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# Design of a Modular and Integrated On-Board System for Freight Train Condition Monitoring

**F. Zanelli[1], A. Galimberti[1], N. Debattisti[1], M. Mauri[1], D. Tarsitano[1], C. Osorio Mendoza[2], S. Negri[1] and G. Tomasini[1]**

**[1]Department of Mechanical Engineering, Politecnico di Milano Italy**
**[2]Direzione Tecnica , MERCITALIA INTERMODAL SpA Italy**

## Abstract

Condition monitoring is becoming an essential tool in the railway industry, allowing to increase the efficiency in vehicles maintenance interventions. This is particularly critical in the case of freight trains, since the majority of wagons is still non sensorized. The research work aims at developing a monitoring system with two main purposes: to be applicable to different wagon typologies and to be an integrated solution for the monitoring of the different mechanical subsystems of the vehicle. The focus is put on the energy harvesting to suitably power supply the wireless sensor nodes and on the identification of the possible malfunctioning of the braking plant. The design of the monitoring system has been driven by an empirical model of the braking plant realized also to support the analysis of experimental data collected by the monitoring devices in the diagnostic stage.

**Keywords:** condition monitoring, wireless monitoring system, freight train, energy harvesting, braking system, predictive maintenance.

## 1 Introduction

In past years, research activities devoted to developing monitoring systems with diagnostics purposes were limited to high-speed trains, since those vehicles represented the spearhead of the railway industry [1]. Recently, due to the increased role of freight rail in the transportation world, companies operating in this field have expressed the need of monitoring the health conditions of the wagons to perform predictive maintenance activities and to make this transportation mean more reliable and efficient. In this view, the concept of smart freight trains (i.e. wagons endowed of a limited set of sensors) has begun to spread and some examples of monitoring systems developed to this aim can be found in literature [2][3]. However, these research activities resulted in projects aimed at solving specific technical problems (such as wheelset defects, break wear, etc..) more than established solutions integrating the information collected from the different subsystems. Moreover, up to now, the majority of the fleet is still composed of wagons lacking any instrumentation useful for the monitoring of possible dangerous situation (i.e. derailments) and for the diagnostics of the different vehicle components. On the other hand, the future perspective of a backbone on the convoy for communication and power supply represented by DAC (Digital Automatic Coupler), paves the way to the use of new monitoring technologies. The innovative idea of research project is then the design of a modular integrated monitoring system able to significantly improve the safety of freight trains. The system will be composed by a "modular" platform, that includes variable compositions. It will be already prepared to take advantage of the future presence of the DAC technology. At the same time, the system could be easily scaled down to fulfil a minimum set of monitoring requirements with the aim of retrofitting standard freight wagons. Finally, the "integrated" platform will be able to manage and elaborate the information coming from possible existing devices already equipping the wagon with those collected by new sensors with the aim to reach the monitoring and diagnostic targets, depending on the technology level of the considered wagon.

## 2 Methods

As already pointed out in the Introduction, the research goal is the development of a wireless monitoring system for the retrofitting of freight trains. The realized system will be tested through an experimental campaign in collaboration with Mercitalia Intermodal. The aim is to carry out diagnostic activities of the braking system and of the suspensions, identifying possible malfunctioning and performing a predictive maintenance approach.

Concerning the braking system, the focus is put on the pressure monitoring in some crucial points of the system which are the main pipe, the weighing valve and the brake cylinder. Some test points are available on these components since pressure measurements are usually carried out as a check when the vehicle is subject to maintenance operations. For the design of the system, an empirical model has been developed taking advantage of experimental data collected in a previous field campaign [4]. In the last section of the paper, some examples of how the comparison between model and experimental data can be used to identify possible faults are shown.

Regarding suspensions diagnostics, it is possible to identify a huge change of stiffness through acceleration measurements, as shown in [5]. This monitoring approach foresees the acquisition of synchronous vertical acceleration time histories from a minimum set of three accelerometers mounted on the bogie as close as possible to the axle-box. The acquired vertical acceleration signals are then combined with each other to obtain the bounce, pitch and roll modes of vibrations. When a suspension failure (i.e. coil spring or friction component fault) occurs at one corner, the symmetry of the modes of vibrations is perturbated, resulting in the coupling of bounce, roll and pitch components of motion detected by the increase of the cross-correlation between the acceleration signals. Indicators for fault detection can then be extracted to assess the suspension diagnostics.

The monitoring system must be integrated and modular to satisfy the constraint of installation on standard and "smart" wagon types. Therefore, the systems to be installed on the two types of wagons share the same architecture. The monitoring system is composed of some wireless sensor nodes communicating wirelessly with a gateway mounted on the wagon chassis.

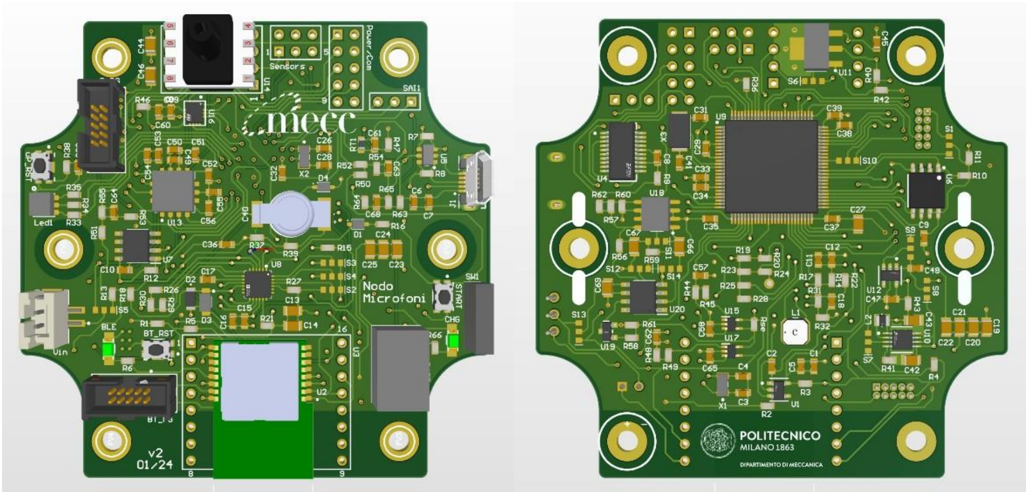
The wireless protocol employed for the device is based on the Bluetooth Low Energy (BLE) protocol. The designed sensors are equipped with a microcontroller STM32U595VJT6 by ST Microelectronics and a BT840Xe BLE transceiver by Fanstel. Concerning the transducers, a pressure sensor SSCDANN150PAAA3 from Honeywell is adopted for pressure measurements necessary for brake system monitoring, while an IIM-42351 triaxial accelerometer from TDK-Invensense is employed for acceleration measurements useful for suspension diagnostics. The main features of the two transducers are summed up in Table 1 and Table 2. A rendering of the designed sensor node is visible in Fig. 1.

| | |
|---|---|
| Sensor type | Absolute |
| Pressure range [Psi] | 0-150 |
| Resolution [bit] | 12 |
| Supply voltage [V] | 3.3 |
| Current consumption [mA] | 2.1 |

Table 1: Pressure transducers features.

| | |
|---|---|
| Full scale range [g] | ±2, ±4, ±8, ±16 |
| Sensitivity [LSB/g] | 16,384 (for ±16 g range) |
| Noise density [μg/√Hz] | 70 |
| Output data rate [kHz] | Up to 8 |
| Supply voltage [V] | 3.3 |
| Current consumption [mA] | 0.3 |

Table 2: MEMS accelerometer features.




**(a)** **(b)**

**Figure 1**: (a) Upper and (b) lower sides of the designed sensor node

Acquired data are sent to the gateway, which is essentially composed of a Raspberrry Pi4, a custom master board used to read through serial communication the data sent wirelessly by sensor nodes, a GPS receiver, a Lo-Ra node and a GSM modem. In both the wagons to be instrumented, the gateway is power supplied by a battery which is recharged through an axle box generator when the train is running.

As already pointed out, the idea is to install the developed monitoring system on one "smart" wagon (already equipped with a minimum set of sensors) and on one standard wagon which is lacking any sort of measurement devices since no power source is present on-board. This choice is justified by the fact that both types of wagons are present in the current fleet and therefore the monitoring activity is significant in both cases. The Lo-Ra node inside the gateway will be used to assess the possibility of sending synthetic information regarding the health status of the braking plant and the suspension from wagon to wagon, with the aim of delivering significant information on the convoy status to the driver in the locomotive. To this aim, the Lo-Ra protocol is chosen to cover possible long distances between the wagons which will be estimated through the use of the GPS devices available in the sending and the receiving gateway. The communication quality will be therefore correlated with the distance occurring between the wagons. The complete monitoring set-up (in the case of the standard wagon) is represented in Fig 2. The standard set of sensors for one wagon is then composed of a gateway, three sensor nodes devoted to pressure measurements on the main pipe, weighing valve and brake cylinder and three sensor nodes devoted to acceleration measurements positioned on the bogie in correspondence of axle boxes.

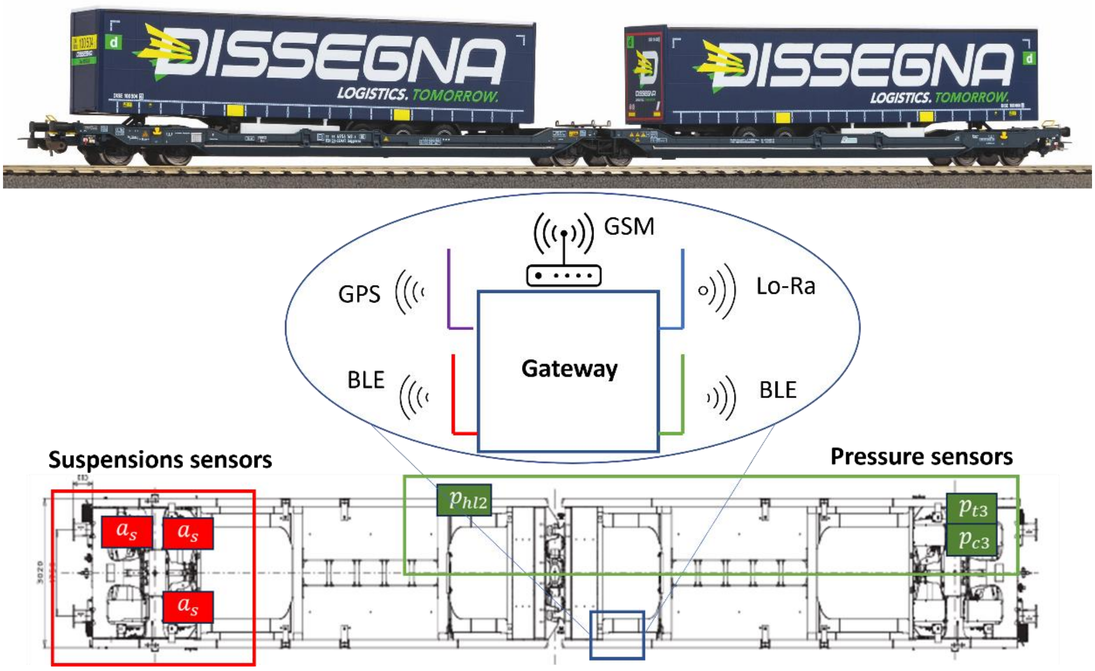
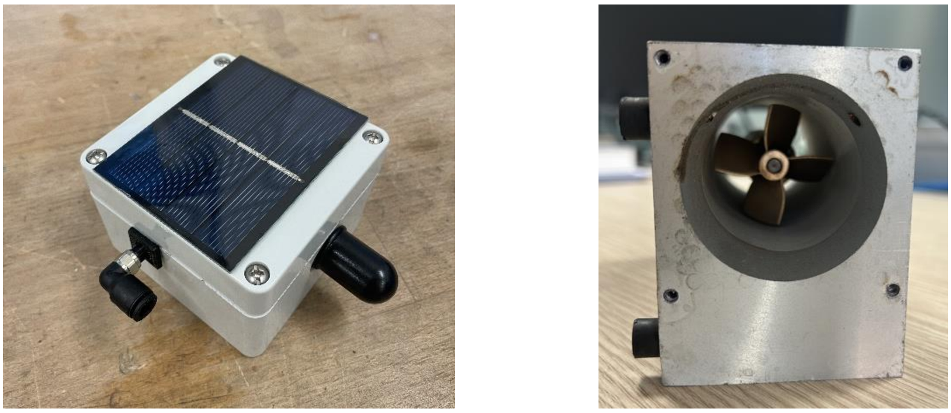



**Figure 2**: Conceptual scheme of the designed wireless monitoring system

Considering the differences between the two wagon typologies, the research activity followed different paths in the two cases. On the standard wagon, as already mentioned, no power source is present. Therefore, while the gateway is power supplied through the axle box generator, the sensor nodes must be energy self-sufficient. Two different energy harvesters were considered in the design phase, namely a mini PV-panel and a cm-scale wind turbine (Fig. 3).



**(a)** **(b)**

**Figure 3**: (a) Solar panel (b) Cm-scale wind turbine

PV panels have been already adopted in previous activities and their performances widely investigated [6] [7]. However, to achieve better performance a new energy harvester Power Management Unit (the ADP5091 by Analog Devices) and a new PV panel have been implemented in the sensor node with respect to the previous versions.

Particular attention was then put on the cm-scale wind turbine as an alternative device for energy harvesting, as reported in [8]. In the new designed sensor nodes, the adopted PMU for the wind turbine is the SPV1050 by ST Microelectronics. This choice allowed to overcome some limitations faced in the previous versions, such as the input voltage which can now reach up to 18 V. Moreover, to assess the best positioning of the sensor nodes equipped with mini wind turbine with respect to the flow below the wagon, it has been taken advantage of Computation Fluid Dynamic (CFD). The results of the analysis are shown in the next section.

Concerning the “smart” wagon, it represents an important step towards the digitalization of freight vehicles. A further step will be represented by the introduction of the Digital Automatic Coupler (DAC), which depending on the technological “level” will guarantee a backbone for power and data transmission on-board the convoy [9]. On the smart train, therefore, the research line focused on improving sensor nodes performances to integrate the existing set of sensors with new functionalities, taking advantage of a stable power supply as it will be in the case of DAC. In this context, the presence of DAC is “simulated” by power supplying the sensor nodes directly through the axle-box generator with a 5 V DC current. This choice will put some limitations in their positioning due to the presence of wires but will allow to maximize their computational performances.

In this view, the acquisition parameter which has a significant influence on braking system monitoring is the sampling frequency, which can be increased from 1 Hz used in previous activities [1] to at least 40 Hz to describe the low time variation and fast dynamics of the first braking phase as shown in Fig.4, without a huge impact on the data transmission rate.

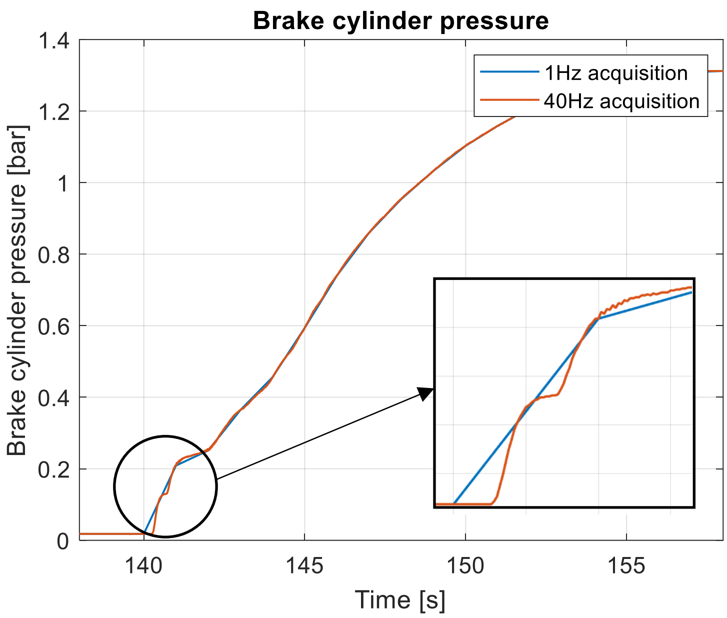



**Figure 4**: Brake cylinder pressure comparison between acquisition at 1Hz and 40Hz

Adopting a 40 Hz sampling frequency (red curve) it is possible to identify the three steps composing the first braking phase: the minimum brake cylinder volume phase, the moving brake cylinder piston phase and the maximum brake cylinder volume phase. The ability of the empirical model described in Section 3 to correctly simulate the first braking phase enables the detection of possible malfunctioning (i.e. manual brake activation during train moving condition and variation of the brake cylinder pressure stroke), difficult to be identified with a purely data-driven approach. The addition of this feature allows then to enhance the diagnostics capabilities of the developed monitoring system.

## 3 Results

As already mentioned in Section 2, a CFD model consisting of one locomotive and nine wagons for an overall length of 200 meters was realized as shown in Fig.5(a). CFD simulations were run considering the convoy travelling a cruising speed of 120 km/h. Multiple virtual probes were positioned along the longitudinal axis of the convoy (taking into account geometrical constraints related to regulations and to wagon operation) to study the flow under carbody with the aim of assessing the best wind turbine positioning for power generation (Figure 5(b)).

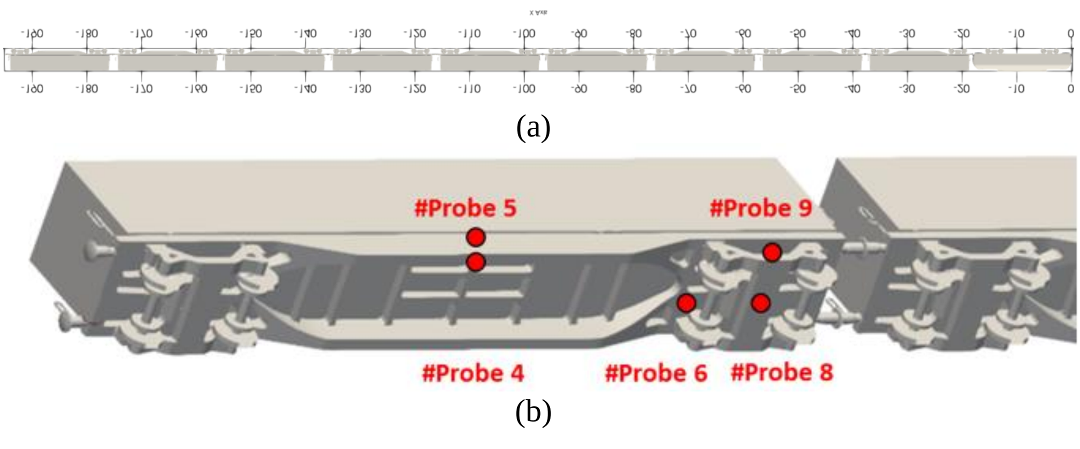



**Figure 5**: (a) CFD train model (b) CFD model of the last wagon and probes position

The results of the analysis are reported in Fig.6 in terms of wind speed time histories at different probes positions on the last wagon. Probe n.5 is characterized by the best aerodynamic performance with a mean speed of 15 m/s and a turbulence intensity of 8.64%, evaluated through the turbulent kinetic energy $k$ given by Equation (1).

$$u' = \sqrt{\frac{1}{3}\left(u'_x{}^2 + u'_y{}^2 + u'_z{}^2\right)} = \sqrt{\frac{2}{3}k} \tag{1}$$

Where $u'$ is the root mean square of the turbulent velocity fluctuations. Probe n.5 is indeed the best aerodynamic point to position the wind turbine since the flow on the lateral surface is more coherent and less turbulent than the one under the carbody.

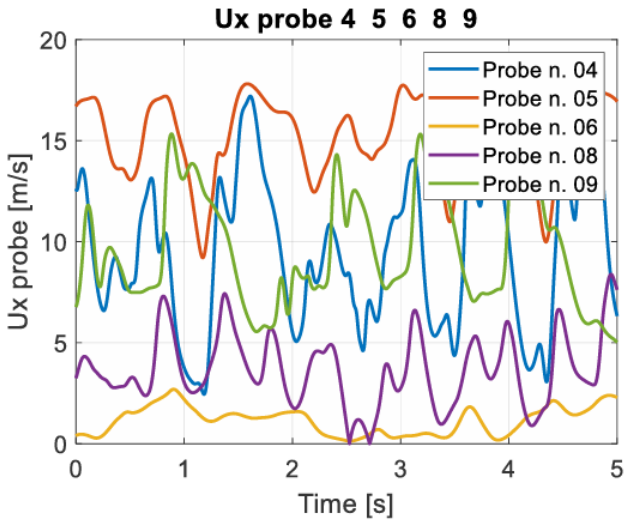



**Figure 6**: Wind speed time history at different probes positions on the last wagon

The results of this analysis will be considered in the wind turbine positioning during the monitoring system installation on the wagon.

The second tool employed to properly design the monitoring system is an empirical model of the freight train braking system. The model has been used to verify the pressure measurement points and thus the number of sensor nodes necessary for the monitoring activity. Moreover, the model is useful to understand the system behaviour in presence of components malfunctioning and will therefore employed to support the analysis of data coming from the field test, as explained in the following. The empirical model has been validated using a database created in a previous field campaign [4].

The model structure is briefly described in the following.

In the acquisition stage, the sensor nodes mounted on the instrumented wagons acquire data concerning the main brake pipe pressure, the brake cylinder pressure and the weighing valve pressure as reported in Fig.7. These three critical positions identified the minimum set of nodes to be installed to perform an efficient monitoring and diagnostic activities.

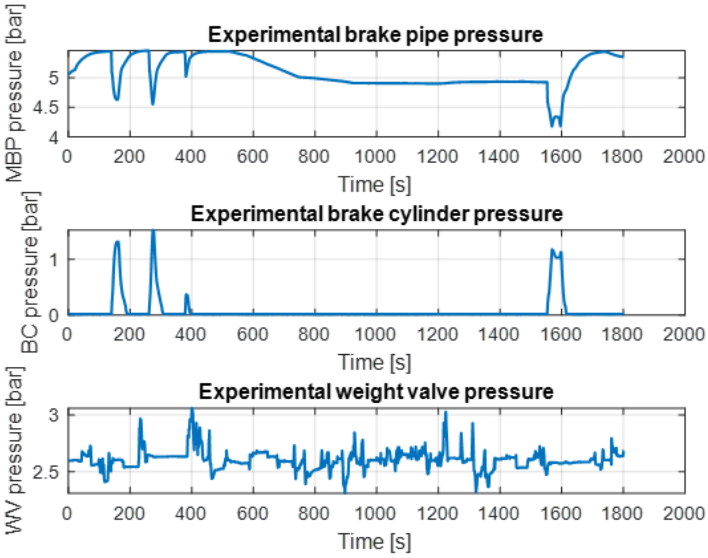
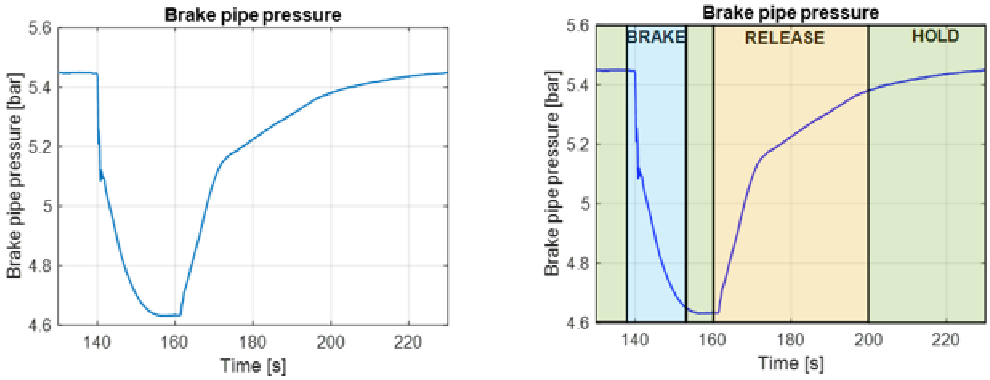



**Figure 7**: Exemplary sensor node acquisitions

Each subsection of the main brake pipe pressure, whose typical curve during a brake event is reported in Fig. 8(a), is obtained using a peak detection algorithm and is used as an input variable in the model. The model evaluates the distributor function as the depression in the main brake pipe. A moving average filter is then used to obtain a smooth distributor function to filter out the fast dynamic variation of the pressure in the main brake pipe coming from the activation of the accelerated chambers. A first order difference pressure of the distributor filtered pressure in then obtained to assess the brake phase partition. Time intervals with positive gradient are classified as braking phase, with negative gradient as releasing phase and with zero gradient as holding phase as in Fig.8(b). It is very important to distinguish these phases since the air brake is a hybrid system whose states and behaviour changes according to valves positioning. A logic like the one described has been implemented in [10]. The main difference from [10] and main contribution of the present work comes from the fact that the phase partition takes also into account the recharging phase of the main brake pipe that due to its slow dynamics doesn't turn on the distributor and the brake cylinder.




(a) (b)

**Figure 8**: (a) Main brake pipe pressure (b) Phase partition and classification

The brake plant is modelled as a hybrid system involving the introduction of transfer function of different braking system components (i.e. weight valve and kink valve) as shown in Fig.9, a new model for the first braking phase based on the correlation between the main brake pipe pressure and the brake cylinder pressure and fluid-dynamic simplified model to simulate the fluid transient behaviour between different components (i.e. auxiliary reservoir and brake cylinder) and the releasing phase.

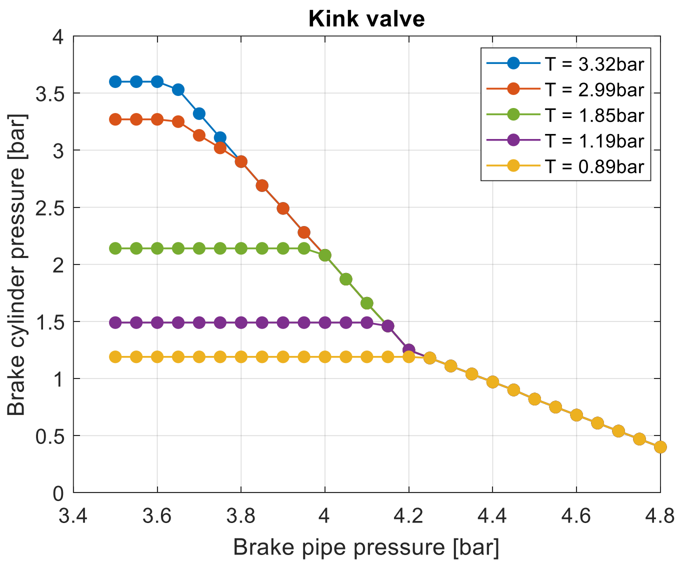



**Figure 9**: Kink valve transfer function

In the last diagnostic phase, the comparison between the brake cylinder pressure obtained through the model and the one measured on the vehicle is used to identify possible brake malfunctions. In Fig.10, an example of brake cylinder pressure comparison is shown. As reported, the model can replicate correctly both the braking and releasing phase.

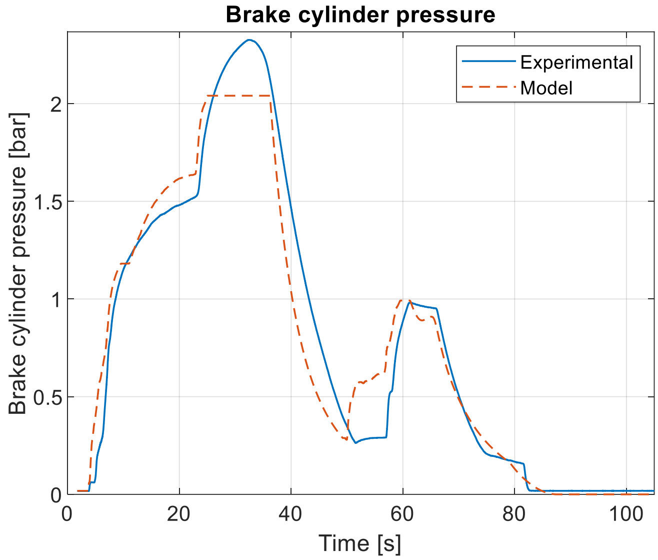



**Figure 10**: Comparison between the model brake cylinder pressure and the experimental brake cylinder pressure

In the end, an example of a braking plant malfunctioning is presented in Fig.11. The difference between a healthy state condition evaluated through the brake model and the experimental brake cylinder pressure highlights the faulty condition as the combination of two base malfunctions. The variation of the cylinder spring stiffness is reported (for a different braking event) in Fig11(1) while the malfunction of the weighing pressure valve is reported in Fig.11(2). The brake cylinder spring variations affects the first braking phase as can be seen in Fig.11(1). The piston movement (simulated by the horizontal curve) starts and ends at lower cylinder pressure and takes higher time to reach the maximum stroke due to a lower mean pressure along the stroke. As the first braking phase expires, the transient and steady state condition of the faulty and healthy condition will approach to the same configuration. The malfunction of the weighing valve results in a simulated weight which is different from the experimental expected one. Fig.11(2) shows that this faulty state results in a different transient and steady state condition without affecting the first braking phase. The maximum pressure reached by the model healthy condition is higher than the experimental one, meaning that the weighing valve is monitoring a pressure coming from a weight which is lower than the actual one on the wagon. Also, the time taken to reach the steady state condition is affected.

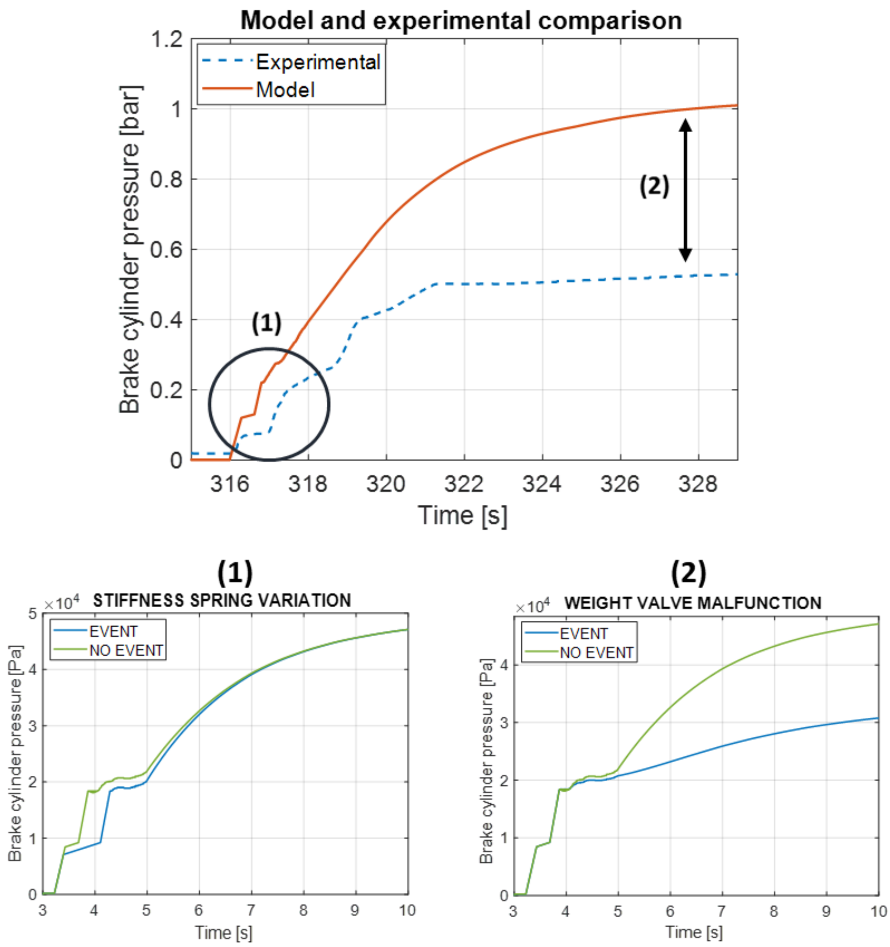



**Figure 11**: Component level faulty state diagnostic

It has then been shown that the developed monitoring system can be used to perform diagnostic activities of the braking plant, allowing to adopt a condition-based maintenance approach in the field of freight vehicles.

# 4 Conclusions and Contributions

The design of an innovative monitoring system has been presented in the paper. Being modular and integrated, the monitoring system meets the needs of installation on old freight wagons where no power supply is available and on "smart" wagons where an already mounted set of sensors can be integrated with additional features. It has been explained that energy harvesting is crucial for powering sensor nodes on a standard wagon, and for this reason a deep study of the wind turbine positioning has been shown. On the other side, it has been discussed how the sensor node performance can be enhanced to provide additional features to the "smart" wagon. An empirical model of the braking system has been created to drive the monitoring system design and to assist the post processing phase of data collected during the field campaign. The developed monitoring system will be adopted during a field campaign on operative freight wagons provided by Mercitalia Intermodal to verify the efficiency of both solutions. Data collected in this framework will be hugely useful to assess the diagnostic purposes of the monitoring system. For a final and complete validation of the system and of the algorithms employed for both braking plant and suspensions diagnostics, a test in a confined environment (i.e.RFI San Donato test circuit) where it could be possible to introduce defects and malfunctioning on the vehicle subsytems is planned in the upcoming months.

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