

Data Acquisition, Transmission, Collection and Analysis for a Fleet of Railway Vehicles in Search of Diagnostic Rules for CBM

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Abstract – This paper presents a roadmap for a Company that manages a fleet of vehicles (or machineries) towards the Condition Based Maintenance that is, in principle, 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 key 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. Two examples of statistical analysis on the data collected from the fleet of vehicles of Bombardier in Europe show how even very simple analytics may lead to important technological and economical results.

I 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 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 carry out all the necessary maintenance actions, without un-necessary actions.

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]. Often the interval between service interventions is 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.

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 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 Section II and III this paper gives an overview of the on-board system and of the off-board system available for Bombardier locomotives. Section IV defines the different maintenance policies that can be implemented, from the “remote maintenance” up to the “predictive maintenance”. Section V describes the roadmap towards better maintenance policies, focusing on the expected benefits of each policy and on the relevant infrastructural costs. Section 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.

Section VII presents the results obtained by means of this tool with two sub-systems: the train main circuit breakers and the air compressor. In both cases the analysis of the historical data using the tool made it possible to identify indicators related to the real operating conditions of the equipment with a substantial reduction of maintenance interventions (with no loss of reliability).

II 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 collected 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 TCMSs 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 process and 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.

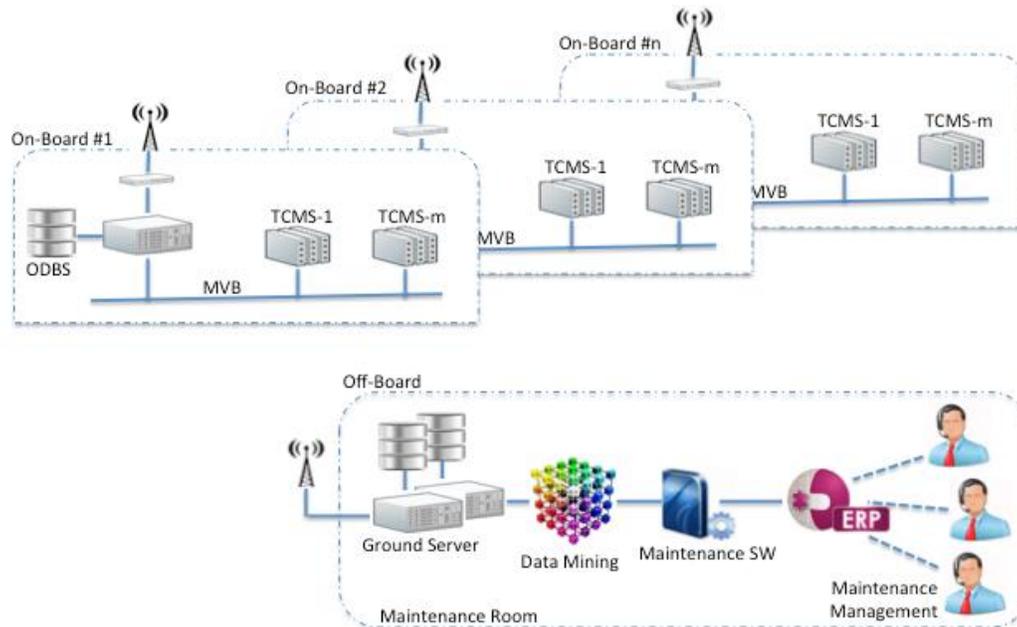


Figure 1 Infrastructure for Condition Based Maintenance

III 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 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”. 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.

IV 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 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.

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.

V 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.

V.I Where we are

The maintenance process of a Company can be positioned in a plane where the x-axis defines the off-board infrastructure, and the y-axis represents 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.

V.II 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.

Several KPIs are defined for the monitoring of maintenance, such as: yearly cost, numbers of faults, total down time, number of scheduled stops in depot, etc. Past experiences show that a very appealing decrease of these KPIs around 15 % is possible.

V.III 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:
 - o 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;
 - o 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:
 - o Technological framework: in addition to the maintenance server, data analysis tools are available. Standardized maintenance reports are created;
 - o 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:
 - o Technological framework: real time algorithms are used to detect abnormal functioning of devices or subsystems and to compute their residual life. Self-

diagnostic alerts are sent to the management tools for the automatic creation of work orders and feedbacks;

- o 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.

VI DATA ANALYSIS AIMED AT CBM

Techniques of Data Mining are useful for analyzing the large amount of data that are received from the trains and stored in the centralized database. Data mining means extracting useful information hidden in the data and to present them in the more simple and usable way. Data mining methods use statistical approach and different mathematical techniques suitable for managing data and database in order to look for correlations.

Basically, a database for CBM purposes contains in the rows different objects -in our case different vehicles of the same fleet- and in the columns the properties and the parameters describing the behavior of the object (see Table I).

Considering such a database structure, it is possible to define three possible approaches to the data analysis:

- 1) Horizontal: analyzes the same property of different vehicles;
- 2) Vertical: analyzes different properties of the same vehicle;
- 3) Mixed: it is a mix of the previous approaches, i.e. different properties of different vehicles or of each single vehicle.

Each analysis is useful for achieving specific results, as described in the following paragraphs.

For each analysis, it is important to define the KPIs of interest.

Table I: Example of CBM oriented database

Vehicle	#1	#2	#3	...	#m
Parameter #1	p ₁₁	p ₁₂	p ₁₃	...	p _{1m}
Parameter #2	p ₂₁	p ₂₂	p ₂₃	...	p _{2m}
Parameter #3	p ₃₁	p ₃₂	p ₃₃	...	p _{3m}
.....
Parameter #n	p _{n1}	p _{n2}	p _{n3}		p _{nm}

VI.I Horizontal analysis

Horizontal analysis allows checking and comparing the behavior of a single vehicle/apparatus/subsystem with the other elements of the fleet. So the analysis may identify the vehicles with abnormal behaviors in the fleet.

KPIs for comparative horizontal analysis should highlight the overall status of the machine, like the total number of stops, the average consumption, etc.

The first and easiest horizontal analysis is the calculation of average values (x_{avg}) and variances (σ). Machines with parameters outside the average value of the fleet with a band of, for example, $\pm\sigma$ or $\pm 2\sigma$ become candidates for a more accurate and precise analysis.

VI.II Vertical analysis

Vertical analysis considers the behaviour of a vehicle/subsystem over the time. Thus, this analysis shows the upcoming of abnormal behaviour or degradation of a parameter. Different approaches exist for the vertical analysis:

- Trend analysis: is the study of the behaviour of a KPI over the time that may identify a deviation from the theoretic trend (see Fig.5);
- Anomalies analysis: with a long-term monitoring, it may identify anomalies in the behaviour of a KPI, like rapid changes or abnormal operations;
- Statistical analysis: it may identify abnormal deviations in the historical behaviour of a KPI;
- Signature analysis of a device: the signature of a device is the set of values that significant parameters of a machine or a system have in normal operating conditions or during the execution of a normal operation. Deviations from the signature indicates abnormal operations. Figure 6 shows an example of signature for a pneumatic actuator: output pressure during an open/close cycle.

VI.III Mixed analysis

The mixed analysis may consider different parameters of the same machine/system or also different parameters of different machines. The main scope of the mixed analysis is to identify correlations between different parameters or events.

The basic techniques used for the mixed analysis are:

- Regression: it is necessary to find a formula that expresses the relation between different selected variables;
- Correlation: an index quantifies the correlation between two or more variable. Several indexes exist for measuring the degree of correlation of different variables. One of the most used index is the "Pearson correlation index". The research of correlation indexes requires the comprehension of the physical relations between the variables (to avoid incongruous results).

VII A CASE HISTORY: BOMBARDIER TRANSPORTATION ITALY

VII.I 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 sections, both locomotors implemented a reactive maintenance policy, and precisely:

- E483:

- o on-board: reactive class B → the diagnostic data are available in a unique database
 - o off-board: reactive class B → the maintenance procedures are extensive and fully defined
- E186
- o on-board: reactive class A → an overall diagnostic concept exists
 - o 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:

- o on-board: remote class C → data are collected by a real time server that can be remotely accessed
- o 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

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.2 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.3).

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.

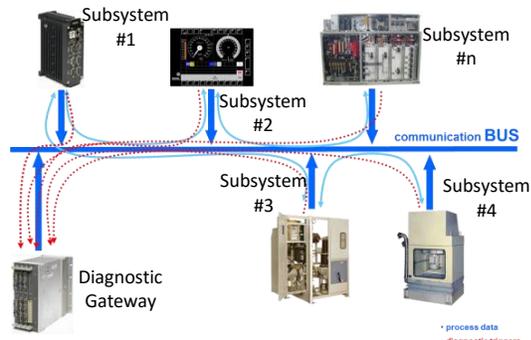


Figure 2: Architecture of the on board system

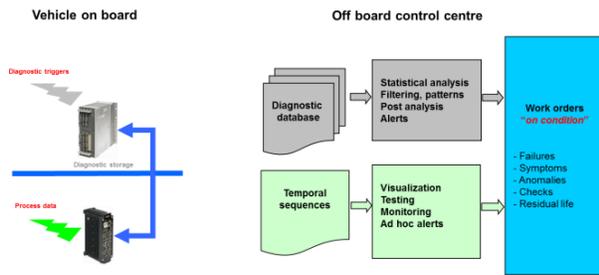


Figure 3: Diagnostic and process data transferred by the on board system

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 alphanumeric string that identifies the diagnostic message; for example in Table II, “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.

Table II Example of the diagnostic database

	A	B	C	D	E	F	G
	Date On	Hour On	Date Off	Hour Off	Subsys	Proc	Text
1	04/03/2013	07:26:02	04/03/2013	09:04:35	PROT	DCPU	21FF - Tensione batteria attiva
2	04/03/2013	07:26:12	04/03/2013	09:04:25	PROT	DCP1	283F - Avvio sistema
3	04/03/2013	07:26:16	04/03/2013	07:27:59	BWG	ZSG	0503 - Test BWG richiesto -> blocco trazione
4	04/03/2013	07:26:16	04/03/2013	09:04:25	PROT	ZSG	04C4 - Cabina di guida 1 attiva
5	04/03/2013	07:26:20	04/03/2013	09:04:25	PROT	DCP2	2A3F - Avvio sistema
6	04/03/2013	07:26:22	04/03/2013	07:26:23	KLEI	ZSG	075F - Protezione press. Cab1 manual, chiusa
7	04/03/2013	07:26:22	04/03/2013	07:26:23	KLEI	ZSG	0760 - Protezione press. Cab2 manual, chiusa
8	04/03/2013	07:26:22	04/03/2013	07:26:23	KLEI	ZSG	0789 - Misura pressostato F2 diff. da impostaz.
9	04/03/2013	07:26:22	04/03/2013	07:26:23	KLEI	ZSG	0788 - Misura pressostato F1 diff. da impostaz.
10	04/03/2013	07:26:34	04/03/2013	09:04:15	PROT	ZSG	1087 - Pantografo sollevato
11	04/03/2013	07:26:49	04/03/2013	09:04:15	PROT	ZSG	064F - Interr.generale (IR) attivo
12	04/03/2013	07:26:49	04/03/2013	07:36:49	PROT	ZSG	0787 - Dati statistici di servizio
13	04/03/2013	07:26:50	04/03/2013	09:04:16	PROT	ZSG	05D5 - HB1 attivo
14	04/03/2013	07:26:50	04/03/2013	09:04:16	PROT	ZSG	05D6 - HB2 attivo
15	04/03/2013	07:26:58	04/03/2013	15:40:34	PROT	DCU1	3459 - Blocco dati info. 1 versioni SW
16	04/03/2013	07:26:58	04/03/2013	15:40:34	PROT	DCU2	4459 - Blocco dati info. 1 versioni SW
17	04/03/2013	07:27:04	04/03/2013	08:56:02	PROT	ZSG	04C6 - Direz.di marcia 1
18	04/03/2013	07:27:05	04/03/2013	07:27:22	PROT	ZSG	060C - Fr-emerg.FABR
19	04/03/2013	07:27:09	04/03/2013	07:28:52	PROT	ZSG	0614 - Consenso trazz. da relé traction safe
20	04/03/2013	07:27:22	04/03/2013	07:28:51	PROT	ZSG	0605 - ASG1 sbloccato
21	04/03/2013	07:27:22	04/03/2013	07:28:51	PROT	ZSG	0606 - ASG2 sbloccato
22	04/03/2013	07:27:22	04/03/2013	07:28:51	PROT	ZSG	060C - Fr-emerg.FABR
23	04/03/2013	07:27:25	04/03/2013	07:27:53	PROT	ZSG	083C - Blocco trazione PNEU
24	04/03/2013	07:27:42	04/03/2013	07:27:51	PNEU	ZSG	080F - Frenatura forzata per causa sconosciuta
25	04/03/2013	07:28:23	04/03/2013	15:43:22	KON	BCU	661F - Guasto filascio freno indiretto
26	04/03/2013	07:28:56	04/03/2013	07:29:47	PROT	ZSG	0605 - ASG1 sbloccato
27	04/03/2013	07:28:56	04/03/2013	07:29:47	PROT	ZSG	0606 - ASG2 sbloccato
28	04/03/2013	07:29:45	04/03/2013	07:30:00	BWG	ZSG	0503 - Test BWG richiesto -> blocco trazione
29	04/03/2013	07:29:46	04/03/2013	07:30:00	PROT	ZSG	083C - Blocco trazione PNEU
30	04/03/2013	07:29:47	04/03/2013	07:29:58	PROT	ZSG	060C - Fr-emerg.FABR

VII.II 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 6. 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 Paragraph 6, it is possible to start three 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,

- mixed analysis: to find out correlation between different parameters.

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).

The next two examples refer to the Bombardier fleet of vehicles, and represent:

- a horizontal analysis for the identification of CBM rules for the main circuit breaker,
- a vertical analysis based on the signature for the air compressor on board.

A) Rules for CBM: Main Circuit Breaker

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 > 3 km/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.4 and Fig.5 show that the Main Circuit Breaker of all the locomotives are working less than expected (both AC and DC).

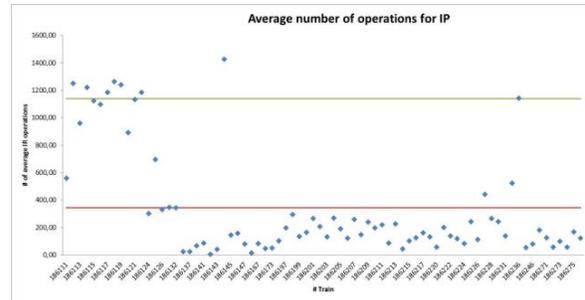


Figure 4: Number of IP-MCB operations per year for a set of locomotives

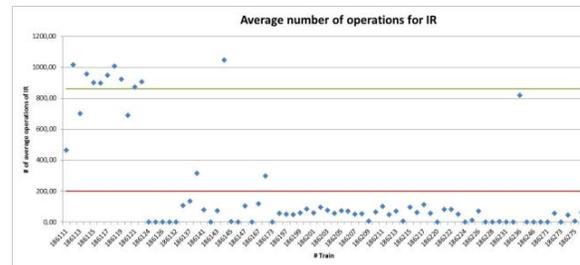


Figure 5: Number of IR-MCB operations per year for a set of locomotives

With an 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).

B) Rules for CBM: Air Compressor

The air compressor in a locomotive is an essential part of the braking system. The compressor has two output sections that supply the main braking circuit at a rated value of 10 bar, and the principal circuit at 5 bar. Pressure losses happen when the brakes operate and for the normal

leakages of the circuits. The compressor is controlled in on/off mode by a pressure switch with a hysteresis of 0,05 bar around the rated value. Typically manufacturers of compressors for railway applications suggest a complete revision after 12.000 working hours.

To have a more accurate maintenance indicator it was defined the “signature” of the compressor. When the train runs in normal coasting between two stations, the pressure losses are only caused by the leakages of the circuits. The compressor compensates these losses and maintains the pressure in the range of 4,95-5,05 bar. For a new compressor the recharging time during the coasting phase is in the interval from 60 s and 65 s. Longer periods, in a reasonable percentage, should be an indicator of an overcoming problem in the compressor, mainly due to malfunctioning of the bearings.

The following quantities are sampled every second:

- Date and time
- Speed
- Pressure in the main pipes

- Pressure in the principal pipes
- Running kilometres

Data were collected for a period of two months on the fleet of 186 locomotors in The Netherlands.

The idea is to identify a “signature” of sound compressors, and to use it as a benchmark for finding out compressors with troubles.

The term “signature” refers to a set of measurement or quantities that can identify in a unique manner the behaviour of a certain component.

The proposed signature for the compressors considers:

- the average duration of a “on” period for the compressor,
- the average duration of a “on” period for the compressor during coasting,
- the load cycle of the compressor when the train is running (percentage of time “on” compared with the total running time).

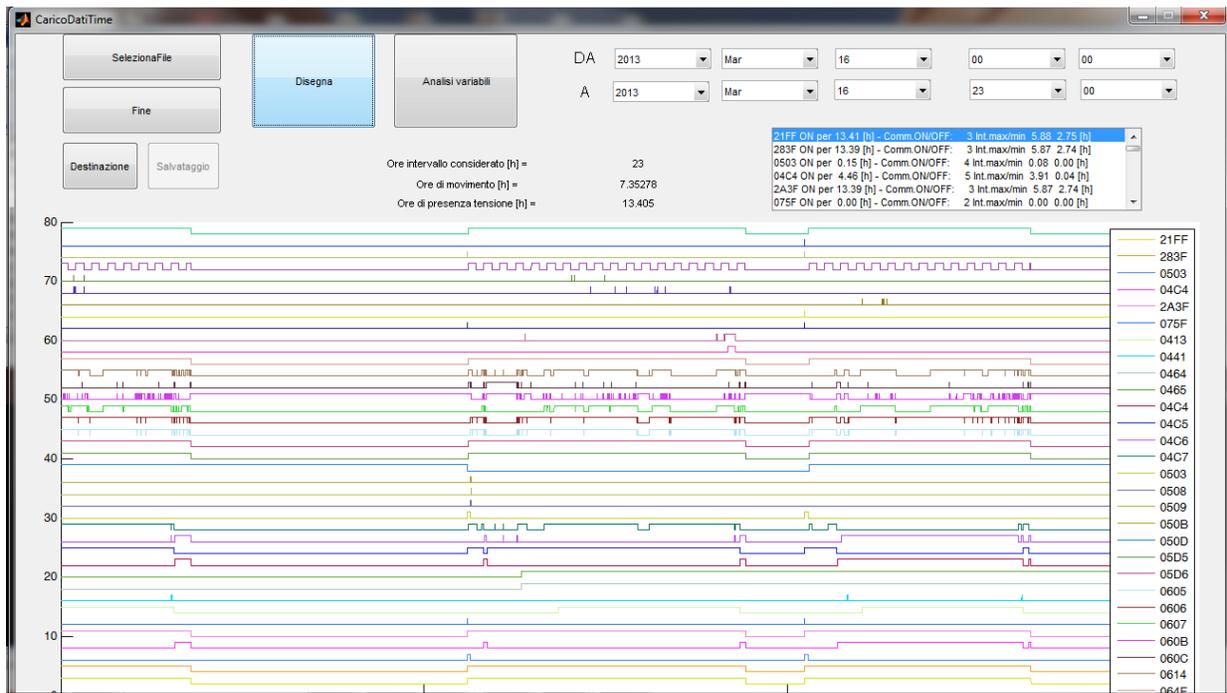


Figure 6: Sample display of the visualization tool

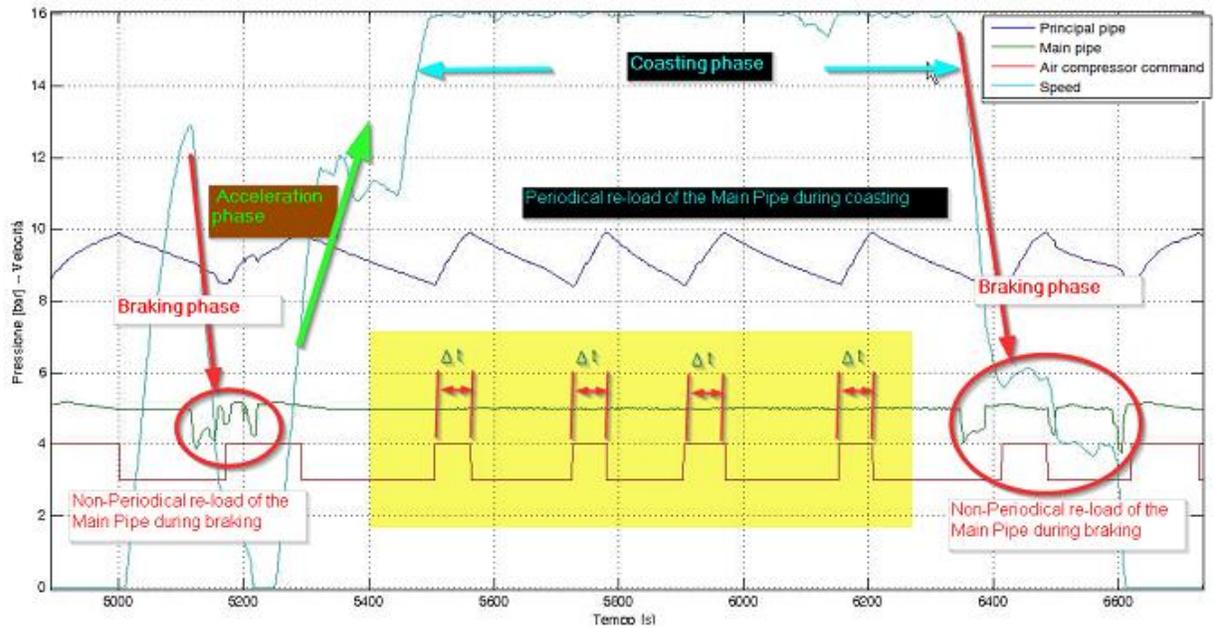


Figure 7: Typical profile of pressure and compressor operations

Figure 13 shows a typical profile of the air pressure during normal operation of a train. Pressure (blue line) increases when the compressor is running (red line), and it decreases when the compressor is off. Coasting is detected considering the train speed (light blue line); when it is constant the train is coasting, and pressure losses are only caused by the pipes leakages. Pressure variation during braking phases depends on the action of brakes, and it cannot be used for analysis of the compressor status. When the three indicators that compose the signature are listed in a table like in Figure 6, some anomalies can be detected.

As Figure 7 shows, compressors work during the coasting phase an average time of about 70 s. A longer time and an increase of this time over different data acquisition could identify an overcoming problem to the compressor. On the other hand, Table III shows that the average value of the working percentage of the compressor is 25%. Again, values higher than the average values may indicate that a failure or a malfunctioning of the compressor is upcoming. For this analysis, we consider the average value and the standard deviation σ to identify the elements or vehicles that shows an abnormal behavior.

Table III: Comparison of KPIs for different locomotors

# Vehicle	Avg Time ON	Avg Time ON coasting	Avg % operation	# Samples
186111	90,83	74,48	25,30%	6
186112	122,91	73,98	30,05%	4
186113	213,59	126,45	48,46%	6
186114	73,81	64,47	18,58%	4
186115	75,49	59,74	16,98%	14
186116	68,27	54,39	16,13%	4
186117	88,11	71,74	25,36%	8
186118	75,79	60,09	22,77%	8
186119	76,03	60,17	18,64%	9
186120	77,69	64,45	22,42%	10
186121	90,03	75,18	26,03%	6
186122	89,81	67,35	26,89%	3
186144	121,95	92,87	32,81%	5
186236	76,05	63,22	21,18%	5

Considering the normal distribution and the standard deviation, Table III shows two vehicles that have a very abnormal behavior: the 186113 and 186144.

The main pipe recharging time, during the coasting phase, is a good indicator of the compressor performance. It is evident that the performances of E186113 and E184144 have a completely different behaviour from the other vehicles of the fleet, and an accurate check of these compressors during the next maintenance stop is scheduled.

As all the compressor manufacturers indicate, another important parameter for maintenance purposes is the total working hours of the compressor. Typically, a complete overhaul action is recommended after 12.000 working hours.

Considering the average daily mileage and the effective percentage of working hour, it is possible to estimate the total worked hours for each compressor, and to evaluate when the target of 12.000 hours will be reached (see Table IV).

Table IV: Estimated remaining life of the compressor

# Vehicle	Daily working hours	Est. remaining life [years]
186111	4,44	7,41
186112	4,54	7,25
186113	9,08	3,62
186114	3,38	9,72
186115	3,07	10,72
186116	1,90	17,27
186117	4,58	7,18
186118	3,79	8,68
186119	3,12	10,54
186120	4,23	7,77
186121	4,16	7,89
186122	4,30	7,64
186144	5,25	6,26
186236	3,39	9,70

The compressor of vehicle 186113 will reach the target working hours in 3,5 years, so this means that it is noteworthy to monitor the behavior of this machine.

VIII 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.

The paper presents the result of a jointed research project between Bombardier Transportation Italy and the University of Genoa – DITEN. An original tool for data analytics was developed and used for defining new maintenance strategies for critical subsystems of vehicles. First results show significant improvements of all the KPIs related to maintenance. The activity continues for detecting other algorithms able to optimize maintenance schedule with the target of CBM.

ACKNOWLEDGMENT

The authors want to thank the Regione Liguria that founded this joint research activity between Bombardier Transportation Italy and the University of Genoa (PO CRO FSE 2007-2013 Asse IV).

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