associates to each maintenance profile the corresponding infrastructure and identifies the expected benefits. Bombardier Transportation Italy applied this roadmap to its structure for maintaining the fleet of locomotives running in Europe. Starting in 2005 from a condition of “reactive maintenance”, it moved towards a “proactive maintenance” where maintenance data are validated and activate monitoring logic that automatically triggers warnings and maintenance requests. These results were achieved both improving the technological infrastructure, and by means of new tools for the analysis of collected data. The analysis of historical data allowed the definition of criteria and rules that narrow down the maintenance activities to the vehicles that in fact require them. A couple of examples of maintenance rules are presented in the paper.

Activities are continuing for validating and improving the already tested rules and for finding new rules for other subsystems of the vehicles.

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