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Monitoring and modeling of railway structures of the high-speed line BPL with asphalt concrete underlayment

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1 **ABSTRACT**

2

3 High-speed railway lines design and durability constitute major challenges in the railway
4 transportation field. In France, a 40-year feedback on field behaviour of ballasted tracks led to
5 improvement of the design rules. Settlement and wear of ballast, caused by dynamic stresses at
6 high frequency, however remains a major problem on high-speed tracks leading to high
7 maintenance costs. Studies have shown that these settlements were linked to the high accelerations
8 produced in the ballast layer by high-speed trains traveling on the track, disrupting the granular
9 assembly. The high-speed line “Bretagne - Pays de la Loire” (BPL HSL), with varied subgrade
10 conditions, represents the first large-scale application of asphalt concrete (GB) as ballast sublayer.
11 This line includes 77 km of conventional track with a granular sub-layer (UGM) and 105 km of
12 track with an asphalt concrete sub-layer under the ballast. Four track sections were instrumented
13 during construction using, among others, accelerometers, anchored deflection sensors and strain
14 gages.

15

16 This paper presents the instrumentation as well as the acquisition system installed on the track.
17 Data processing is explained first, and followed by a presentation of the ViscoRail software,
18 developed for modelling railway tracks. The bituminous section’s behavior and response is
19 modelled using a multi-layer dynamic response model, implemented in the ViscoRail software. A
20 good match between experimental and calculated results is highlighted.

21

22

23 **Keywords:** Ballasted railways, asphalt concrete, monitoring, railways modeling

1 INTRODUCTION

2 In France, a significant feedback in the field of ballasted high-speed tracks with granular sublayers
 3 allowed to improve the track’s design rules (1). The phenomena of settlement and wear of the ballast, under
 4 dynamic loads, however remain an important problem on high-speed tracks and lead to high frequencies
 5 and maintenance costs. Several studies have shown that these settlements are linked to the high
 6 accelerations produced in the ballast by high-speed trains’ circulation (2). To alleviate the problem, it has
 7 been proposed to insert an asphalt concrete layer under the ballast.

8 The use of asphalt sublayers under the ballast has been identified as a possible solution for
 9 improving track structures. By interposing a semi-rigid layer of asphalt concrete (GB) between the ballast
 10 and the UGM layer, the behavior of the overall structure is greatly improved. This applies to both high-
 11 speed passenger and freight lines. The use of asphalt concrete (GB) in railway construction has emerged in
 12 different countries. Indeed, over the last decade 322 km of sub-ballast layers have been built for new
 13 projects in the Midwestern United States, mainly for heavy freight traffic (3).

14 In 2005, SNCF built a 3 km long test section in the East HSL (LGV Est), linking Paris to Strasbourg,
 15 with a GB sublayer. The data retrieved from this first instrumented test indicated satisfactory performance
 16 of the experimental railway section (4-5). The presence of the asphalt sublayer has proven to reduce the
 17 aggressiveness of the loading applied by passing trains, leading to an increase of the structure durability.
 18

19 **TABLE 1. Structure of the sections with and without asphalt concrete**

Conventional track	Innovative track with GB sublayer
30 cm of ballast	30 cm of ballast
20 cm of UGM layer	12 cm of GB4 layer
35 cm of earthwork treated layer (EV2 = 80 MPa)	15 cm of UGM layer
Earthwork treated layer (EV2 = 80 MPa)	Earthwork treated layer (EV2 = 80 MPa)

20
 21 The high-speed line Bretagne - Pays de la Loire (between Rennes and Le Mans, in the West of
 22 France) is the first large-scale application in France of the new asphalt sub-layer technique, with varied
 23 subgrade conditions, and using a high-performance asphalt concrete (GB4). 105 km of track were built with
 24 an asphalt sublayer under the ballast on its east route while the remaining 77 km have a classical granular
 25 sub-layer (UGM) on its west route. An asphalt concrete of class 4 (GB4), according to French standard NF
 26 EN 13-108-1, has been used for this project. The unbound granular material (UGM) has a particle size
 27 0/31.5 mm, and is of type A, according to French specifications. The innovative track structure, described
 28 in **Table 1**, includes the upper part of the earthworks (PST), which is treated with lime and hydraulic
 29 binders. The PST is surmounted by a 15 cm thick Unbound Granular layer (UGM), and a 12 cm thick
 30 asphalt layer. The standard structure comprises a 20 cm thick granular sublayer in addition to a cement-
 31 treated subgrade layer.

32 In order to compare the responses of these different structures, two sections, with granular sub-
 33 layer and with bituminous sub-layer were instrumented. The aim of this instrumentation is to monitor and
 34 compare the mechanical response of these two types of structures used on BPL HSL, by measuring
 35 accelerations, sub-ballast structure displacements, horizontal and vertical deformations and temperatures in
 36 different layers, and also water contents at the top of the subgrade.

37 Data acquisition and analysis started at the end of 2016, when trains were first put into circulation
 38 (for a test phase). The line was opened to commercial traffic in July 2017 with trains travelling at a speed
 39 of 320 km/h.

This paper focuses on the measurements and results of the sections with asphalt concrete sublayers.

INSTRUMENTATION OF HSL BPL

Sensors

The choice of sensors was made by IFSTTAR, drawing on its experience in the field of pavement monitoring. Section 4, with a bituminous sub-layer, is instrumented with 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.

Accelerometers, used to monitor the track's dynamic behavior, are positioned at several levels: under the sleepers and at the top of the asphalt concrete layer. The anchored sensors measure the structure's total vertical displacement under the ballast (GB + granular layer + subgrade for section with bituminous sublayer). Temperature probes are placed at the base and at the top and bottom of the GB layer, to monitor temperature variations. 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 plan showing the positions of accelerometers and anchored displacement sensors on section 4 (asphalt sublayer) is presented in **Figure 1**.

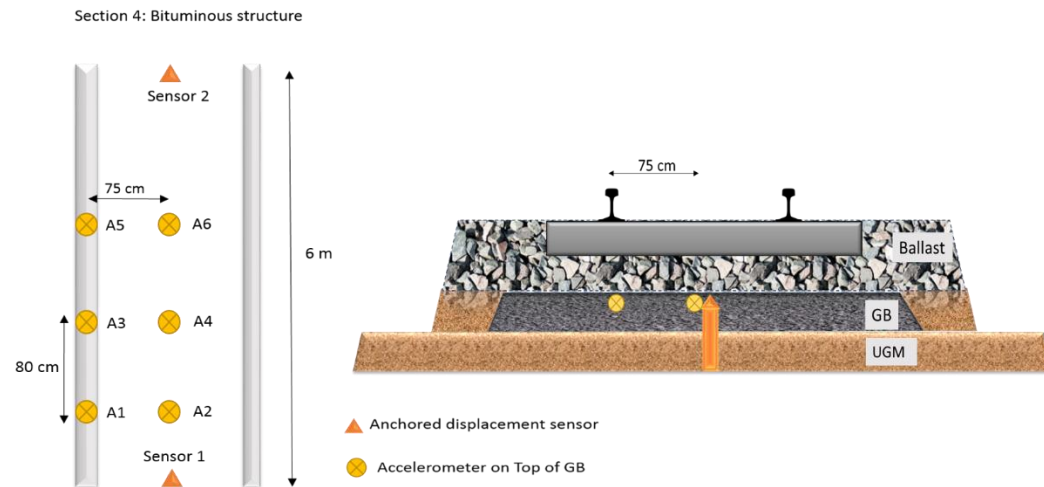


Figure 1 Section 4: instrumentation layout for accelerometers and displacement sensors

Data acquisition system

Based on its performance and experience feedback, the data acquisition systems installed on each instrumented section are based on the Pegase platform developed by IFSTTAR (6). Generic Experts Platform for Embedded Wireless Applications (PEGASE) is a concept derived from intelligent and wireless instrumentation. This system has been designed to support instrumentation needs such as wireless communication, dating, signal processing. As an example, on section 4 (with bituminous under layer), there are 5 Pegase data acquisition boards: two 0-10V input boards for the 16 accelerometers, a strain-gauge bridge board for the 6 vertical gauges and two temperature sensors, one RS232 input board for the 4 moisture probes, and a strain-gauge bridge board for two anchored displacement sensors.

For all sections, the systems are fully autonomous in electricity. The power supply is provided by solar panels and batteries, for continuous year-round operation without interruption. Each system supports its connected sensors. Collected data on each section is transferred continuously via 4G network (within a few hours maximum) to a remote server. Each system is autonomous in energy and data transmissions. Results are stored in a relational database, enabling fast-multi-criteria searches. For each data acquisition board, one can visualize, in real time, slow and fast measurements associated with each sensor of the resource.

1 At each section's level, two types of measurements are performed: "slow" measurements and "fast"
2 measurements. Slow measurements concern temperature probes, water content probes, weather data and
3 anchored displacement sensors. These measurements are recorded continuously every 5 minutes. Fast
4 measurements include accelerometers, vertical and horizontal extensometers and anchored displacement
5 sensors. Fast measurements are recorded under the passage of trains. They are triggered when the measured
6 acceleration at the top of the first sublayer exceeds a certain threshold level. This level is set at a very low
7 value, in order to record all train passages. The signal acquisition frequency is 2000 Hz (7).
8 The measurements made on the BPL HSL can be divided in two phases. The first phase, entitled "speed
9 up phase", corresponds to a 3 months test phase of the track, between November 2016 and January 2017,
10 before the start of commercial traffic. During this phase, the same train, with known characteristics (10
11 cars, 13 bogies), circulated on the track at increasing speeds, ranging from 160 to 352 km/h. The second
12 acquisition phase corresponds to the commercial traffic phase, where the average train speed is 320 km/h,
13 and where different high-speed trains, with different bogie loads and characteristics pass on the track. The
14 results presented in this paper concern only the speed up phase. Comparisons between results obtained on
15 the two structures, with granular and asphalt concrete sublayers, are detailed in (8).

16 17 **DATA PROCESSING**

18 A train journey on the BPL railway track generates more than 50 data files that need to be treated
19 and plotted. In view of the large amount of data recorded, it was essential to develop procedures for
20 automating data processing. Scilab, a free numerically oriented programming language was therefore used
21 to automate signal processing. Several routines were programmed, to determine the date and the exact time
22 of each train's passage, to calculate the train velocities, to filter the recorded sensor signals using a low pass
23 filter and finally to plot them.

24 After selection and filtering, a method called "superposition of carrier bogies" is used to process
25 the measurements. Based on the recordings made, for a given sensor, for a train passage at a known speed,
26 the procedure consists in separating the signals corresponding to each carrier bogie (excluding the motor
27 bogies), and plotting them from the same time origin. It is thus possible, for each sensor, to calculate the
28 mean curve and the curves corresponding to +/- one standard deviation. From these mean curves,
29 maximum accelerations and displacements, corresponding to a train passage, can be calculated and used
30 for comparing the response of different structures. This processing method has been automated using
31 Scilab, for the two instrumented sections.

32 To illustrate this processing method, **Figure 2** presents an example of typical vertical displacement
33 (or deflection) signals and vertical acceleration signals recorded on section 2, with a granular sub-layer, for
34 a train speed of 320 km/h. **Figure 2a** shows the deflection signals, corresponding to the 7 carrier bogies,
35 and the calculated average signal. **Figure 2b** shows similarly the 7 acceleration signals, and the calculated
36 average signal. On these figures, positive values correspond to upwards accelerations and displacements.

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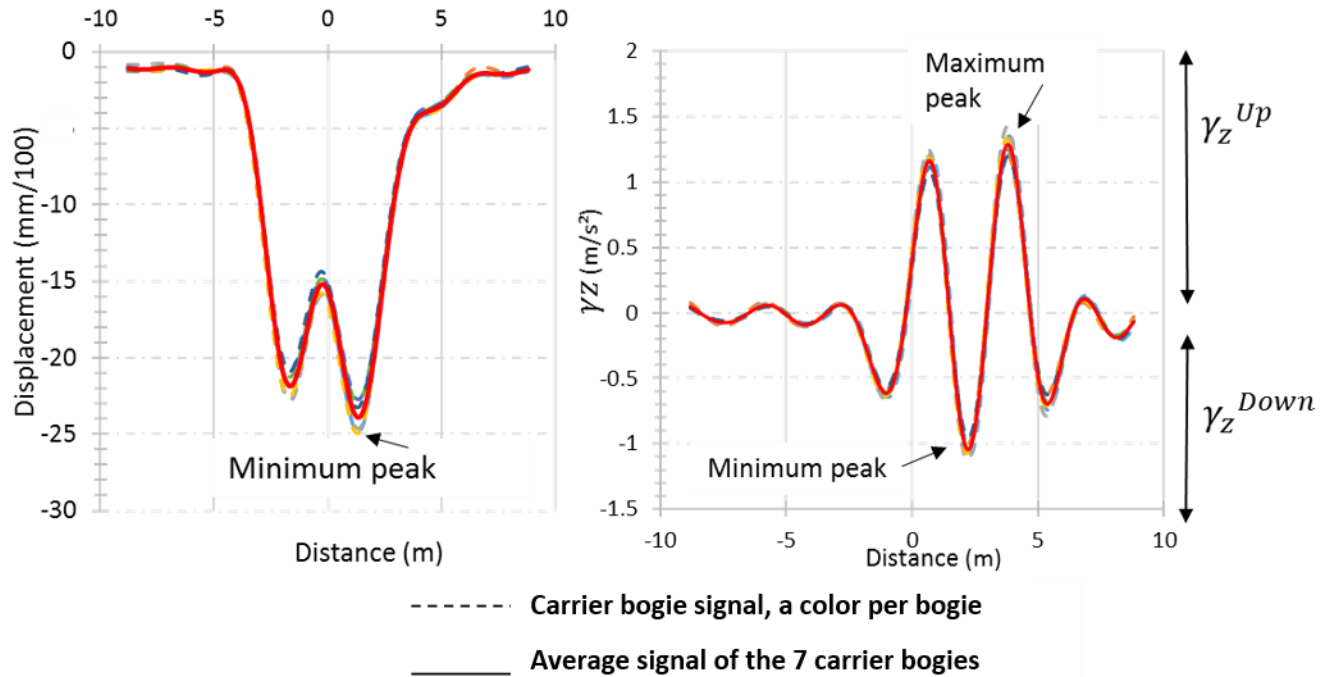


Figure 2 Typical vertical displacement and vertical acceleration signals recorded under the seven carrier bogies, and calculated average signals, for a train speed of 320 km/h

For the analysis of the results, it is also important to highlight that the speed up phase was carried out between November 2016 and January 2017. Temperature variations during this period were limited. The average temperature in the asphalt concrete layer was $7\text{ }^{\circ}\text{C} \pm 1$ (with a minimum temperature of $2\text{ }^{\circ}\text{C}$, and a maximum temperature of $10\text{ }^{\circ}\text{C}$). Therefore, it is possible to compare all the signals recorded during this period, neglecting the influence of temperature variations on the stiffness of the asphalt layer.

MODELLING OF THE MECHANICAL RESPONSE OF THE SECTION WITH ASPHALT CONCRETE SUBLAYER USING THE VISCORAIL SOFTWARE

Main principles of ViscoRail

ViscoRail (9-10) is a semi-analytical calculation code dedicated to the determination of the dynamic response of railway structures under moving loads (at constant magnitude and speed). This numerical program is well adapted to the simulation of railways incorporating either granular or asphalt layers as encountered on HSL BPL. The method implemented in this tool (9-10) extends the quasi-stationary approach used for road pavements and adopted in ViscoRoute© 2.0 (11) to the case of railways for which the load transfer to the infrastructure is performed through sleepers discontinuously distributed along its surface. As shortly explained further, this method is based on a specific decomposition of the pressure distribution under the discrete supports which makes it possible to consider the assumptions related to the quasi-stationary approach.

ViscoRoute© 2.0 is a numerical program that solves the equations of motion for semi-infinite layered media subjected to constant moving loads. The problem of quasi-stationary motion is solved in the reference frame ($X = x - Vt$) moving simultaneously with the loads. In this calculation code, the structural layers are assumed homogeneous and their constitutive behavior can be set as isotropic linear elastic (Hooke's law) or as viscoelastic according to the Huet–Sayegh thermosensitive model (12-13). The latter is particularly well suited for asphalt materials. This model is represented by a purely elastic spring in the first branch

1 connected in parallel to two parabolic dampers in series with an elastic spring in the second branch. Either
2 sliding or fully bonded interfaces between the layers can be considered (14).
3 ViscoRail extends the original ViscoRoute© 2.0 software in the sense that it also integrates the track system
4 composed of the rail and the sleepers. The solving method in ViscoRail is based on a sub-structuring
5 procedure that consists in splitting the initial model (railway track and structure) into two subsystems and
6 in solving the global response iteratively (fixed-point iteration). The first subsystem that corresponds to the
7 rails secured on the periodically positioned sleepers is modelled by Euler-Bernoulli beams and vertical
8 springs. The second subsystem (or sub-structure) representing the multilayer track structure is modelled as
9 a stacking of semi-infinite layers. The connection between these two subsystems is made through the
10 vertical stress distribution $p(x, t)$ under the sleepers (at the interface between the subsystems), which is
11 straightly correlated to the load transfer across the track system. In the solving process, $p(x, t)$ is first
12 initialized arbitrarily prior to running the iterative process that matches this pressure distribution with that
13 resulting from the dynamic response of the global coupled system after convergence. The mechanical
14 response of the railway structure to a moving train loading is that obtained once $p(x, t)$ has converged.
15 Note that at each iteration, the dynamic response of the sub-structure to $p(x, t)$ is computed using
16 ViscoRoute© 2.0 after an ad hoc decomposition of this pressure distribution into “loading waves” has been
17 performed to conform to the quasi-stationary assumption. The solution is then obtained by recombination
18 of the individual contribution due to each loading wave. The reader is referred to (10) for more detail on
19 this technique.
20 Output results from ViscoRail allow us to plot the spatial and temporal evolutions of the various mechanical
21 fields in the structure (displacements, accelerations, strain and stress fields, etc.), for any horizontal plane
22 located at a given z-coordinate.
23 Some advantages of ViscoRail are that the computation time is small because of the semi-analytical
24 approach and viscoelasticity of asphalt concrete layers can be considered. Moreover, this is a tool of simple
25 use that facilitates the pre- and post-treatment phases, as compared to finite element computations or
26 example.

27 **Inverse calibration of the model parameters**

28 The modelling of HSL BPL structures by means of ViscoRail requires defining the model input parameters
29 which are not all measured on site (e.g. the Young modulus of UGM or soil...). Layers modulus values used
30 for the design of track structure ($E_{ballast} = 200 \text{ MPa}$, $E_{UGM} = 3 \times E_{soil} = 240 \text{ MPa}$, $E_{CF} = 240 \text{ MPa}$,
31 $E_{soil} = 80 \text{ MPa}$) weren't qualified to reproduce the track's mechanical response. True sensors data were
32 nowhere near computed results with ViscoRail. Thus, the model input parameters are obtained from back
33 calculation by minimizing the gap between the simulated response and that recorded by the instrumentation.
34 To accomplish this, the measurements stemming from the granular section (deflections, strains and
35 accelerations at different locations) for train velocities $V = 160$ and 320 km/h are selected.
36 The model parameters to be determined are the Young moduli of the different layers and the stiffness of
37 the rail pads. The values of these parameters are bracketed within ranges of variation that we define as
38 acceptable for the problem under consideration:

- 39
40
- 41 - Modulus of the ballast $E_{ballast}$ between 150 and 600 MPa
 - 42 - Modulus of the granular sublayer E_{UGM} between 200 and 1000 MPa
 - 43 - Modulus of the cement-treated capping layer E_{CF} between 400 and 5000 MPa
 - 44 - Modulus of the subgrade E_{soil} between 80 and 200 MPa.
 - 45 - Stiffness of the rail pads k between 50 and 150 MN/m.
- 46

47 Then, series of ViscoRail calculations are performed for different combinations of parameters values picked
48 out in the ranges defined previously, until a good match between the simulation results and the
49 measurements is reached. The following set of parameters leading to satisfactory results for the two
50 velocities $V = 160 \text{ km/h}$ and $V = 320 \text{ km/h}$ is obtained:

51

$$\left\{ \begin{array}{l} E_{ballast} = 250 \text{ MPa} \\ E_{UGM} = 860 \text{ MPa} \\ E_{CF} = 2750 \text{ MPa} \\ E_{soil} = 160 \text{ MPa} \\ k = 100 \text{ MN/m} \end{array} \right\}$$

Later on, these track components are tested for adequate results outcome when it comes to other train speeds.

In a second step, it is considered that the stiffness of the granular materials and of the subgrade is very similar on all the sections of the HSL BPL. Therefore, the elastic moduli determined previously on the granular section are assumed also valid for the asphalt section for which a layer of asphalt material (GB4) is simply added under the ballast. The behavior of the asphalt layer is modelled using the Huet-Sayegh viscoelastic model whose parameters are determined from complex modulus tests performed in the laboratory. The parameter values are given in **Table 2** and are kept the same in all the simulations.

TABLE 2. Huet-Sayegh model parameters for the bituminous layer

E_{∞} (MPa)	E_0 (MPa)	k	h	δ	τ_0 (s)	$A1$ ($^{\circ}\text{C}^{-1}$)	$A2$ ($^{\circ}\text{C}^{-2}$)
32655	11	0.193	0.592	2.244	18.973	-0.397	0.00195

The complete characteristics of the track section with asphalt sublayer determined by this calibration process are given in **Table 3**.

TABLE 3. Geometric and mechanical characteristics of the asphalt track structure model

	ρ ($\text{kg}\cdot\text{m}^{-3}$)	E (MPa)	ν	e (m)
Ballast	1800	250	0.4	0.3
GB sublayer	1800	Huet-Sayegh model	0.4	0.12
UGM layer	1800	860	0.4	0.15
Capping layer	1800	2750	0.4	0.35
Subgrade	1800	160	0.4	6
Bedrock	1800	$100\cdot 10^3$	0.4	∞

Comparison of ViscoRail calculation results with real measurements

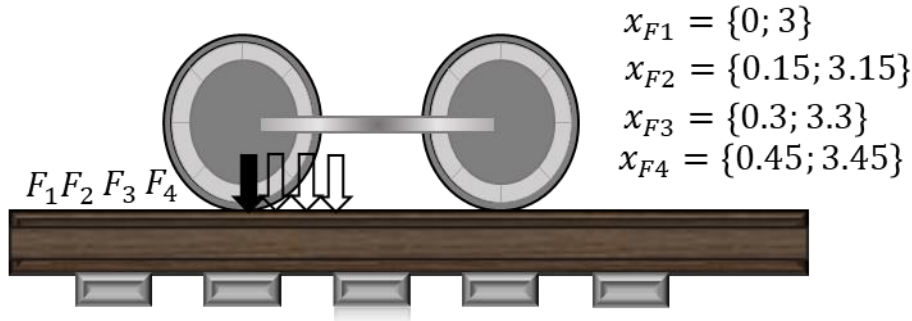
After determining the model parameters, calculations with ViscoRail are performed for the section with an asphalt sub-layer and compared with the sensor measurements.

Data processing routines filter the measurements using a low-pass filter adjusted according to the train velocity. The applied filter eliminates the dynamic effects observed at high frequencies linked to unsprung masses dynamics. We thus obtain data signals comparable to theoretical signals computed with ViscoRail, assuming the applied load as constant intensity load.

The cut-off frequency f_c is thus calculated as a function of the 3 meter "wheel" wavelength and the train speed. As it happens, the "wheel" frequency is the frequency at which one point of the wheel (and therefore possibly the defect point) comes into contact with the rail, $f_c = V/2\pi R$. The frequency obtained is increased by 10% to avoid any significant signal loss.

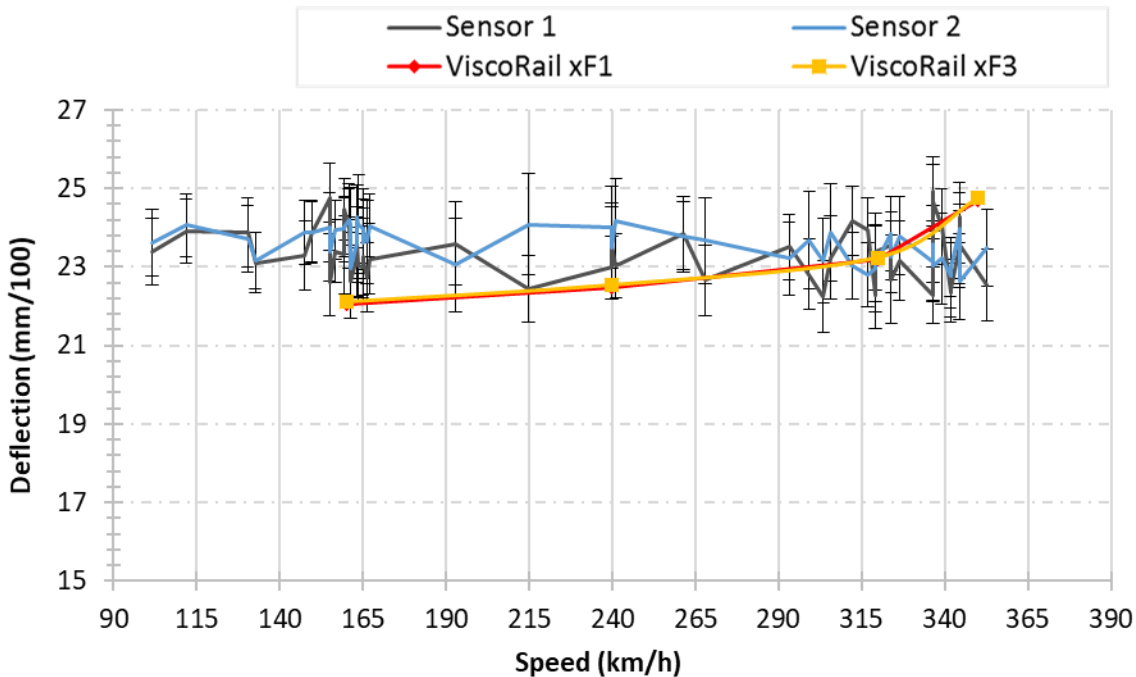
Furthermore, ViscoRail computations are performed for four different traffic speeds: $V = 160, 240, 320$ and 350 km/h, and for a typical high-speed train carrier bogie composed of two axles spaced 3m apart and loaded at 160 kN each (80kN per wheel).

1 The longitudinal profiles can be calculated using ViscoRail for four different load instants, corresponding
 2 to the following positions x_{Fn} of the bogie's two axles, occupying identical relative positions with respect
 3 to the track as seen in **Figure 3**: wheels above the center of the sleeper: $x_{F1} = \{0; 3\}$ m, above the left edge
 4 of the sleepers: $x_{F2} = \{0.15; 3.15\}$ m, above midpoint between the sleepers: $x_{F3} = \{0.3; 3.3\}$ m and above
 5 the right edge of the sleeper: $x_{F4} = \{0.45; 3.45\}$ m.
 6 In the carried calculations and for every train speed, two different wheel positions are considered: position
 7 x_{F1} and position x_{F3} .
 8



9
 10 **Figure 3 Consecutive load positions (x_{Fn}) considered in the calculations**

11
 12 *Comparison in terms of deflection*



13
 14 **Figure 4 Comparison of maximum deflection between predicted values with ViscoRail for $x_F = \{0;3\}$ and $x_F = \{0.3;3.3\}$, and measured values with anchored deflection sensors**

15
 16
 17 The curves in **Figure 4** compare the maximum deflection measured on the asphalt section with the two
 18 anchored deflection sensors, and the deflections values calculated with ViscoRail, for 4 train velocities
 19 $V = 160, 240,$ and 350 km/h. It can be seen that the deflections measured are low (between 0.21 and 0.25
 20 mm). The measurements recorded indicate no variation of the deflection level with speed. The maximum
 21 values of deflection calculated with ViscoRail for two-wheel positions (on the sleeper and between two

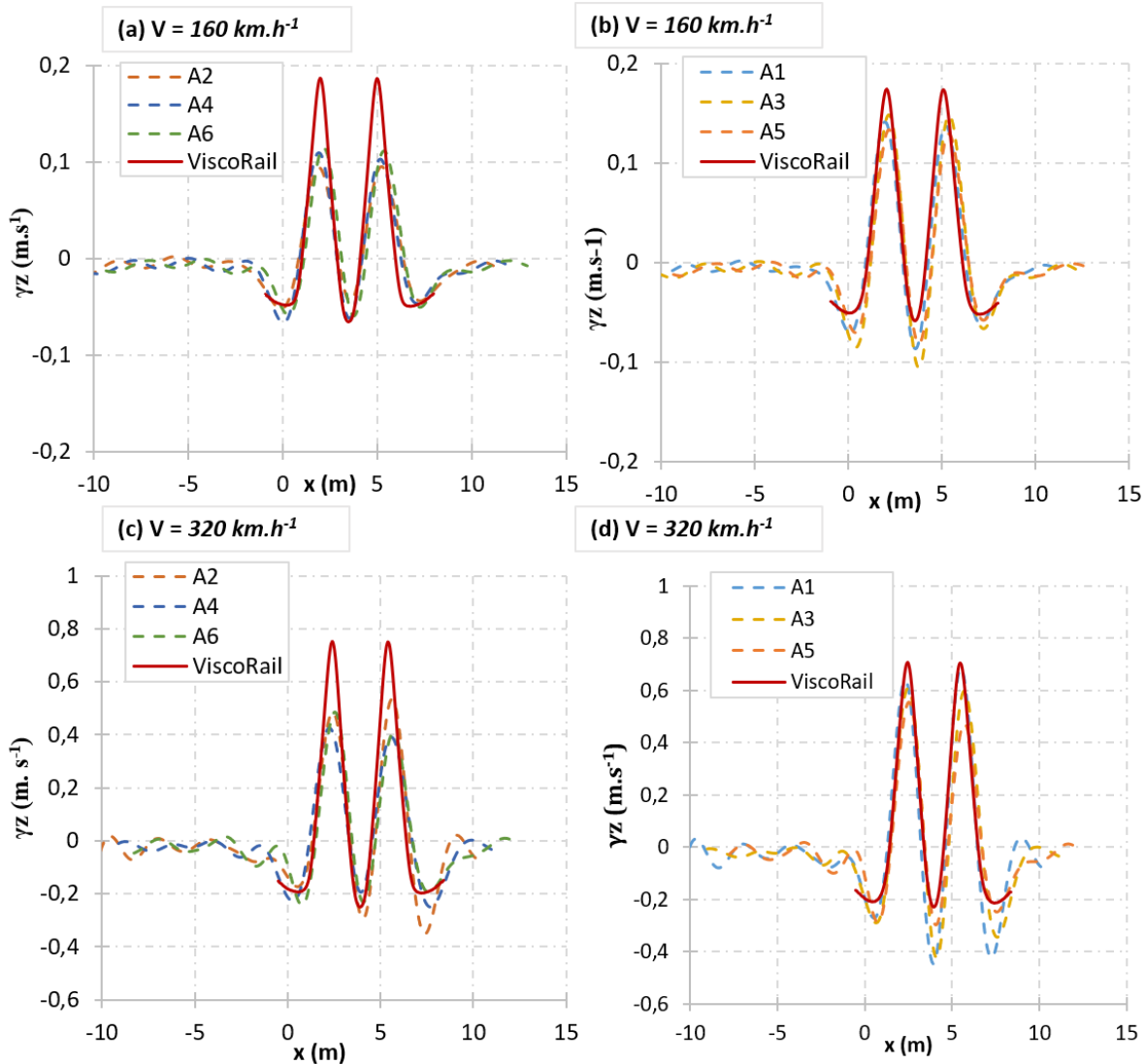
1 sleepers) are very close to the experimental curves, although the model predicts a very slight increase of
 2 deflection with speed.

3 *Comparison in terms of vertical acceleration*

4
 5 The vertical acceleration signals obtained from ViscoRail are compared with those from the accelerometers
 6 located at the top of the GB layer in the asphalt section for two train speeds: $V = 160$ and 320 km/h.

7 **Figure 5** compares the average signals of accelerometers A2, A4 and A6 located between the rails (graphs
 8 (a) and (c)), and of accelerometers A1, A3 and A5 located under the axis of the rail (graphs (b) and (d))
 9 with the modelling results. The graphs show that ViscoRail predicts correctly the accelerometer signals
 10 both in shape and in amplitude for the two speeds. The predictions seem somewhat better for the
 11 accelerometers located under the rails (graphs (b) and (d)).

12

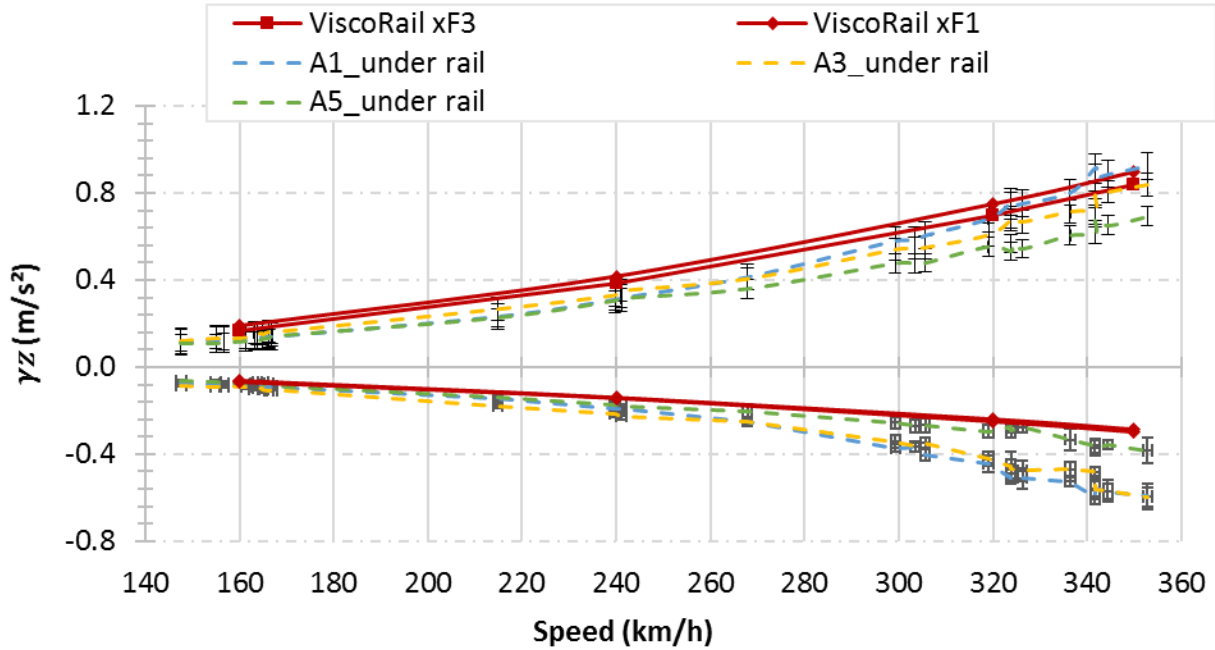


13 **Figure 5** Comparison between predicted and measured longitudinal acceleration profiles at the top
 14 of the GB layer (a) between the rails at $V = 160$ km/h, (b) under the rail axis at $V = 160$ km/h, (c)
 15 between the rails at $V = 320$ km/h, (d) under the rail axis at $V = 320$ km/h

16
 17
 18 To illustrate the effect of the train speed on the vertical acceleration in the track structure, **Figure 6** presents
 19 a comparison between the maximum measured and calculated values of the upward and downward

1 accelerations recorded at the top of the GB layer under the rail axis, for speeds varying between 160 and
 2 352 km/h. Again, the calculations are carried out for two load positions $x_{F1} = \{0; 3\}$ m and $x_{F3} = \{0.3; 3.3\}$
 3 m. The ViscoRail software estimates well the levels of vertical acceleration under the ballast layer as a
 4 function of speed and reflects well the nonlinear trend. Similar calculations (not presented in detail here)
 5 performed for the structure with a granular sub-layer show that ViscoRail also predicts correctly the 2-fold
 6 reduction in ballast accelerations associated with the introduction of the bituminous layer.

7
8



9
10

11 **Figure 6 Comparison of measured and predicted maximum accelerations at the top of the GB layer**
 12 **under the rail axis, on the asphalt section, for two load positions, $x_{F1} = \{0; 3\}$ and $x_{F3} = \{0.3; 3.3\}$**

13

14 **CONCLUSIONS**

15 Two sections of the BPL high-speed line, with granular sub-layer and asphalt sub-layer
 16 have been largely instrumented, to study their mechanical response, under high-speed train loading. The
 17 measurements, made for speed levels varying between 160 and 352 km/h have shown that the introduction
 18 of a bituminous sub-layer under the ballast reduces significantly (approximately by a ratio of two) the
 19 vertical accelerations under the ballast.

20 The behavior of the two sections was modeled using the ViscoRail software, developed for the
 21 prediction of the dynamic behavior of railway structures, and based on a multilayer model, considering
 22 elastic and viscoelastic behavior. A calibration procedure has been developed to determine the model
 23 parameters from sensor measurements at two speeds, 160 km/h and 320 km/h. After calibration, good
 24 predictions of the response of the two structures have been obtained. Vertical acceleration, deflection and
 25 vertical deformation have all been well reproduced, for the granular and bituminous sections, and for a wide
 26 range of speeds. The differences in maximum accelerations between the granular and bituminous sections
 27 were also confirmed by the calculations.

28 All these results are very encouraging, and confirm that the model of ViscoRail predicts correctly
 29 the response of ballasted track structures, with and without bituminous sub-layers. ViscoRail therefore
 30 appears as an efficient tool for fast calculations of the response of railway structures, for design applications,
 31 or parametric studies. In particular, it can be used to calculate mechanical parameters like acceleration
 32 levels in the ballast layer, which could be used as a criterion to evaluate the stability of the ballast (i.e. the

1 risk of settlements), and the maximum tensile strains in the asphalt layer, which can be used to evaluate its
2 fatigue life.

3

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7

8 **AUTHOR CONTRIBUTIONS**

9 The authors confirm contribution to the paper as follows:

10 Study conception and design: Diana Khairallah, Olivier Chupin, Jean-Michel Piau;

11 Data collection: Diana Khairallah; analysis and interpretation of results: Diana Khairallah, Juliette Blanc,
12 Pierre Hornych

13 Draft manuscript preparation: Diana Khairallah, Olivier Chupin, Juliette Blanc, Pierre Hornych.

14 All authors reviewed the results and approved the final version of the manuscript.

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