Experimental Analysis
of Mechanical Vibrations and Wind Speed
for a Rail Vehicle WSN fed by Energy Harvesters

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Abstract— **Real-time diagnostic and monitoring on railway vehicles for goods transportation is considered. The results of a preliminary experimental activity aimed to model mechanical vibrations and wind speed for autonomous monitoring and diagnostic wireless sensor network fed by means of energy harvesters are reported and commented.**

Keywords—diagnostic, energy harvesting, rail vehicles, safety, WSN.

I. Introduction

The increased use of railways transport systems as a smart and green transport mean (in line with the European directives for sustainable mobility of HORIZON 2020), has led, in recent years, to the study of technological and methodological solutions aimed to prevent threat phenomena of railways safety and to the surrounding environment characterized by low investments and costs [1]-[3]. One of the levers to pursue the increase in safety and a reduction in operating costs is the optimization of monitoring and diagnostics. The final aim is to develop a condition-based maintenance, which adapts maintenance interventions to the real (wear) condition of the components. To achieve these results reliable information on the infrastructure condition of the vehicles and of the areas concerned are crucial.

In this context, the MODISTA project is aimed to the study, definition and proposal of innovative technological and methodological solutions. The project is articulated in five Work-Packages: WP1) Monitoring of railway infrastructure and surrounding areas by SAR satellite technology and a MEMS system directly on site; WP2) Monitoring of trains by using fast linear cameras; WP3) Monitoring the status of goods; WP4) Prognostic monitoring of railways vehicle fleet and vehicle operator data exchange; WP5) Application of Green Technologies.

In the paper reference is made to results of a preliminary experimental activity aimed to model vibrations and wind speed for autonomous monitoring and diagnostic WSN fed by energy harvesters in the framework of WP 3 to 5. To the knowledge of the authors the results of similar comprehensive experimental activity are not present in the relevant literature.

II. Autonomous Monitoring and Diagnostic System

Alternative monitoring and diagnostic systems, which are suitable to applications without electric supply and convenient for the industrial development and diffusion, which means low cost, good reliability, and high integrability are considered. Recent studies demonstrated the possibility to generate directly onboard the electric power needed to the supply of the systems based on low power sensors and integrated wireless transmission modules.

The final objective is to design a platform composed of an onboard and a wayside system in order to monitor both the vehicle health conditions and the status of goods, in particular, dangerous goods or those which can be considered as such, under certain conditions. The platform to be implemented aims to prevent accidents and increase safety (e.g. leakage of toxic liquids in densely populated areas), and also to increase security aspects.

The onboard system will be constituted (see Fig. 1) by:

- A control unit for the acquisition of data collected by the sensor units installed onboard and for the subsequent pre-processing with the aim of obtaining aggregate data to be used by the control center.
- A wireless communication module (e.g. GSM) to send the acquired data to the control center.
- A geolocation module (GPS) of the wagon from which different user services could be offered, such as traceability and dwell times of freight wagons. By equipping each wagon, or part of them with these modules information on train integrity will be obtained.
- An autonomous power supply system due to the absence of a power supply on board freight wagons. The control unit and the sensor units will be fed by means of energy-harvesting systems and energy storage sized in function of energy requirements of the on board system.
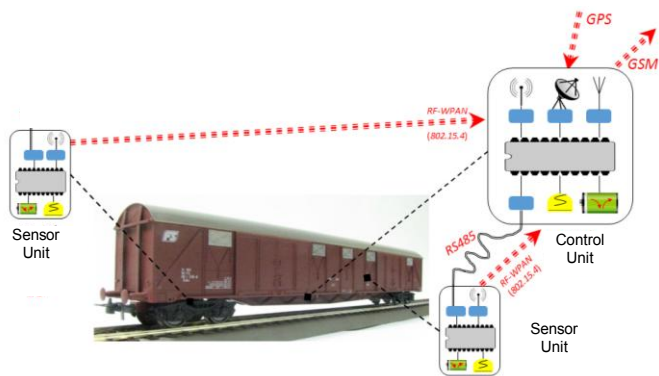
Fig. 1. Autonomous Monitoring and Diagnostic System.

The challenge is to provide an onboard system that, once fully implemented, could be easily adapted to different types of wagons. Past data and experts' judgment have been used to identify the type of wagon, including those carrying dangerous goods, which has a prominent interest in terms of both railways security/safety and human life in general, in order to apply the feasibility demonstration of this solution to that type of wagon.

All operating data monitored are collected onboard by each equipped vehicle of the fleet, sent to the control center and compared in terms of the fleet and for different service periods. These infrastructures are also used to create a system for the collection and exchange of data between the railways operator and the end-user, which aims to improve the quality of service and to optimize the operating costs. All collected data, together with expertise of involved stakeholders, constitute the primary source of information for developing and implementing effective maintenance strategies allowing to increase the fleet availability, while satisfying the safety requirements.

III. PRELIMINARY EXPERIMENTAL ACTIVITY

The project proposes the use of both traditional (wind) and additional alternative (mechanical vibrations) power sources to supply the onboard monitoring and diagnostic system.

For this reason a preliminary experimental activity aimed to obtain the necessary data to properly select commercial energy harvesters or to design specific prototypes has been conducted.

The vehicle used in the experimental activity is a freight train equipped with Y25 bogies, which are currently the most diffused in Europe for this kind of vehicles.

16 train rides have been performed on a path whose length is 25 km for different speeds and in two different operating conditions: no load and loaded, for a total number of 400 km.

Fig. 2 reports an example of the freight train speed profile recorded, with a sampling frequency of 1 Hz, in one of the rides versus the time. It is possible to observe that some time intervals are characterized by an almost constant speed, as planned in the design stage of the experimental activity. The aim of separately studying different sets of different speeds was to evaluate and characterize the energy harvesting sources (mechanical vibrations and wind) in a more detailed and comprehensive way.
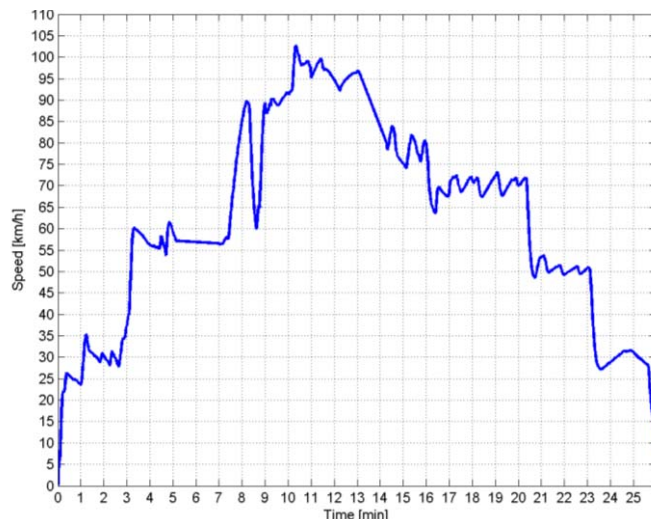

Fig. 2. Freight train speed profile versus the time.

Once characterized the different speed sets, specific "reference" rides, composed by juxtaposing different sections of the route with constant speeds, can be built.

Fig. 3 reports the histogram of the speed profile depicted in Fig. 2. It is possible to observe that seven main classes can be appreciated. For this reason, the seven classes reported in Table I have been selected.

TABLE I - SPEED CLASSES

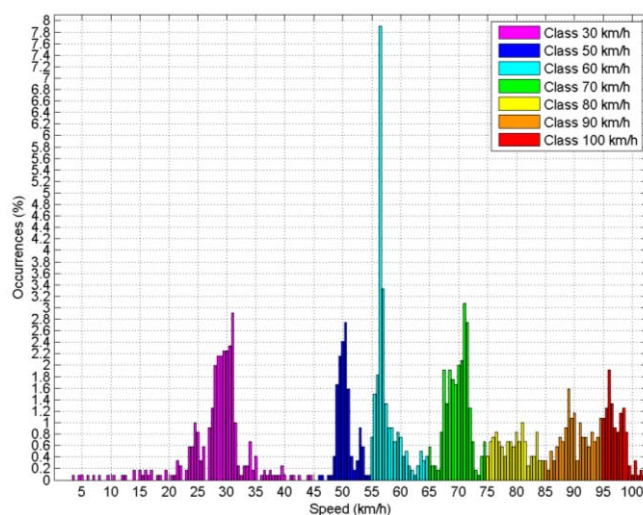| Class	Speed min	Speed max
1	1	45
2	46	55
3	56	65
4	66	75
5	76	85
6	86	95
7	96	105

Fig. 3. Freight train speed hystogram.

IV. Vibration Data Analysis

Energy harvesting from mechanical vibrations has been widely studied in the relevant literature[4]-[9]. Commercial energy harvesters from vibrations, based on piezoelectric [10] and electromagnetic [11] technologies, are also available.

During the experimental activity, two data loggers have been used. They are Slam Stick X - LOG-0002 produced by Mide [12]. The main characteristics of the data logger are: sampling rate: 100 Hz to 20 kHz; tunable anti aliasing filter tunable; acceleration ranges: ± 25 g, ± 100 g & ± 500 g; storage size: 2GB; size (in): 3 x 1.18 x 0.59; mass: 40 & 65 grams; sensors: triaxial accelerometer, temperature, pressure.

The sampling frequency used was set to 20 kHz and the anti aliasing filter to 4 kHz. X, Y and Z accelerations have been recorded.

Accelerometers have been installed in different positions of the freight train as reported in Fig. 4. Among the 16 rides, 6 rides in position A, 4 in position B, 2 in position C and 4 in position E, have been performed.
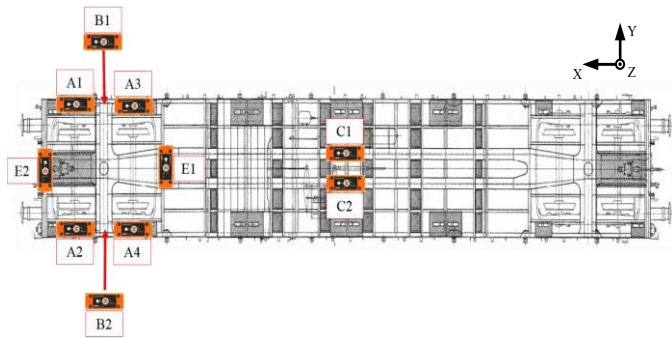

Fig. 4. Accelerometers positions.

In what follows the analysis of the recorded data is performed with the aim of showing the different behaviors among the three axes and the different positions along the freight train. Then, a comparison between the two different load conditions, no load and full load, is performed. In the last subsection some final considerations are given.

A. Analysis on the three axes

Fig. 5 reports the aggregated spectra of the accelerations measured on the three axes in positions A4 (see Fig. 4) versus frequency, for the different speed classes introduced in the previous section. Aggregated spectra have been calculated over the total number of 1 s length vibration data corresponding to the train speed samples contained in each class. So the frequency resolution of the spectra is 1 Hz.
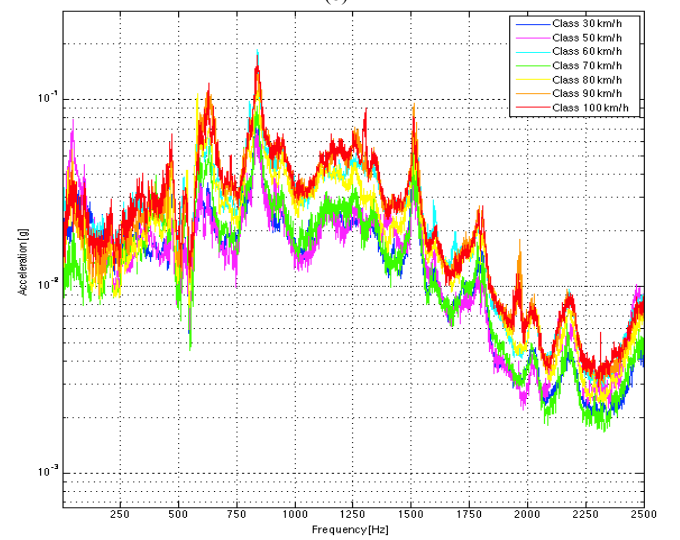It is possible to observe that:

- as expected, the maximum accelerations are registered on the Z axis;
- the higher the train speed the higher the acceleration amplitudes are with a maximum value around 0.2 g;
- the maximum of the vibrations energy is concentrated around 850 Hz with a broad band behavior.

(a)

(b)

(c)
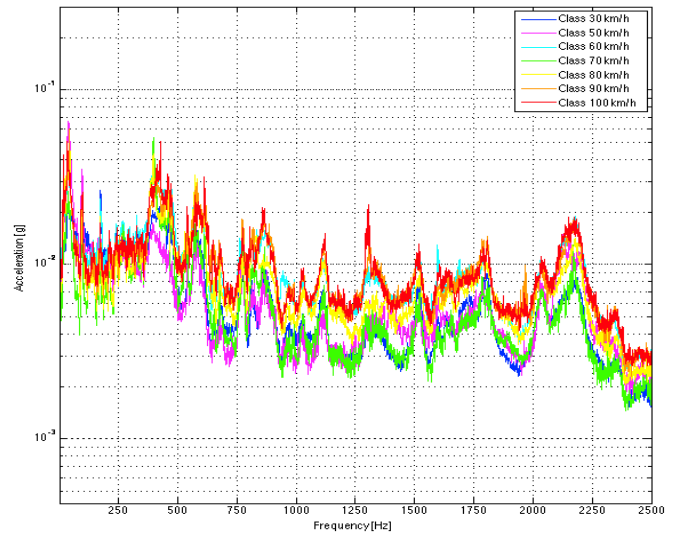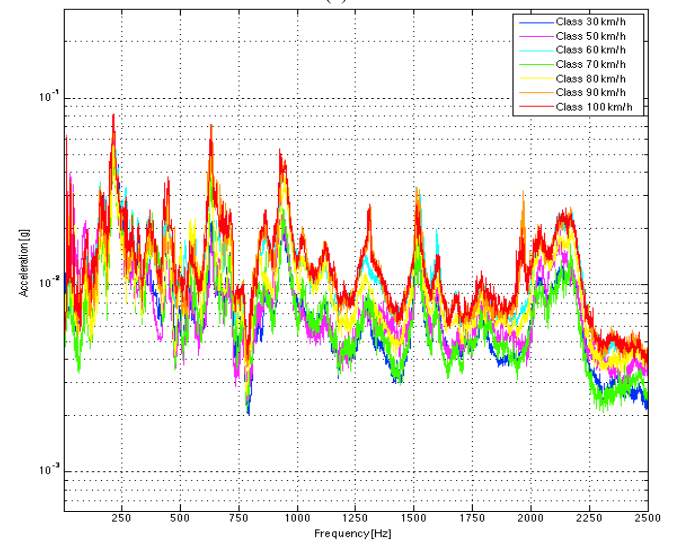
Fig. 5. Freigth train loaded: average spectra of the acceleration in positions A4 versus frequency for different speed classes: a) X axis; b) Y axis; c) Z axis.

B. Comparison of different positions

Fig. 6 reports the freight train spectra of the acceleration versus frequency for different speed classes and different positions: a) A1; b) B1; c) C2; d) E1. The train was loaded.

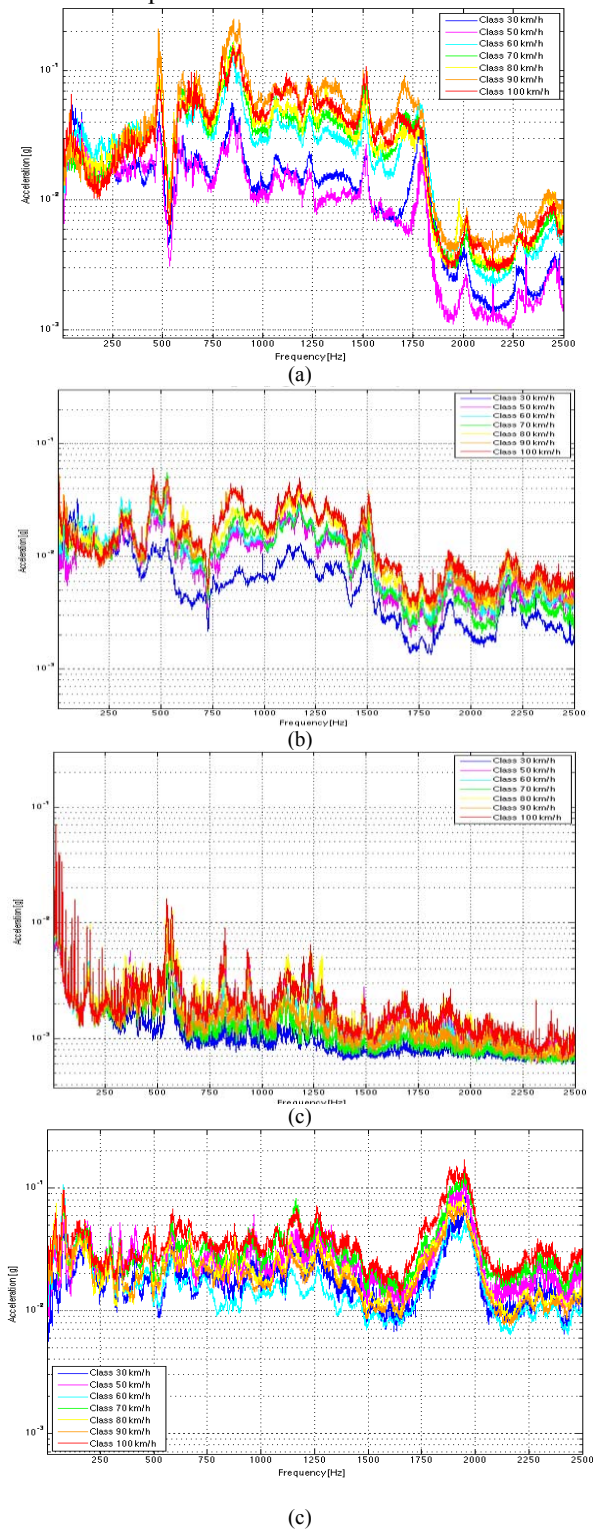It is evident that positions A1 and E1 are characterized by the maximum amplitudes.

(a)

(b)

(c)

(c)

Fig. 6. Freigth train spectra of the acceleration versus frequency for different speed classes and differen positions: a) A1; b) B2; c) C1; d) E1 (see Fig.4).

C. Comparison of different load conditions

Fig. 7 reports the freight train spectra of the acceleration versus frequency for different speed classes and different load conditions: a) No load; b) loaded.

It is possible to observe that the presence of the load doesn't change the frequency positions of the main tones but their amplitude is amplified in the range centered around 850 Hz where their amplitude is maximum.
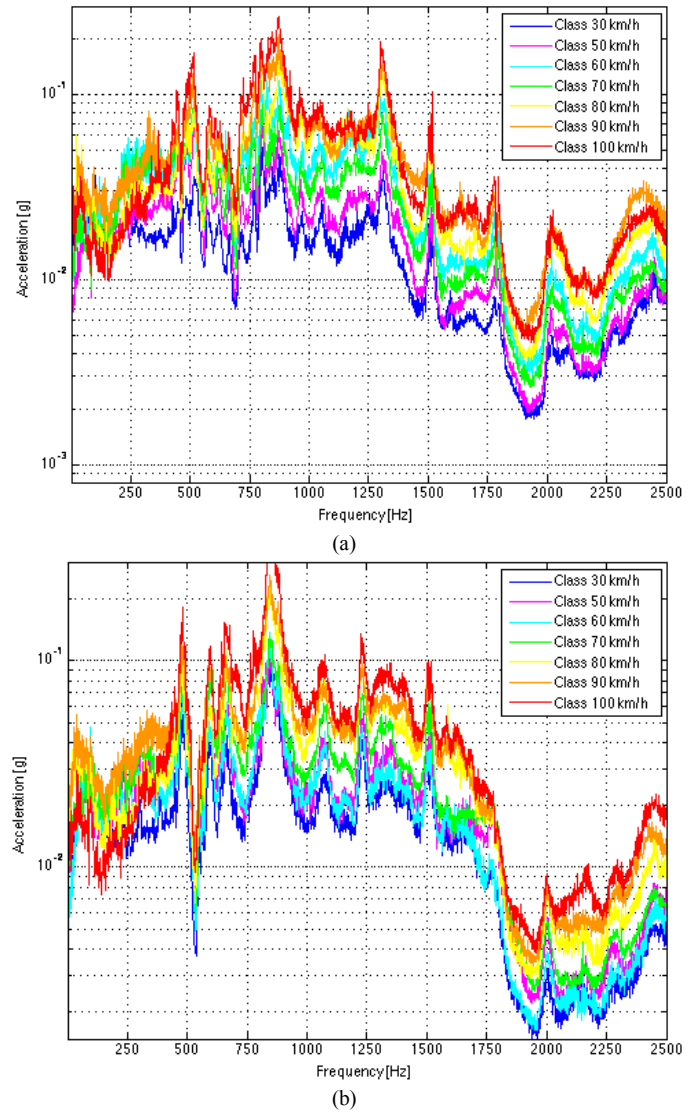

(a)

(b)

Fig. 7. Freigth train spectra of the acceleration versus frequency for different speed classes and different load conditions in position A1: a) No load; b) Loaded.

D. Final considerations

From the analysis of the results reported in this section it is possible to conclude that:

- maximum accelerations are registered on the Z axis, as expected;
- positions A, B and E show the maximum potential energy around 850 Hz, 500 Hz and 1900 Hz, respectively, with maximum amplitudes of 0.2 g, 0.06 g and 0.17 g.

V. Wind Data Analysis

The main objective of the wind speed measurement campaign arises from the need to do the best choice of a wind generator in terms of type, characteristics and requirements on the market. In fact, given the lack of wind generators that are specifically designed for the rail sector and in particular for the installation of a railway wagon, the authors have been obliged to choose among the various types of wind generators designed and used for other sectors. In fact, in the relevant literature it is possible to find only prototypes for the railway sector [13]-[17]. Basing on dimension considerations and on expected vibrations from the environment and therefore on requirements for mechanical strength appropriate to rail applications, a wind generator designed for marine environment sector was chosen. The wind speed generator is a vertical axis 10 W with a start-up wind speed of 6 m/s [18].

During the measuring campaign, anemometers have been installed in two different positions of the freight train, called EXT and INT, as reported in Fig. 8.
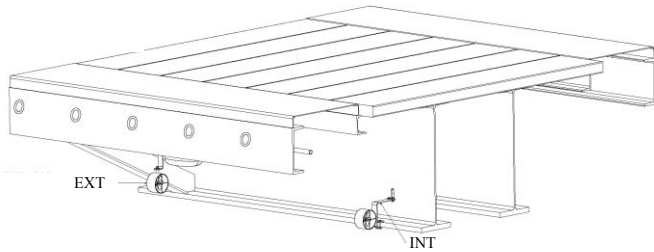

Fig. 8. Anemometers positions.

The statistical analysis of the measured data has been conducted introducing Wind speed Classes (WC) and Train speed Classes (TC), respectively. Basing on the measured ranges of the corresponding quantities, 7 WC with amplitudes of 2 m/s and 6 TC with amplitudes of 20 km/h have been considered. Moreover, in order to correlate WC with wind data producing electrical energy to the corresponding TC, a minimum wind speed of 6 m/s has been chosen. Those classes (whose symbol is underlined) have been called "Significant Classes".

From the analysis of the wind speed measurement results, it was observed that among the 16 rides done, 40% and 31% of the samples were characterized by amplitudes higher than 6 m/s for the EXT and for the INT anemometers, respectively.

In what follows the analysis of the results of one of the rides performed (ride #5) are reported because it is characterized by the maximum mean values.

Fig. 9 reports EXT and INT wind speeds and train speed versus the time. It is possible to observe that, as expected, external wind speeds are higher than internal. Moreover, it is clear that the start-up wind speed of 6 m/s corresponds to the speed train of about 50 km/h, that is to say that electrical energy production starts from that train speed. Finally, a strong correlation, again expected, is shown between train speed and wind speeds.

For this last observation Fig. 10, which depicts EXT (a) and INT (b) wind speeds versus train speed and corresponding estimated regression lines, has been drown.

The abovementioned linear relation has been found for all of the rides performed. Moreover, comparing the statistical analysis results of rides #1 and #5 reported in Table II, it is possible to observe that an increment of "significant" train speed classed from 53% to 65% corresponds to an increment of from 49% to 61% of "significant" wind speed classes for the external position of the anemometer and from 38% to 46% for the internal position of the anemometer, that is to say a linear relationship.

TABLE II - "Significant" Classes Statistics

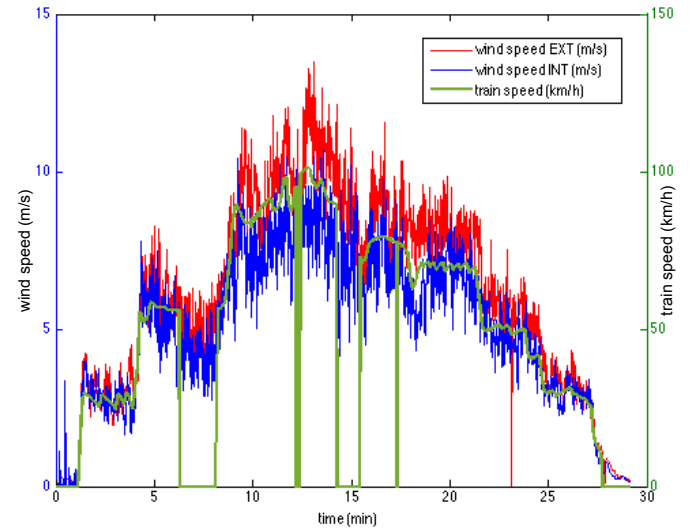| Ride (#)	Mean train speed (km/h)	$\underline{TC}$ (%)	$\underline{WC_{EXT}}$ (%)	$\underline{WC_{INT}}$ (%)
1	53	53	49	38
5	59	65	61	46

Fig. 9. Ride #5: EXT and INT wind speed and train speed versus the time.
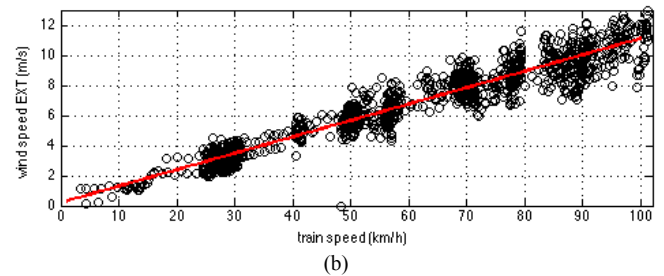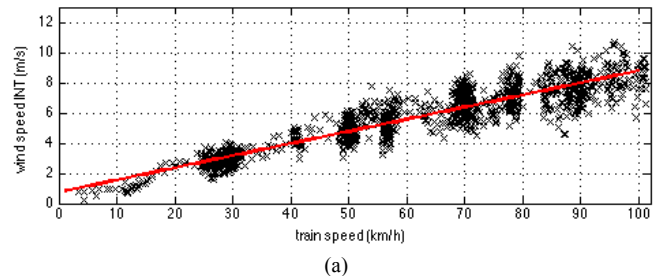

(a)

(b)

Fig. 10. Ride #5: EXT (a) and INT (b) wind speed versus train speed and corresponding estimated regression lines.

VI. Conclusions

The results of a preliminary experimental analysis aimed to model mechanical vibrations and wind speed for autonomous monitoring and diagnostic system fed by means of energy harvesters have been reported and commented.

This experimental activity has been conducted in the framework of a research project on real-time diagnostic and monitoring on railway vehicles for goods transportation.

The main outcome of the paper is that energy harvesters both from mechanical vibrations and wind can be developed for the aim of the project.

Acknowledgment

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