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# Monitoring of railway structures of the high speed line BPL with bituminous and granular sublayers

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**Abstract** - The phenomena of packing and wear of ballast, under dynamic stresses lead to high maintenance frequencies and high maintenance costs. Several studies have shown that these settlements were linked to the high accelerations produced in the ballast by the passage of high-speed trains. Bituminous sublayers are used since the 1980s in several countries like the United States, Italy, Spain, especially on high-traffic and high-speed lines, to increase the stiffness of the track structure, and reduce these high acceleration levels. Recently in France, this technique attracted interest following the satisfactory behavior of the East European HSL. A high scale project with an asphalt concrete sublayer on the “Bretagne-Pays de la Loire” (BPL) high speed line, was launched. The innovative underlayment is intended, among other things, to reduce the amplitude of the accelerations produced at the passage of high-speed trains.

HSL BPL has 105 km of innovative track with an asphalt concrete (GB) sublayer under the ballast, and 77 km with untreated granular (UGM) underlayment. In order to study the dynamic responses of these different structures and to understand the effect of the different layers on the dynamic response, four sections were instrumented (3 sections with an asphalt concrete track structure, and one with a standard granular structure) using, among others, accelerometers, strain gauges, temperature probes, etc. More than 100 sensors have been installed in the railway infrastructure at different positions and depths. Data acquisition has been performed during the speed up test phase, under controlled conditions; the same train crossing the line with speeds ranging from 160 to 352 km/h. Commercial traffic has been traveling on the BPL line since July 2017.

In this paper, we will present the instrumentation as well as the acquisition system installed to collect all the measurements. Different results obtained during the speed up test phase are drawn, with a focus on comparisons of measurements between the different sections with UGM and GB layers.

## Introduction

Ballast deterioration, under dynamic loads, remains an important issue on high-speed tracks that can lead to high maintenance costs. Several studies have shown that these settlements are related to the high accelerations produced in the ballast by high-speed trains (Pita et al., 2004; Quezada, 2012; Saussine, 2004; Suiker, 2002).

The use of asphalt sublayers under the ballast has been identified as a possible solution for improving track structures. By interposing a semi-rigid layer of asphalt concrete (GB) between the ballast and the UGM layer, the behavior of the overall structure is greatly improved. This applies to both high-speed passenger and freight lines. The use of asphalt concrete (GB) in railway construction has emerged in different countries. Indeed, over the last decade 322 km of sub-ballast layers have been built for new projects in the Midwestern United States; mainly for heavy freight traffic (Rose and Souleyrette, 2015).

In 2005, SNCF built a 3 Km long test section in the East HSL (LGV Est), linking Paris to Strasbourg, with a GB sublayer. The data retrieved from this first instrumented test indicated satisfactory performance of the experimental railway section (Cardona et al., 2016; Robinet and Cuccaroni, 2012). The presence of the asphalt sublayer has proven to reduce the aggressiveness of the loading applied by passing trains, leading to an increase of the structure durability.

In spring 2014, the project "Monitoring of HSL BPL" has been launched to instrument several sections of the new high-speed line (HSL) Bretagne-Pays de la Loire (BPL) (between Rennes and Le Mans, in the West of France). HSL BPL is the first large-scale application of the asphalt concrete sublayer technique in France (next to the East European HSL in its second phase), with varying subgrade conditions, and using higher performance asphalt materials. Data acquisition and analysis started at the end of 2016, when trains were first put into circulation (for a test phase). The line has officially initiated its operations in July 2017 with trains travelling at a speed of 320 Km/h.

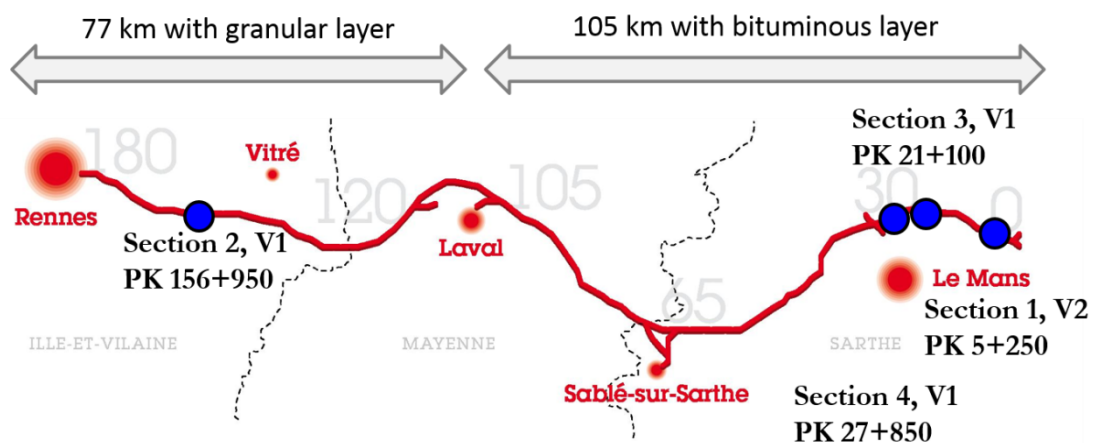


Figure 1 - HSL "Bretagne Pays de la Loire" lane

## Structure of HSL Bretagne-Pays de Loire

HSL BPL consists of 105 km of innovative track with an asphalt concrete (GB) sublayer under the ballast on its east route, and 77 km with a granular underlayment on its west route. An asphalt concrete (GB) of class 4 (GB4), according to French standard NF EN 13-108-1, has been used for this project. The unbound granular material (UGM) has a particle size 0/31.5 mm, and is of type A, according to French specifications. The innovative track structure, shown in Figure 2, includes the upper part of the earthworks (PST), which is treated with lime and hydraulic binders. The PST is surmounted by 15 cm of Unbound Granular layer (UGM) and a

12cm thick asphalt layer. The standard structure comprises a 37 cm thick granular sublayer in addition to a cement-treated subgrade layer.

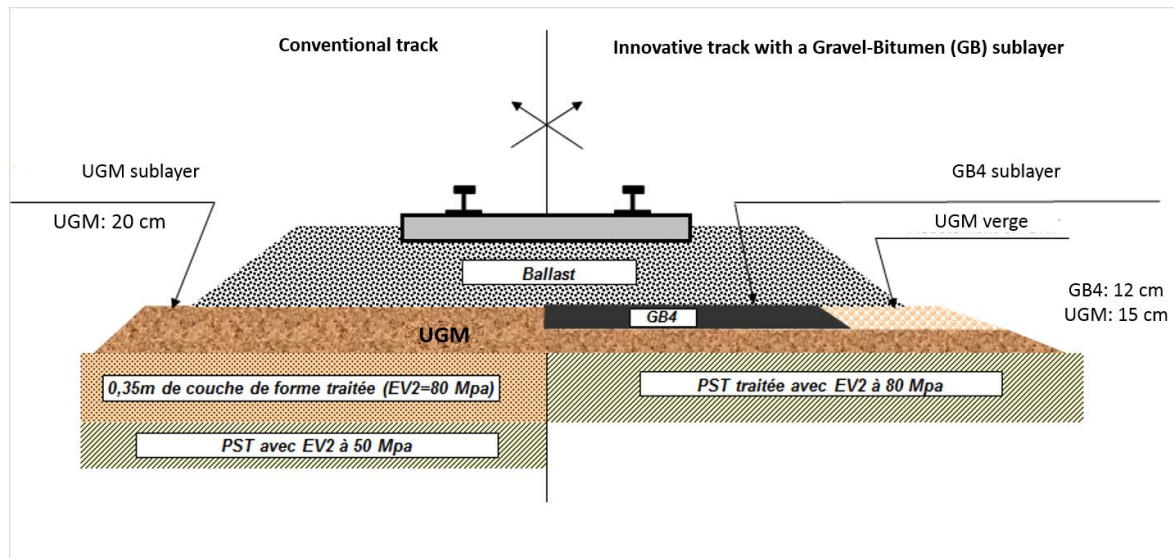


Figure 2 - Structure of the different sections with and without asphalt concrete.

Four sections were instrumented (Figure 1): three sections with asphalt concrete underlayment and one with a standard granular structure (Khairallah et al., 2017). The objective of this instrumentation is to monitor the mechanical response of the different structures used on BPL HSL, by measuring accelerations, sub-ballast structure displacements, horizontal and vertical deformations and temperatures in different layers, and also water contents at the top of the subgrade.

## Instrumentation: Sensors, Measurements and Acquisition system

The aim of the instrumentation is to monitor dynamic responses of the different structures, and thus to better understand the effect of different layers on dynamic response and track durability. The sensors were chosen and implemented by IFSTTAR. Accelerometers, weather stations, anchored displacement sensors, horizontal and vertical strain gauges, moisture probes and temperature sensors were used for the instrumentation of the sections.

Section 2 is instrumented with 6 vertical strain gages in the UGM layer, 16 accelerometers placed at different levels, 4 moisture content probes in the UGM, 2 temperature sensors, 2 anchored displacement sensors and a weather station. As for section 4, 6 vertical strain gages, 10 horizontal strain gages in the asphalt layer, 8 accelerometers, 4 moisture content probes, 3 temperature sensors, 2 anchored displacement sensors and a weather station monitor the track.

Accelerometers are installed to record the track's vertical dynamic behavior, with measurements at several levels: under the sleepers, at the top of the asphalt concrete layers and at the top of the granular layer. Anchored displacement sensors measure the structure's total vertical displacement under the ballast (GB + granular layer + subgrade for section with bituminous sublayer or UGM + subgrade for section with granular sublayer). Strain gages are installed at the base of the GB layer to measure longitudinal and transverse strains along with temperature sensors placed at the top and bottom of the layer. Moisture content probes quantify water content variations. Vertical strain gages monitor deformation levels of the unbound

granular material (UGM). As a result, effects of seasonal moisture content variations can be inferred from the measured deformations.

A scheme of the implementation of accelerometers and anchored displacement sensors for section 2 (granular sublayer) and section 4 (asphalt sublayer) is presented in Figure 3.

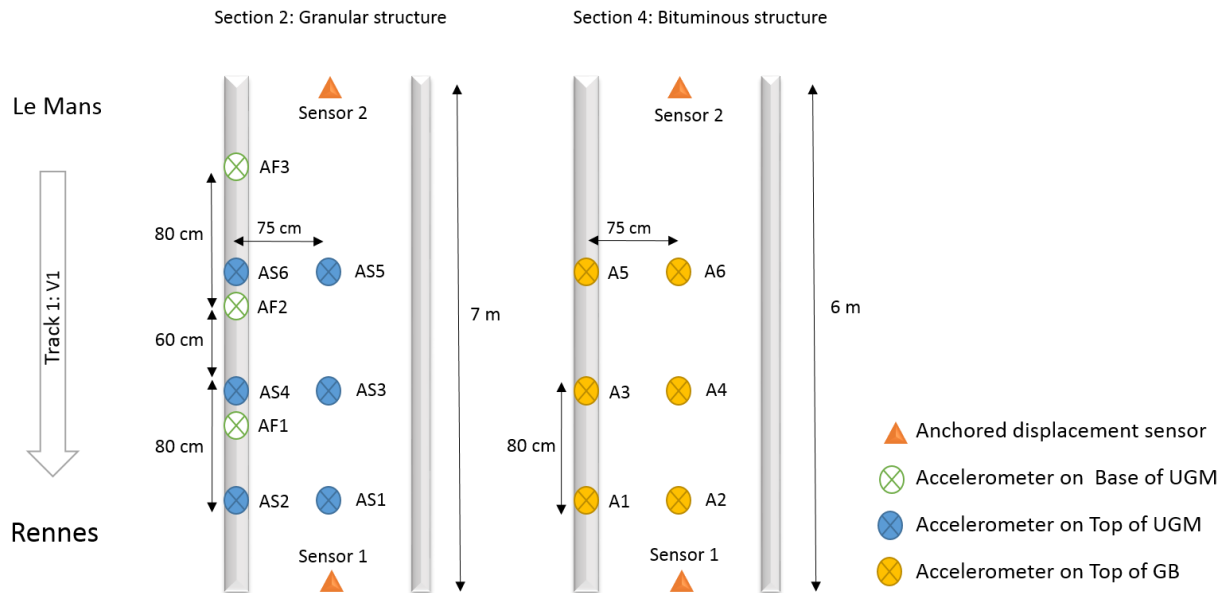


Figure 3 – Sections 2 and 4: instrumentation layout for accelerometers and displacement sensors

At each section's level, two types of measurements are performed: "slow" measurements and "fast" measurements. Slow measurements involve temperature probes, water content probes, weather data and anchored displacement sensors. These measurements are recorded continuously every 5 minutes. Fast measurements include accelerometers, vertical and horizontal extensometers and anchored displacement sensors. Fast measurements are recorded under the passage of trains. They are triggered when the measured acceleration exceeds a certain threshold (threshold set for an accelerometer placed at the top of the first sublayer). The threshold is fixed at a very low value in order to record all train passages. The signal acquisition frequency is 2000 Hz (Khairallah et al., 2017).

On each site, acquisition systems are installed in a weatherproof cabinet resistant to vibrations of trains with 320 km/h velocity. Cabinets are powered by a built-in system (solar panels + batteries) for uninterrupted year-round operation. Based on their performance and previous experience, acquisition systems based on the Pegase platform developed by IFSTTAR (Le Cam et al., 2010) and produced by A3IP were chosen. Saved results on all sections are transferred continuously via 3G network (within few hours at most) to a remote server. Results are stored in a relational database, enabling fast-multi-criteria searches. Acquisition parameters can be configured remotely, through a web application. For each acquisition board, the slow and fast measurements can be visualized in real time.

Data acquisition carried out on BPL HSL is divided in two phases. The first phase, entitled "speed up phase", corresponds to a test phase of the track, before the start of commercial traffic. The passing train characteristics are known, with increasing speeds ranging from 160 to 352

km/h. The train is composed of 13 bogies. The second acquisition phase corresponds to the commercial traffic phase; where the average train speed is 320 km/h, and where different high-speed trains, with different bogie loads and characteristics pass on the track.

### **Data processing during the speed-up test phase**

Before opening the BPL track to commercial traffic, a series of tests were performed on the track, at increasing speeds, between November 2016 and January 2017. These tests were performed with the same high speed train (HST), with known loads, and train speeds varying from 160 Km/h to 352 Km/h. Since the loads were always the same, responses obtained on different sections, and at different speeds, can be easily compared.

A train journey on the BPL railway track generates more than 50 data files that need to be treated and plotted. Scilab, a free numerically oriented programming language is used to automate signal processing.

Different routines and functions have been developed, using Scilab, to complete the following steps, leading to visualization of signals:

- Scale the measurements of the various sensors installed.
- Calculate the speed of the passing HST train at this date.
- Filter the recorded sensor signals using a low pass filter.
- Select the desired sensor(s) to plot their signal(s).
- Visualize the needed time signals.

These steps have been programmed with Scilab for all the sections. The section(s) to study can be selected at the beginning of the data processing program. It is possible to run multiple calculation functions, read data files, scale, filter, calculate velocities, process and plot graphs.

The test train is composed of 8 wagons, with 7 intermediate carrier bogies, with practically identical loads. To evaluate the response of the track to the train loads, it was decided to calculate the average signal, corresponding to these identical bogies. For each sensor signal thus filtered, the cumulative method of carrier bogies is then applied to the HST's seven carrying bogies as shown in Figure 4 on the displacement signal. The filtered signal of a displacement sensor is cut off to isolate the sequences in connection with the seven carrier bogies passage. For each sensor, a statistical treatment is then applied, to calculate the mean curve and the curves corresponding to +/- one standard deviation.

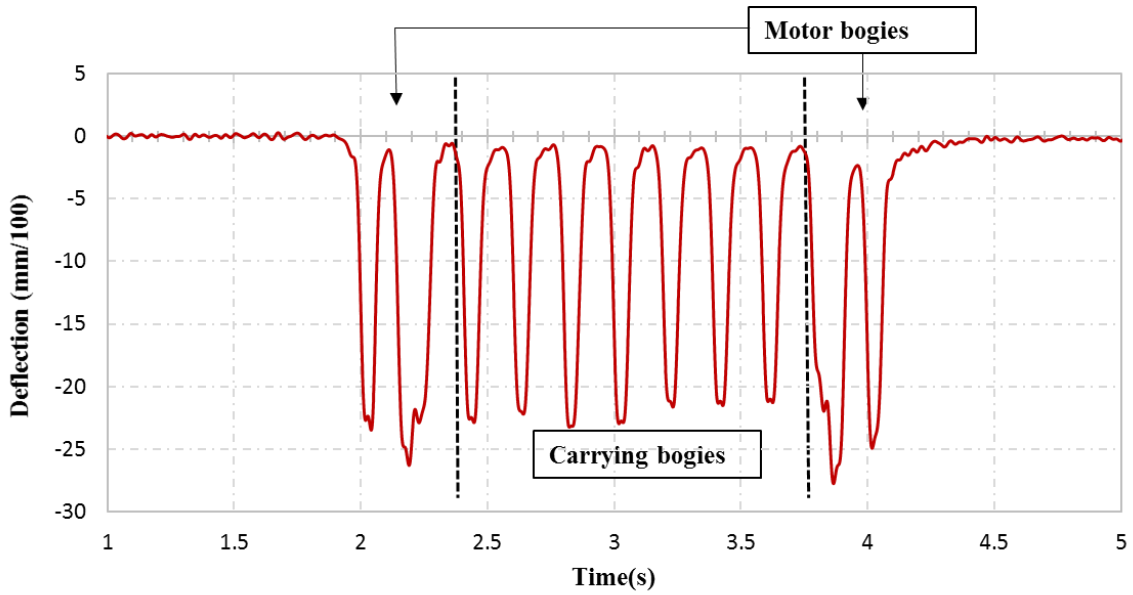


Figure 4 - Filtered displacement signal for a train passage – Train speed 320 km/h

Acceleration (as in Figure 5) and displacement (as in Figure 6) signals corresponding to the 7 carrier bogies of the train have been superimposed on the same graph, and represented as a function of distance (converting the time to distance, using the train velocity). The "average response" of the considered sensor has then been calculated point by point.

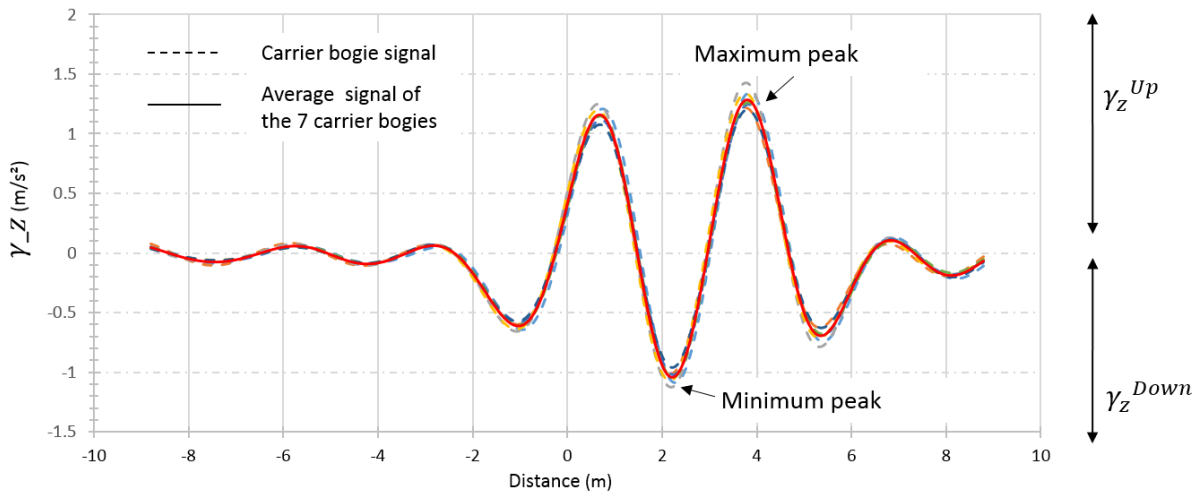


Figure 5 – Superimposed acceleration signals of the seven carrier bogies, and average signal.

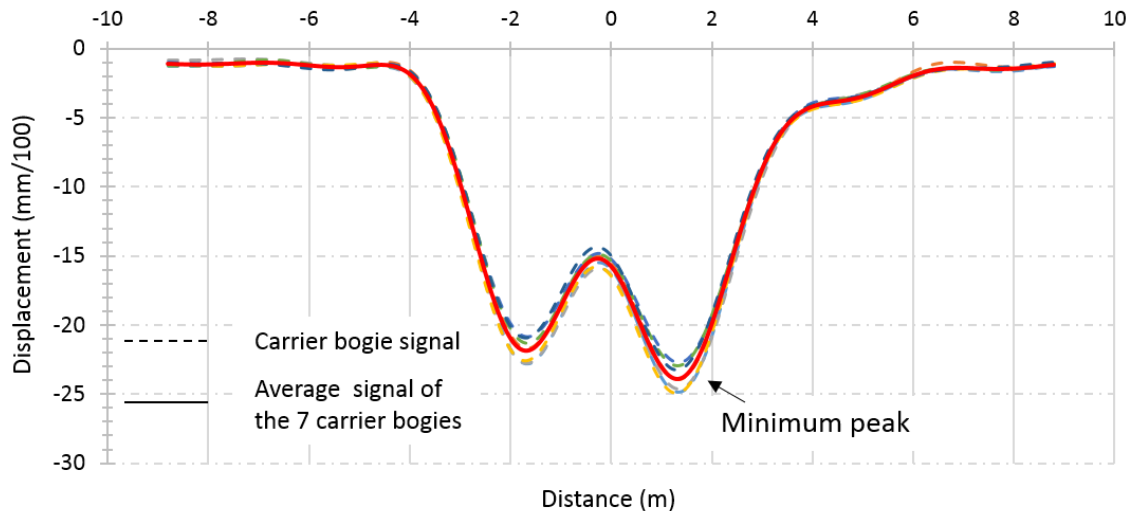


Figure 6 – Superimposed displacement signals of the seven carrier bogies and average displacement signal

## Comparison of the response of the structures with granular and asphalt sublayers

One of the objectives of the project on “Monitoring of the BPL High Speed Line” is to evaluate the behavior of the structures with asphalt sublayers, and to compare it with traditional structures with granular sublayers.

Since the behavior of bituminous materials is strongly dependent on temperature, it is important to note that during the three months of the speed up test phase (between November 2016 and January 2017), only small temperature variations were observed. Temperatures at the top of GB and UGM layer reached at maximum 10°C degrees in November and at minimum 2°C degrees during the coldest days in January. Therefore, temperature variations were neglected in the analysis of the results.

The objective is in particular to compare the maximum downward vertical accelerations generated by the passage of the trains, which have the most damaging effect for the ballast layer, as they reduce the apparent weight of the ballast grains and the inter-granular friction forces (Chupin and Piau, 2011). To compare the response of the two sections, "maximum" positive accelerations (oriented downwards) and "minimum" negative accelerations (oriented upwards) are compared along with the maximum deflections of the track (oriented downwards). These values and the standard deviation are determined from the mean signals of the seven bogies obtained with the Scilab “averaging” procedure.

Figure 7 shows the maximum vertical deflection values measured on sections 2 (granular sublayer) and 4 (bituminous sublayer) as a function of train speed, during the speed up test phase. The displacements obtained on the two sections are very close, and of the order of 25 mm/100. These low and stable deflections are due to the high bearing capacity of the subgrade, which consists of cement treated soil on all the instrumented sections of the BPL line. The results also indicate no significant increase of deflections with speed. For the highest speed, reaching 352 Km/h, maximum deflection values do not exceed 27 mm/100, on both sections.



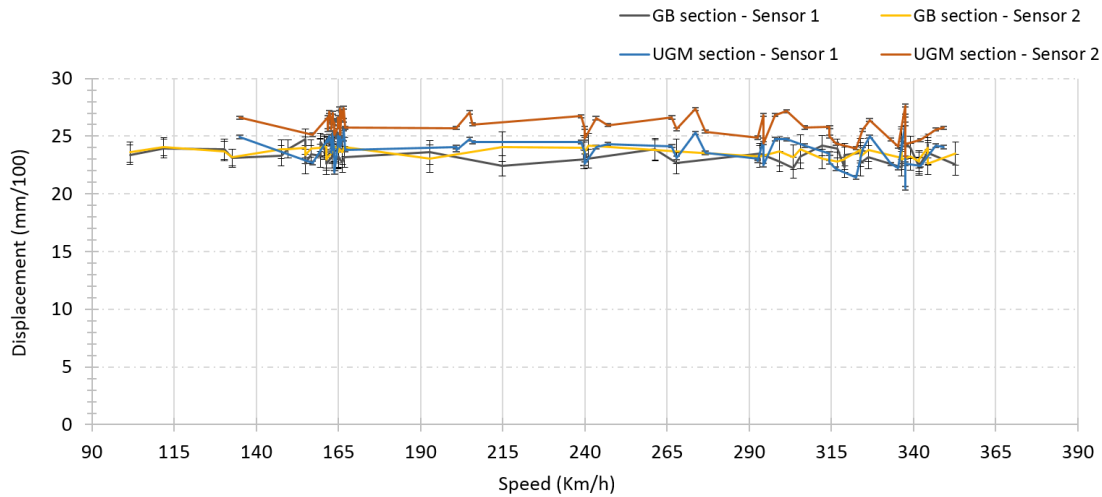


Figure 7 – Variation of vertical deflections, in function of train speed, for the sections with bituminous and granular sublayer.

Figure 8 presents a comparison between the average signals of the anchored displacement sensors on granular section 2 and asphalt section 4, for two trains passing at a speed of 320 Km/h. It can be seen that the shape of the displacement signals is somewhat different and smoother on the asphalt section (blue and red curves), rather than on the granular section (gray and yellow curves). The displacements on the asphalt section show a smaller decrease between the two peaks than on the granular section, where the drop between the two peaks is more important.

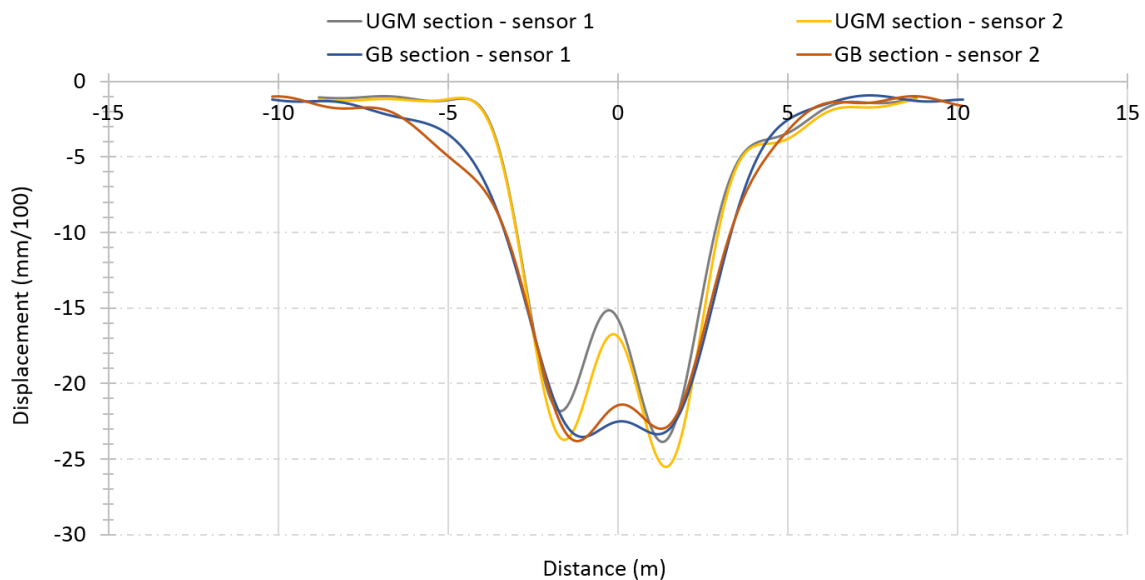


Figure 8 – Average signals of anchored displacement sensors on granular section 2 and bituminous section 4 – Speed 320 km/h.

Figure 9 and Figure 10 present respectively the minimum and maximum accelerations for the accelerometers installed between rails (Figure 9) and under the outer rail (Figure 10).

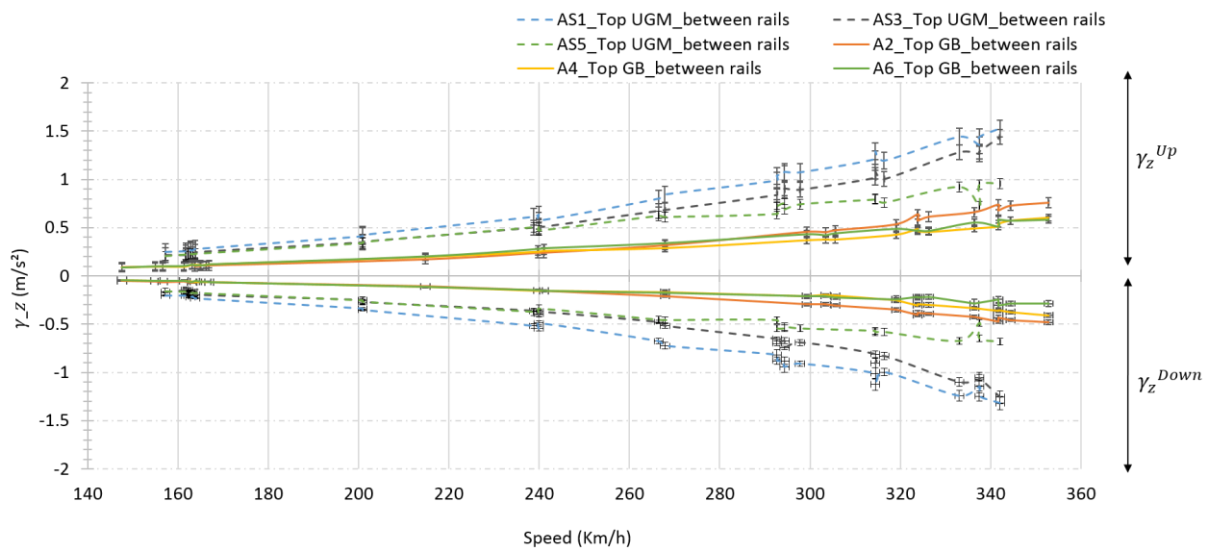


Figure 9 – Comparison of maximum accelerations on the granular and bituminous sections, for accelerometers installed between rails.

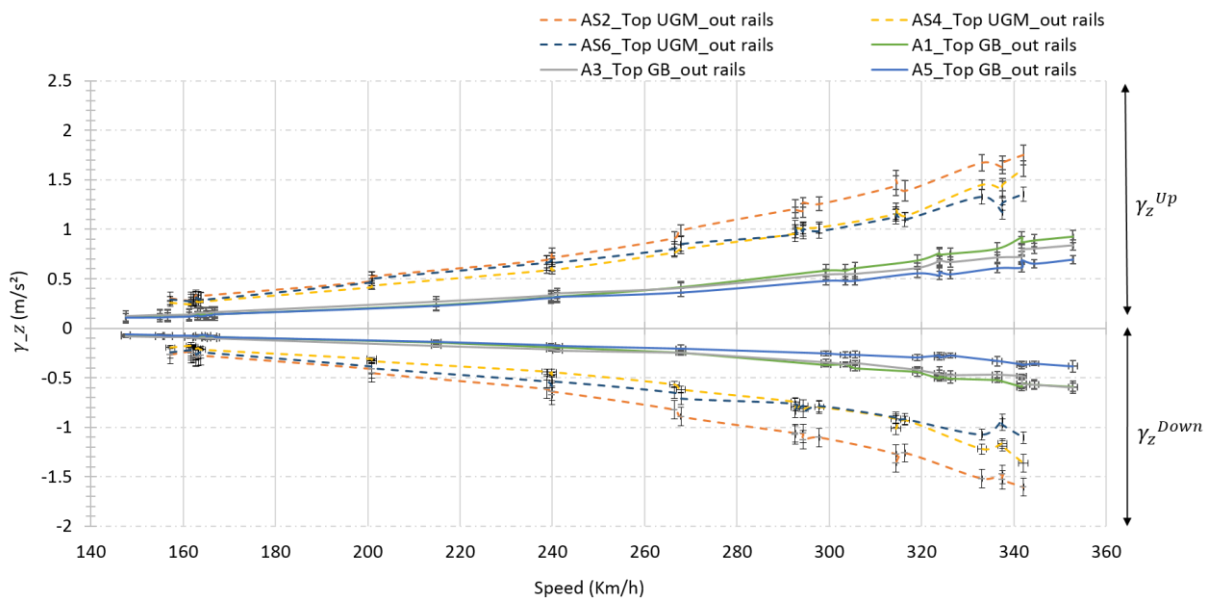


Figure 10 - Comparison of maximum accelerations on the granular and bituminous sections, for accelerometers installed under the outer rail.

The dashed lines represent the accelerometers of the granular section (2) and the full lines those of the asphalt section (4). For all the sensors, and for both upward and downward accelerations, the maximum accelerations at the top of the asphalt concrete sublayer are by far lower than those measured at the top of the granular sublayer. In other terms, from the different curves presented above, it can be concluded that the presence of the asphalt layer in the structure leads to a significant reduction (almost by a factor of two) of the accelerations under the ballast. For the bituminous section, it can also be concluded that the accelerations between rails are lower than those measured under the outer rail. This reduction is not observed on the granular section.

## Conclusion

In order to study the influence of the asphalt sublayer, and the dynamic responses of the various railway structures with asphalt concrete and granular sublayer, four different sections of the “Bretagne – Pays de la Loire” high-speed lane have been instrumented using accelerometers, strain gages, displacement sensors, temperature sensors and moisture probes. The acquisition system is fully remotely controllable and data are transmitted via 3G network.

Programed Scilab routines are used to automate data treatment; filter sensor measurements, calculate train velocities, plot sensor outputs, superimpose signals of individual train bogies and determine curve peaks.

In this paper, evolutions of track vertical accelerations and displacements, as a function of train speeds have been analyzed for two different instrumented track structures: a standard section with granular sublayer and an innovative section with asphalt concrete sublayer. It can be concluded that the presence of an asphalt layer in the structure reduces the acceleration levels under the ballast, which is beneficial for its stability. As for deflection levels, the asphalt concrete sublayer affects the shape of the deflection curves. Other studies are under way to analyse the very large database of results generated by the instrumentation of the BPL line, and in particular also the slow measurements (temperatures, moisture contents, settlements) and the strain gage measurements

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