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Monitoring of railway structures with bituminous and granular sub-layers: assessment after four years of use

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Abstract

Tamping and ballast wear, due to dynamic stresses, lead to frequent and costly maintenance operations. To mitigate the impact, an innovative track structure combining a bituminous (asphalt concrete) layer below the ballast has been built on the Bretagne-Pays de la Loire High-Speed Line (BPL HSL). The track is intended to reduce the amplitude of the accelerations produced by passing High-Speed Trains (HST) which are the main reason for the settlement of ballast. BPL HSL includes 105 km of asphalt concrete sub-layer below the ballast and 77 km of granular sub-layer. In order to study the dynamic responses of these different structures, some track sections have been instrumented with anchored deflectometers, accelerometers, strain gauges and temperature probes. The aim of this paper is to present the results achieved after four years of commercial traffic. The data processing methods developed for this acquisition phase and the measurements of the substructure deflection, the vertical accelerations under ballast, and the vertical and horizontal strain of the various sections were presented. Deflection measurements, vertical strains and vertical accelerations peaks at the top of the sub-layer are compared between the granular and the bituminous track structures and shows that there is no evolution of the measurements during the four years of monitoring. The study clearly demonstrated that the presence of the bituminous layer in the structure reduces the acceleration levels under the ballast that cause its deterioration. Such conclusions suggest that a bituminous sub-layer might contribute to lower track maintenance needs over the service life of the line, decreasing operational costs and increasing capacity.

1. Introduction

Bituminous mixtures are mainly used in road pavement applications. However, the use of bituminous materials, in particular asphalt concrete (GB), as sub-layers under the ballast, has emerged as a possible solution for improving railway tracks' durability in different countries [1-6].

Mostly used for the construction of new high-speed lines (HSL) in western Europe, bituminous sub-layers have been observed to constitute trackbeds with high levels of flexibility and bearing capacity, which are needed to achieve safe and comfortable ride quality at high speeds (V > 220km/h) [7-8]. Used as a structural element of the trackbed, replacing the conventional unbound granular material (UGM) sub-layer, asphalt concrete provides a uniform bearing capacity layer that increases the track's safety and structural reliability. Indeed, bituminous track experiences in Italy and France, dating of as early as 1977, have presented excellent mechanical behavior and durability, equivalent to or even better than conventional tracks built with granular materials. Moreover, rutting does not seem to be an issue for bituminous sub-layers, as implied by the high stability of the track geometry in the Italian and French HSLs. For example, the manager of the Italian "Direttissima" HSL avoided mandatory sub-layer renewal works as a result of verifying the excellent state of the bituminous layer after 25 years of track service [9-12].

Bituminous sub-layers have also proven to be adequate for low speed and heavy load train traffic, which are characteristic of the North American railway industry. Mostly used in the United States during renovation projects on existing tracks, many examples found in the literature give evidence of the effectiveness of using asphalt concrete to treat track sections with weak subgrade-related problems [13].

Besides providing a reliable support for the track, asphalt concrete has also been found to reduce the amplitude of the acceleration levels induced by high-speed trains in the ballast layer [14,15], and to attenuate the solid-borne vibrations transmitted to the embankment, thanks to its damping properties. It also provides an impermeable drainage layer, minimizing the risks related to ballast fouling and to freeze-thaw action on the soil. Moreover, during the construction phase, the bituminous sub-layer offers a platform with very good bearing capacity facilitating the circulation and operation of engines [4, 6, 8- 9, 11-12, 16-20].

Compared to cement-bonded materials, asphalt concrete offers a stiff support that can be loaded shortly after being built, which is advantageous for upgrading and rehabilitation track works (Rose, 2017). It also provides higher flexibility to the track system, which is beneficial for increasing traffic speeds.

The "Bretagne - Pays de la Loire" high-speed line (BPL HSL) is one of the 4 recent major railway projects built in France with private-public partnership, and the largest-scale application of bituminous sub-layers in France. The choice of building more than half of the new track (150km) with a French GB4 sub-layer was mostly based on economic reasons, particularly the lower global price (including transport) of the asphalt compared to conventional granular materials. Later on, during the design and construction phases, the GB4 layer turned out to provide several of the above-cited advantages of using bituminous sub-layers, which increased the economic advantage of the bituminous track structure respect to a granular one [6].

The BPL HSL combines several platform compositions: 77 km of conventional track with a granular ballast sub-layer and 105 km of bituminous underlayment (Figure 1).

Given the exceptional length of the BPL bituminous track structure, it constitutes a unique site for monitoring the behavior of bituminous sub-layers and assessing the evolution of the expected advantages of this technique over time.

In order to monitor and compare the behavior of the different track structures, the BPL track was equipped with a fine adequate instrumentation, consisting of more than 100 sensors distributed over

4 different test sections, covering both granular and bituminous sub-layers and different types of soil [21].

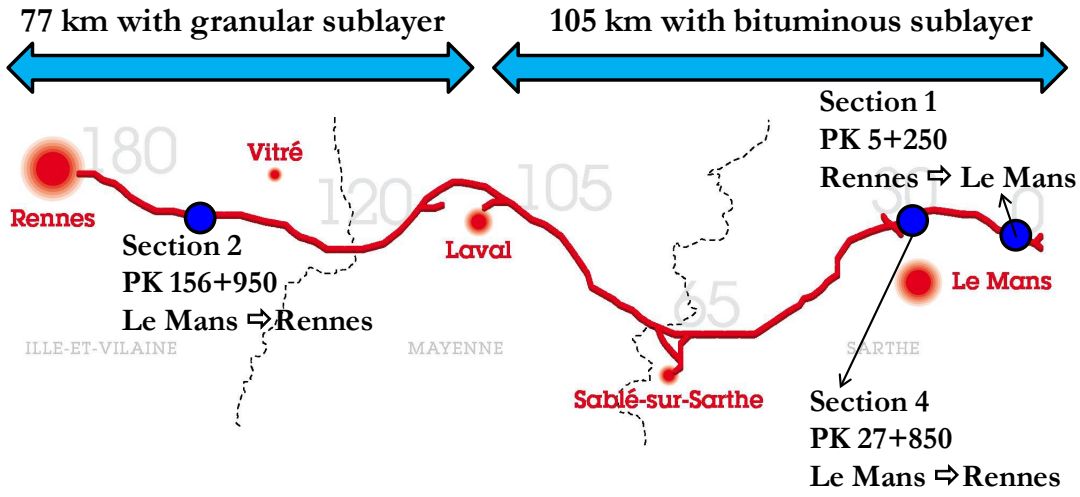

Figure 1. Location of the instrumented sections

The acquisition of data on BPL HSL has been completed in two phases:

- The first phase, entitled “speed up test phase”, corresponds to the track test phase before the commercial traffic starts. Passing HST characteristics are known, with increasing speeds ranging from 160 to 352 km/h. The study of the measurements recorded during this phase have been presented in [21] and have demonstrated that, during the speed-up test phase, the acceleration levels under the ballast increase with HST velocity for all types of structure. The comparison of the data between the structures with and without GB layer has revealed that the presence of the GB layer below the structure reduces the acceleration levels under the ballast responsible for its deterioration. The damping role of the GB layer has also been highlighted.
- The second acquisition phase corresponds to the commercial traffic phase, during which the theoretical train speed is 320 km/h and on which different high-speed trains with different bogie loads and characteristics travel on the track.

The objective of this new study is to examine and present the results after four years of commercial traffic. This study analyses then more than 60 000 train passages, at different speeds and under different environmental conditions. This study allows, for the first time, observing the continuous behavior over a representative period of time, and under real working conditions, of bituminous sub-layers.
The present paper therefore focuses on the analysis of the data recorded during the commercial traffic phase, which began on July 1, 2017. The data analysis is based on measurements carried out in real traffic conditions for four years between July 2017 and July 2021.

First, the instrumented sections on HSL BPL are quickly described. Then, the data processing methods developed for this second acquisition phase and the results for substructure deflection, vertical accelerations under the ballast and vertical and horizontal strain of the various sections are presented. In addition, the deflection, the vertical strain measurements, and the vertical acceleration peaks obtained at the top of the sub-layer are compared for the granular and the bituminous track structures. Finally, a comparison is made between the vertical leveling and the vertical acceleration measurements obtained on some sections of the HSL.

2. Structure of the HSL Bretagne-Pays de Loire (BPL) and instrumentation

2.1. Structure of the HSP BPL

The railway underlayment of the BPL HSL is made with granular sub-layer on the 77 km of the western part of the track and with bituminous sub-layer on the most easterly 105 km. The road base asphalt concrete is a Class 4 bitumen-bound gravel material (French GB4) in compliance with the NF EN 13-108-1 French standard. The unbound granular material (UGM) is of the A type with a particle size of 0/31.5 mm.
The innovative track structure consists of a 15-cm thick UGM adjustment layer reinforced by a 12-cm thick GB4 layer. The standard track structure consists of a 35-cm thick treated soil reinforced by a 20-cm thick UGM capping layer. Both structures rest on a subgrade layer treated using lime and hydraulic binders. The different structures are shown in Figure 2.

It is important to specify that the support layer of the bituminous structure is a soil treated with lime and hydraulic binders, with a minimum bearing capacity objective of 80MPa. The treatment was very effective and the bearing capacity (EV2) on this layer was found to be higher than 250MPa in most of the linear section (maximum level measurable by the dynamic device). This is also the case for the treated layer under the UGM in the area with a conventional structure.

Three instrumented sections are examined in this paper: Section 2, with the classical standard structure resting on a granular sub-layer, and Sections 1 and 4, with the innovative structure resting on a bituminous sub-layer. The soil beneath the earthwork treated layer is composed mainly of shale on section 2 (granular sublayer) and of yellowish clay with a broad sandy channel and scattered blocks on section 4 (bituminous sublayer). Sections 2 and 4 are built on embankments. No water infiltration was detected in these two clay sections when a 6.5-m deep drilling campaign was conducted in September 2015. On the contrary, Section 1 with bituminous sublayer, is located in a cutting, and the subgrade, composed of yellowish fine sand, greyish, and greenish broad sandy channel showed water infiltration at 4.5 m in depth, with a similar drilling made in September 2015.

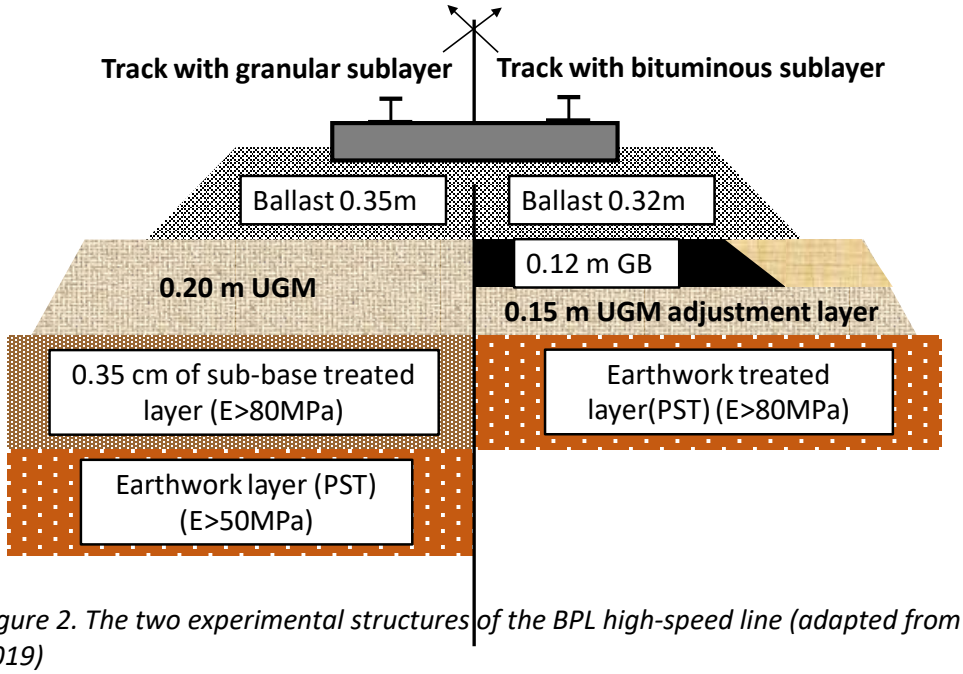

Figure 2. The two experimental structures of the BPL high-speed line (adapted from Khairallah et al., 2019)

2.2. BPL instrumented sections

The HSL track instrumentation is described in detail in [21-22]. Figure 3 presents the layout of the instrumentation for accelerometers, displacement sensors, vertical and horizontal strain gauges for the three instrumented sections:

• Accelerometers (reference 2210-005 of Alliantech brand) to record the track's vertical dynamic behavior, with measurements at several levels: under the sleepers, at the top of the bituminous layers and at the top of the granular layer. Acceleration measurements allow, in particular, comparing the sections' dynamic responses, with bituminous or granular sub-layer.

• Strain gages (TML brand KM-100HAS) to measure longitudinal and transverse strains at the base of the GB layer, and temperature sensors (KIMO PT100 probes), placed at the top and bottom of the layer.

• Vertical strain gages (TML brand KM-100B) to measure deformation levels of the unbound granular material (UGM). As a result, effects of seasonal moisture content variations can be inferred from the measured deformations.

• An anchored displacement sensor, measuring the total deflection between the top of the GB for section with asphalt sub-layer and the top of the UGM for the section with granular sub-layer, and a reference point located at 6 m depth. This sensor measures the structure's total displacement under the ballast (GB + granular layer + subgrade for section with bituminous sub-layer or UGM + subgrade for section with granular sub-layer).

Two types of measurements are performed: "slow" measurements and "fast" measurements. Slow measurements involve temperature probes 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. The signal acquisition frequency is 2000 Hz [22].

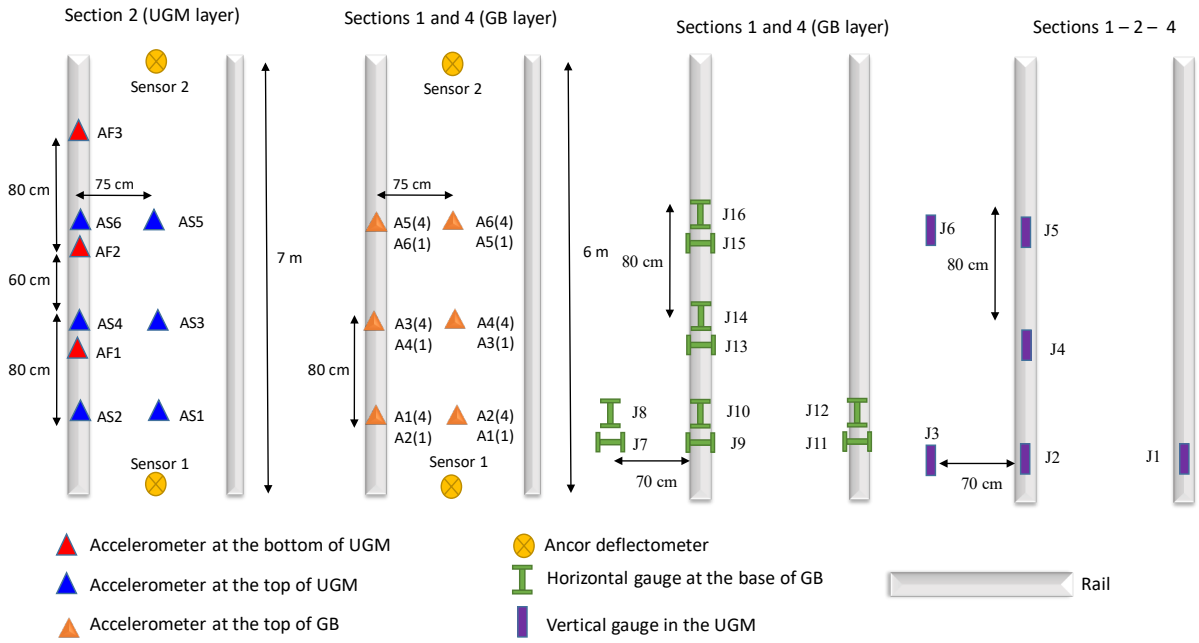

Figure 3. Layout of the instrumentation for accelerometers, displacement sensors, vertical and horizontal strain gauges

3. Evolution of the temperatures and deflection over four years

The temperature at the top and at the bottom of the bituminous layer (on Section 4 and 1) and at the top and the bottom of the granular sub-layer has been measured continuously every 10 minutes during four years from 2017 to 2020.

Table 1 presents the minimum and maximum values of the temperature recorded each year, at the top of the bituminous layer, for the section 4. During the four years of measurements, the mean temperature was 13.0°C and the standard deviation was 5.3°C. During this time, the maximum temperature at the top of the bituminous layer has been 24.3°C during summer 2020 and the minimum temperature 1.3°C during winter 2018. The same observation was made on the Section 1 (with bituminous sub-layer): the mean temperature was 14.0°C and the standard deviation was 5.2°C. During this time, the maximum temperature at the top of the bituminous layer has been 24.8°C during summer 2018 and the minimum temperature 1.0°C during winter 2017. Consequently, the bituminous material presents limited temperature variations, whether it is winter or summer.

On section 2, (with granular sub-layer), the mean temperature at the top of the UGM layer was 12.7°C and the standard deviation was 4.4°C. During this time, the maximum temperature at the top of the UGM layer has been 20.7°C during summer 2019 and the minimum temperature 3.6°C during winter 2017.

No negative temperatures have ever been measured at the bottom of the ballast layer, on the BPL instrumented sites. In summer, the temperature has rarely exceeded 24°C. A study conducted by [23] presents similar temperature measurements for a bituminous sub-ballast layer in Kentucky, USA. The maximum temperature of the bituminous mixture is 24°C during the summer and the minimum is 2°C in winter.

Table 1. Minimum and maximum values of the temperature at the top of the bituminous layer (Section 4)

Year	T° Min	Date	T° Max	Date
2017	1.43°C	01/21/2017	21.75°C	06/22/2017
2018	1.31°C	02/08/2018	23.82°C	07/26/2018
2019	3.69°C	01/30/2019	23.29°C	08/11/2019
2020	4.69°C	01/25/2020	24.25°C	08/18/2020

Figure 4 presents the histogram of the temperature distribution recorded during four years (from 2017 to 2020) at the bottom of the ballast layer, on the three sections. 90% of the temperatures stand within the range of 6°C- 24°C. The two main occurrences for the variation of the temperature are around 6°C-8°C and 18°C. Comparable measurements have been carried out on an HSL with a bituminous sub-layer from 2007 to 2013, in the East of France, and similar observations have also been made, with two main occurrence peaks at 7°C and 16°C [12]. These limited temperature variations within the railway structure are very favorable because they limit the decrease of the bituminous layer modulus. They also hinder the risk of rutting at high temperatures and of thermal cracking at low temperatures. The anti-freeze protection role of the ballast had already been underlined by [24].

As a result, the temperature variations are neglected in analyzing the present results.

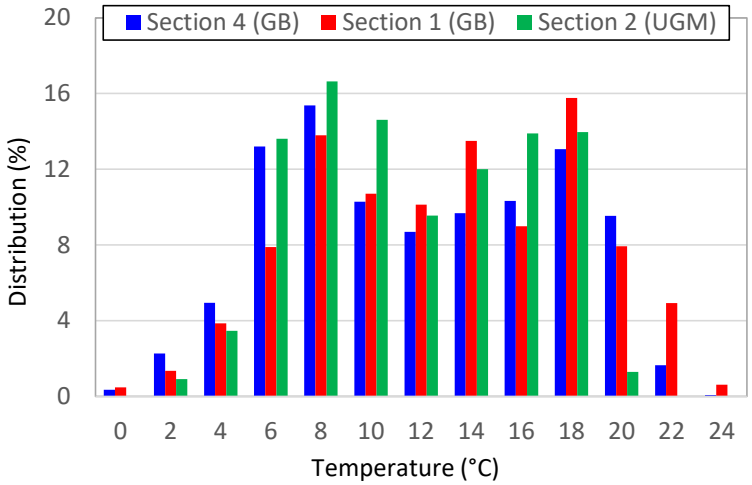

Figure 4. Histogram of the temperature distribution over 4 years (2017-2020) at the bottom of the ballast layer, for the three instrumented sections

The anchored displacement sensors also record the long-term vertical displacement of the railway structures. The vertical displacements recorded on all instrumented sections from October 2016 to May 2021 are displayed in Figure 5. The curves represent the track vertical settlement recorded during the first four years of service, for the three instrumented structures. Two anchored sensors failed shortly after installation: Sensors n°1 of Sections 1 and 4.

Figure 5 reveals the change in the vertical settlements from July 2017 when the BPL track was opened to commercial traffic. Before July 2017 the traffic was limited to various test phases. Since the opening to commercial traffic, trains of different types and loads travel on the line at a theoretical speed of 320 km/h. Settlement values increase slightly on the three instrumented sections after this date and are higher on Section 1, the section with bituminous sub-layer and sandy soil.
Figure 5 does not significantly indicate a trend for soil consolidation, which would otherwise most likely lead to steady settlement effects over the entire period. Additionally, there is no significant

difference between the settlements occurred on the bituminous sections and on the granular section. Yet, it is difficult to provide an accurate analysis of soil movements due to lack of data about water content variations.
However, Sections 2 (with a granular sub-layer) and 4 (with a bituminous sub-layer) present the same seasonal behavior characterized by a shrink-swell cycle causing limited downward displacement: swelling (probably due to the increase in moisture content) during winter and shrinking during summer. The presence of clay soils with expansion and retraction capacities on both sections is probably the cause. The displacements observed on Section 1 (with bituminous sub-layer and sandy soil), are the opposite: settlements are observed during winter whereas the slight surface uplift observed occurs during summer. Khairallah et al. [25] already made this observation, but only during the first two years of observation.
In summary, Figure 5 illustrates how settlements observed during the four-year study period are very limited for all the sections, ranging from 0.5 to 2.1 mm. These values are far below the 10-mm settlement limit set by the SNCF for high-speed railway tracks.

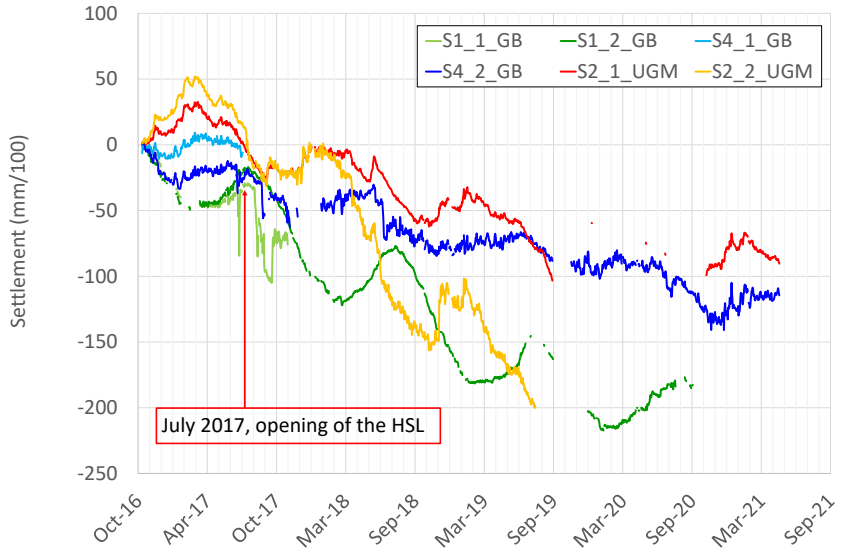

Figure 5. Evolution of track settlement on Sections 1, 2 and 4 during four years

4. Commercial traffic: identification of trains

The BPL high-speed line was inaugurated to commercial traffic on July 1, 2017 to connect Rennes to Paris. Many trains have traveled the track both ways since (an average of 23 trains per day per section). Four different types of HST operate on the experimental sections. Figure 6 shows the deflection profiles obtained for simple and double trains with 13 bogies (a), 26 bogies (b), 15 bogies (c) and 30 bogies (d), respectively, when they passed on bituminous Section 4 on July 1, 2017, the day of opening of the line. The good repeatability of the measurements of anchored displacement sensors and the good definition of the signals show the reliability of the data recorded by the sensors.

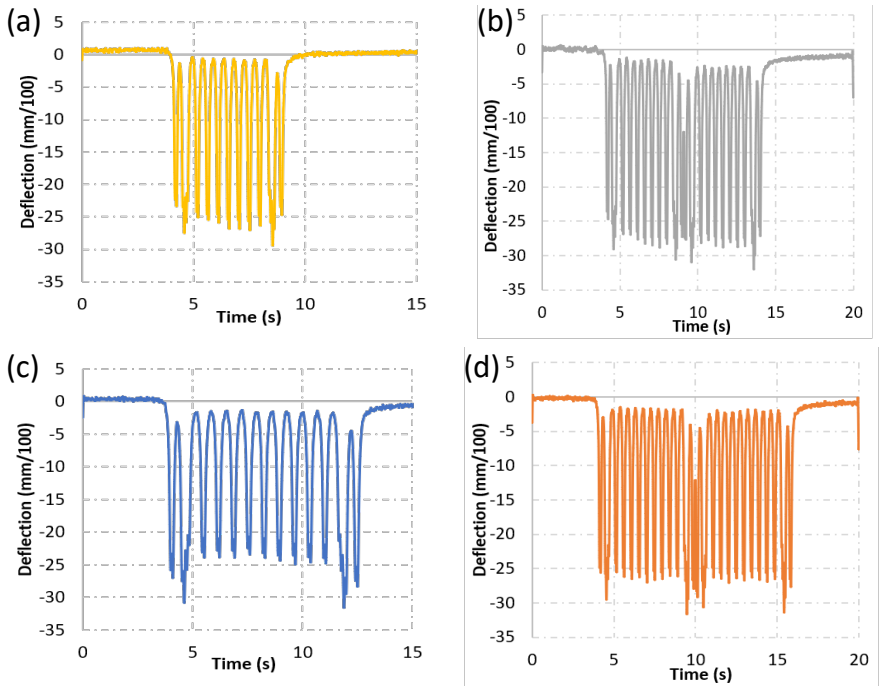

Figure 6. Example of temporal deflection signals from both single and double trains with (a) 13 bogies, (b) 26 bogies, (c) 15 bogies and (d) 30 bogies, running Section 4 on opening day

Figure 7a presents the number of trains passing on Section 4 (with bituminous sub-layer). The red arrows indicate the beginning of the three lockdowns in France. The number of trains highly decreases due to travel restrictions.
Figure 7b presents the distribution of type of train operating, each month, on Section 4 (with bituminous sub-layer). At the opening of the lane, most trains are HST with 15 bogies. In 2021, most trains are now HST with 13 or 26 bogies. The number of trains with 26 bogies, on the other hand, remains stable over the 4-year period of measurements (about 25%). For this reason, this type of train is preferred for the study and for simplification of the figures.

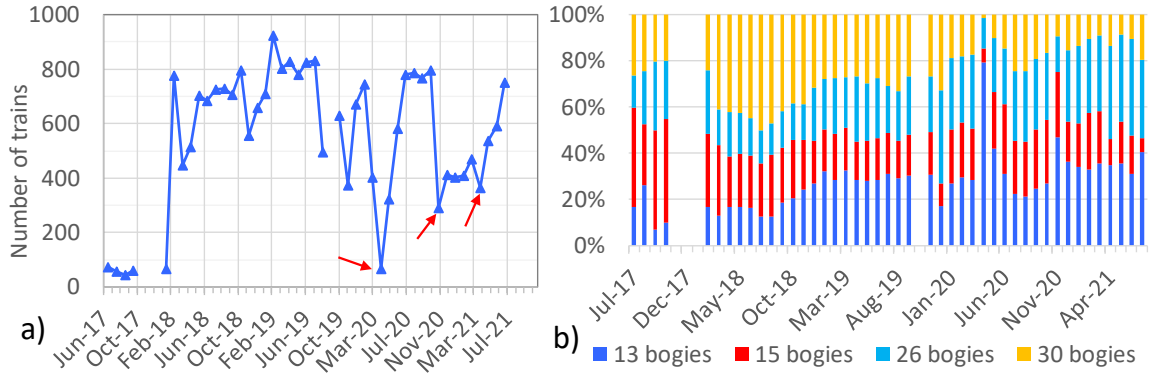

Figure 7. Number on train (a) and distribution of type of train (b) operating, each month, on Section 4 (with bituminous sub-layer)

5. Data processing used for commercial phase recordings

5.1. General description

The very busy train services on the line have generated a large number of measurement files from the different experimental sections. More than 60 000 train passages, at different speeds and under different environmental conditions were analyzed. On that account, the applied automatic data processing procedures made it possible to read the data files, obtain the precise date and time of passage of each HST on the desired section, calculate the train speed *V* using the vertical acceleration signals and calculate one reference comparison value for each type of signal (vertical acceleration, deflection, vertical strain and longitudinal and transversal strain in the bituminous layer). The different data processing stages are further described hereafter.

5.2. Calculation of train speed

After identifying a train passing (time, date and direction), the first stage of data processing is to calculate its speed.

Each peak of a vertical acceleration signal corresponds to the passing of a train axle on top of the considered accelerometer. Therefore, the interval Δt between successive peaks of a vertical acceleration signal corresponds to the time it takes for the train to travel the distance between successive axles.
Knowing that the distance between successive train axles is 3 m, the train speed *V* is calculated by dividing this distance by the corresponding time interval ($V = 3m/\Delta t$) (Figure 9).

Figure 8 presents the speed distribution, for Section 4, from July 2017 to July 2021. It reveals that the speed of 65% of the trains ranged between 280 and 300 km/h (88% have a speed ranging between 260 and 320 km/h). The same observation was also made for the two other instrumented sections. Consequently, all the tables in this paper present yearly-average values calculated with a speed ranging between 280 and 300 km/h.

These observations are within the expected speed range, since the commercial speed of HST is supposed to be 320 km/h.

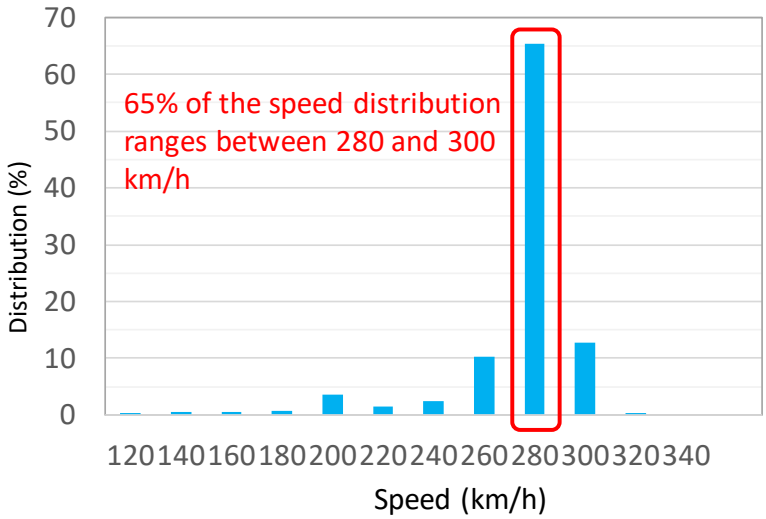

Figure 8. Speed distribution on Section 4 from July 2017 to July 2021

5.3. Signal filtering

At the next stage of data processing, the recorded sensor signals are filtered through a low-pass filter, adjusted according to train speed, in order to remove high frequencies related to dynamic effects (in particular wheel defects). The cut-off frequency of the filter, f_c, was calculated based on the "wheel wavelength" (approximately 3 m) and on the train speed, which define the "wheel frequency". This is the rate at which the same given point of a wheel (possibly the same given defect) comes into contact with the rail (f_c=V/2πR with R the wheel radius). The obtained frequency was increased by 10% to avoid significant signal loss.

5.4. Determination of "reference comparison values"

In order to easily compare all the data recorded during four years, one single point of comparison is defined for each type of signal. This paper presents results for acceleration, deflection and vertical and horizontal strain signals.

This means that each recorded signal is characterized by a single point, which corresponds to an extremum (minimum or maximum value) of the signal. In HST, the axle load of a given bogie can significantly vary from one train to another. However, the axle load on the first motor bogie is rather constant for all HST, at 17 tons approximately. Hence, the extremum value under the second peak of the first motor bogie is used to define the "reference comparison value" of the acceleration and strain signals (Figure 9).

The sign convention states positive values as upward accelerations and negative ones as downward accelerations. For the strain gauges, the sign convention defines positive values as extension and negative ones as contraction.

For vertical acceleration (upward and downward acceleration), one point of comparison is defined for each of the acceleration senses (positive and negative). The main objective is to use a very simple processing system.

Consequently, the following points are used as "reference comparison values":

- For vertical acceleration signals, the "second peak" of positive accelerations (oriented upwards) and the "second peak" of negative accelerations (oriented downwards) (Figure 9).
- For vertical track displacement, the maximum deflection values of the signal (oriented downwards) (Figure 10).
- For vertical strain, the second peak of the strain signal (oriented downwards, in contraction mode) (Figure 11).
- For horizontal strain, the maximum positive value of the strain signal (oriented upwards, in extension mode) (Figure 12).

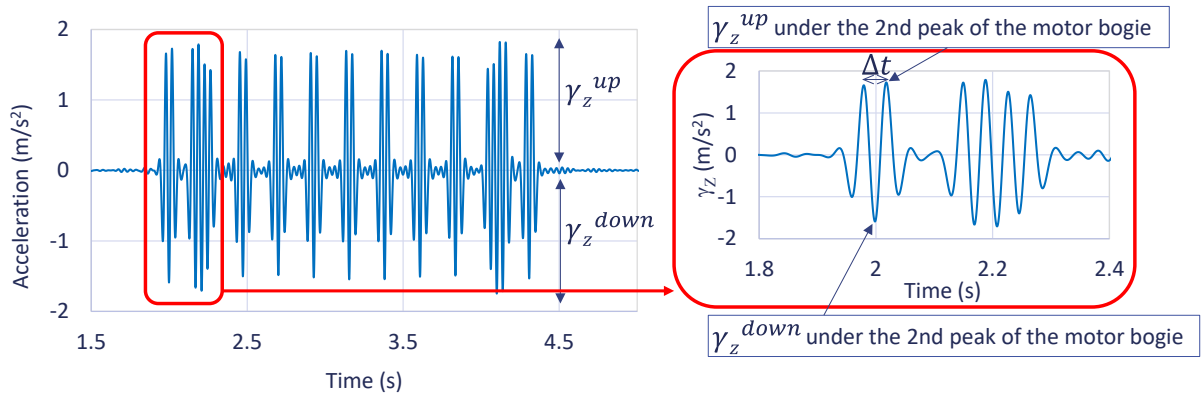

Figure 9. Vertical acceleration signal after filtering (and zooming) recorded on Section 2 (with UGM layer) with AS1 accelerometer, V=295 km/h

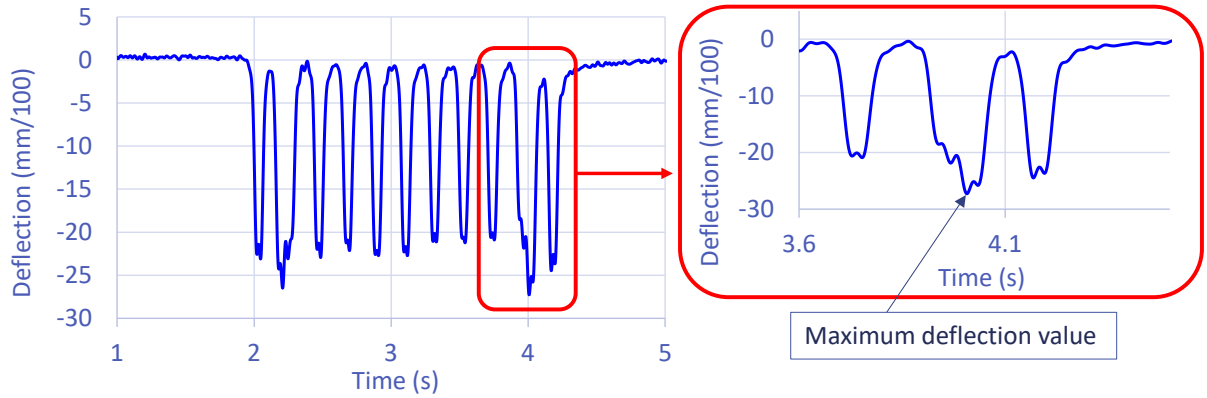

Figure 10. Deflection signal recorded on Section 2 (with UGM layer) with sensor 2, V=320 km/h

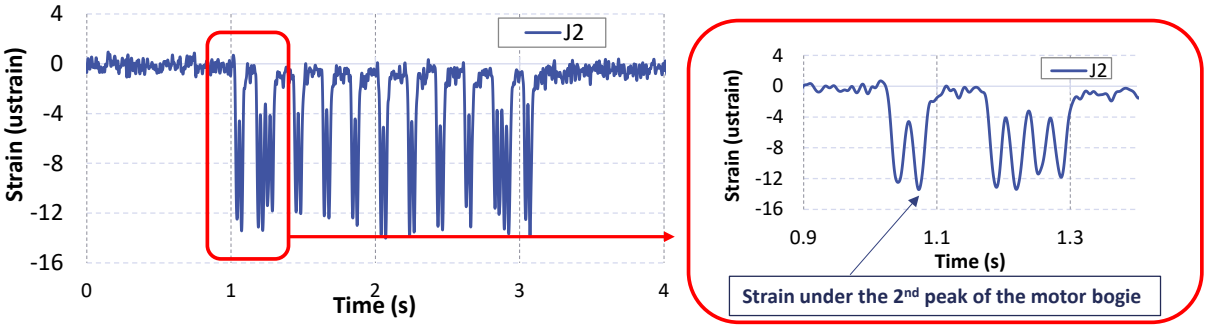

Figure 11. Vertical strain signal (and zooming) recorded on Section 2 (with UGM layer) with J2 strain gauge, V=160 km/h

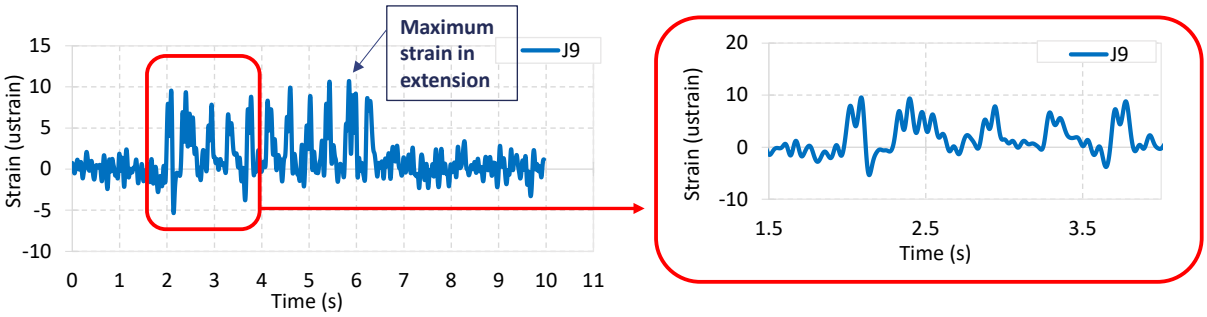

Figure 12. Transverse strain signal (and zooming) recorded on Section 4 (with GB layer) with J9 strain gauge, V=165 km/h

6. Results of the measurements during the four-year period

One of the main objectives of this instrumentation is to assess the behavior of the experimental structures including bituminous sub-layers and to compare it with the behavior of traditional structures with granular sub-layers. The measurements obtained from the anchored displacement sensors installed in pairs within the asphalt and granular sections are first compared. Then, the strain levels (for the vertical gauges within the UGM and the horizontal gauges at the top of the GB layer) are studied. Finally, the acceleration levels are analyzed, in particular those obtained at the base of the ballast layer, which strongly influence the wear and settlement of the whole ballast layer [26-28].

In her PhD thesis, Khairallah [29] shows that the measurement results do not vary with changes in train type. Consequently, for more convenience regarding the number of points, only data for trains with 26 bogies are presented on the figures.

6.1. Deflection

The graph displayed in Figure 13 plots the maximum deflection values measured on Section 2 with the granular sub-layer and Sections 4 and 1 with the bituminous sub-layer from July 2017 to June 2021, for speed between 280 and 300 km/h. In addition, Khairallah et al. [30] has showed that there is no evolution of the deflection with the train speed.

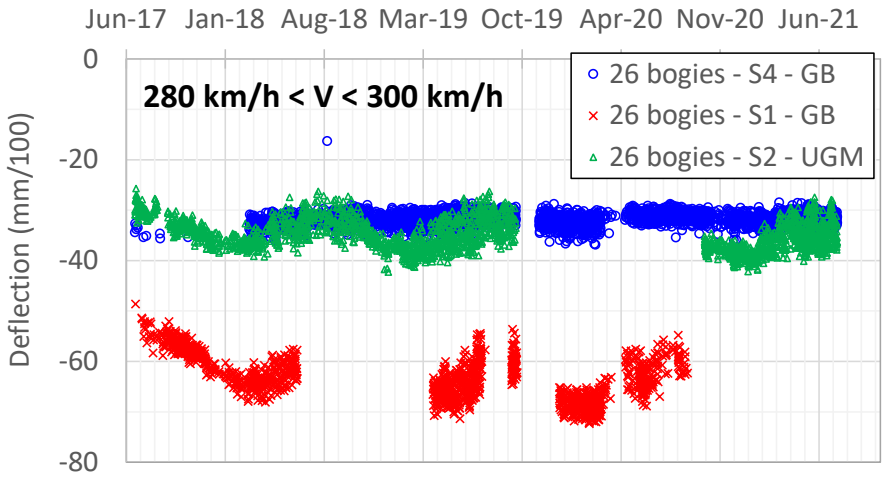

Figure 13. Comparison between the maximum deflection values measured on Section 2 (with granular sub-layer) and Sections 4 and 1 (with bituminous sub-layer) from July 2017 to July 2021, for trains with 26 bogies, for a train speed ranging between 280 and 300 km/h

The amplitude of the deflection peaks for Sections 2 (granular) and 4 (bituminous) are quite similar (35 mm/100, +/-3mm/100 and 32 mm/100, +/-1.4mm/100, respectively, for the mean value over the four-year period of measurement). However, their evolution over time below the ballast is fairly different for both sections. The bituminous structure deflection remains stable whatever the season. In contrast, no stabilization is observed on the granular track section. Deflection obviously varies with seasonal changes. The displacement values obtained on both sections are very close (c.f.

Table 2). These low deflection values are due to the high bearing capacity of the subgrade, which consists of cement treated soil for all the instrumented sections of the BPL line.

Deflection measurements for Section 1, because of its asphalt concrete sub-layer and sandy soil, are greater than for sections with clay soils and range between 50 and 73 mm/100. Some seasonal variations are detected: the values increase during winter, reaching 73 mm/100, and decrease during summer. Inflows having been observed in the sub-structure during the geotechnical surveys, this may explain its loss of bearing capacity during rainy periods.

Table 2. Average values of deflection (and standard deviation in percent) from August 1st to July 31th during the 4-year measurement period for trains with 26 bogies and a train speed within the range of 280-300 km/h, for the three sections studied

	Deflection (mm/100)		
	Bituminous sub-layer		**Granular sub-layer**
	S1 (sandy soil)	S4 (clay soil)	S2 (clay soil)
Aug. 2017 – Jul. 2018	60.3 (6%)	32.4 (4%)	34.1 (7%)
Aug. 2018 – Jul. 2019	64.5 (5%)	31.6 (4%)	35.0 (9%)
Aug. 2019 – Jul. 2020	65.9 (6%)	31.9 (4%)	33.0 (7%)
Aug. 2020 – Jul. 2021	-	31.4 (3%)	36.1 (8%)

No significant change in the average level of deflection (which may reflect the deterioration of the track) is noticed on any of the experimental track sections during the 4-year follow-up. The coefficient of variation of the anchor deflectometer is between 3% and 9%, which is very low and indicates good performance of the sensor.

6.2. Vertical strain

According to the study by Khairallah [29], the vertical gauges J2, J1 and J2, located beneath the rail axis in the GNT layer of bituminous Section 4, bituminous Section 1 and granular Section 2, respectively, record the largest vertical deformations. The second peaks of the different signals processed from these gauges are shown in Figure 14. Results are displayed from July 2017 to July 2021 for 26 bogie-trains only.

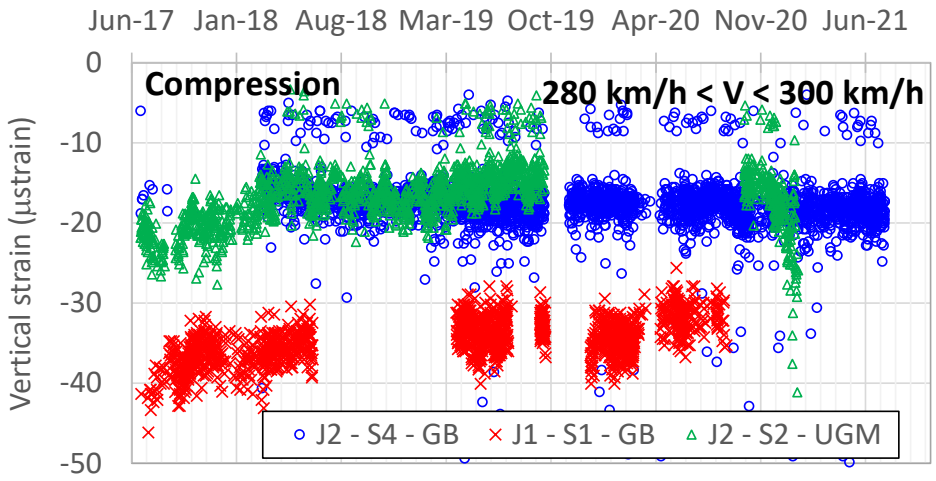

Figure 14. Comparison between the maximum vertical strain values in compression mode measured on Section 2 (with granular sub-layer) and Sections 4 and 1 (with bituminous sub-layer) from July 2017 to July 2021 for 26 bogie-trains and a speed ranging between 280 and 300 km/h

The same observations about deflection are also valid for vertical strain. The vertical strain values measured on Sections 2 (granular) and 4 (bituminous) are similar. Yet, their evolution over time below the ballast is different. Vertical strain remains stable on the bituminous structure whatever the season; the mean value is approximately 18 µstrain (+/- 7 µstrain). In contrast, the vertical strain obviously varies with seasonal changes on the granular track section. The mean value is approximately 22 µstrain (+/- 4 µstrain). The vertical strain values achieved for both sections are very close (c.f. *Table 3*).
Like for deflection values, vertical strain measurements for Section 1 because of the geotechnical nature of its asphalt concrete sub-layer and sandy subsoil, are greater than for sections with clay soils, with a mean value around 34 µstrain (+/- 3 µstrain). Vertical strain variations are likely due to seasonal changes.

The values recorded on the three sections are not significantly given the low vertical strain levels (less than 34 µstrain) reached in the granular layer (which makes the measurements less accurate). In comparison, in road pavements, vertical strains in granular subbase layers are generally of the order of several hundred microstrains.

Table 3. Average values of vertical strain (and standard deviation in percent) from August 1st to July 31th during the 4-year measurement period, for trains with 26 bogies and a train speed within the range of 280-300 km/h, for the three sections studied

	Vertical strain (µstrain)		
	Bituminous sub-layer		**Granular sub-layer**
	S1 (sandy soil)	S4 (clay soil)	S2 (clay soil)
Aug. 2017 – Jul. 2018	36.4 (6%)	16.1 (35%)	18.1 (19%)
Aug. 2018 – Jul. 2019	33.5 (6%)	17.7 (33%)	15.3 (19%)
Aug. 2019 – Jul. 2020	33.7 (7%)	17.7 (33%)	13.8 (21%)
Aug. 2020 – Jul. 2021	-	19.1 (37%)	16.6 (22%)

6.3. Horizontal strain in the GB layer

Regarding horizontal strain measurements at the bottom of the asphalt concrete layer, the data about the largest extension results from the transverse gauge J9 and the longitudinal one J10 located beneath the rail axis on Section 4 are discussed. Figure 15 presents the maximum transverse and longitudinal strain values from gauge J9 and gauge J10, respectively, recorded from July 2017 to July 2021 for 26 bogie-trains. Extension strain values at the bottom of the GB layer are around 11 µstrain (+/- 2 µstrain) for transverse and longitudinal strains, which is very low. Strain levels likely to cause fatigue damage within bituminous materials are traditionally higher than 50 µstrain. This threshold is far from being reached in the case of Section 4. The values obtained in extension mode remain stable over the four-year measurement period, except for a small increase, which is seen in summer, and likely due to higher temperatures. This observation is confirmed by the results summarized in Table 4: the yearly-average strain value is very stable over the four-year measurement period for both types of strain gauges (longitudinal and transverse).

Consequently, the GB layer fatigue behavior over time is considered insignificant even after four years of use. Rose et al. [23] and Ramirez [12] have made similar observations on two different structures with a bituminous sub-layer (one studied in the USA, one in the East of France). They conclude that the sub-ballast bituminous layer might have an extremely long fatigue life because of low load-induced pressure levels.

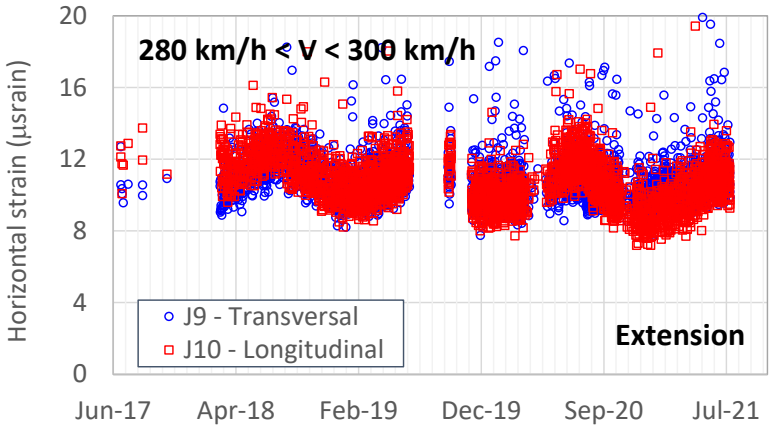

Figure 15. Maximum values for transverse and longitudinal strain from gauge J9 and gauge J10, respectively, recorded for 26 bogie-trains on Section 4 (with bituminous sub-layer) as a function of time from July 2017 to July 2021, for a train speed ranging from 280 to 300 km/h

Table 4. Average values for transverse and longitudinal strain recorded on Section 4 (with bituminous sub-layer) from gauge J9 and gauge J10 (and standard deviation in percent), respectively, from August 1st to July 31th during the 4-year measurement period for 26 bogie-trains and a train speed ranging from 280 to 300 km/h,

	Transverse strain (µstrain)	Longitudinal strain (µstrain)
Aug. 2017 – Jul. 2018	11.5 (17%)	12.1 (9%)
Aug. 2018 – Jul. 2019	11.1 (20%)	10.9 (10%)
Aug. 2019 – Jul. 2020	11.0 (24%)	10.6 (17%)
Aug. 2020 – Jul. 2021	10.9 (20%)	10.4 (13%)

6.4. Vertical acceleration

For all figures and tables of the study, positive values correspond to vertical upward accelerations and negative values to downward accelerations.

Section 4, with bituminous sub-layer

Figure 16 compares positive and negative vertical acceleration changes at the top of the GB layer recorded by accelerometers A1, A3 and A5 (located below the outer rail) from July 2017 to July 2021, as a function of speed. Regarding signal processing, this comparison considers the second peak of the filtered signal referring to the motor bogie of the trains. Overall, the measurements show the same trend: the acceleration follows a non-linear increase with train speed and upward acceleration levels are higher than downward accelerations. The same trend is found for the accelerometers located between the rails. The maximum acceleration levels are around 3 m/s^2 (for a speed of 320 km/h). The accelerations remain at a relatively low level that can be considered as safe with respect to the risk of ballast settlement under the repeated passage of HST.

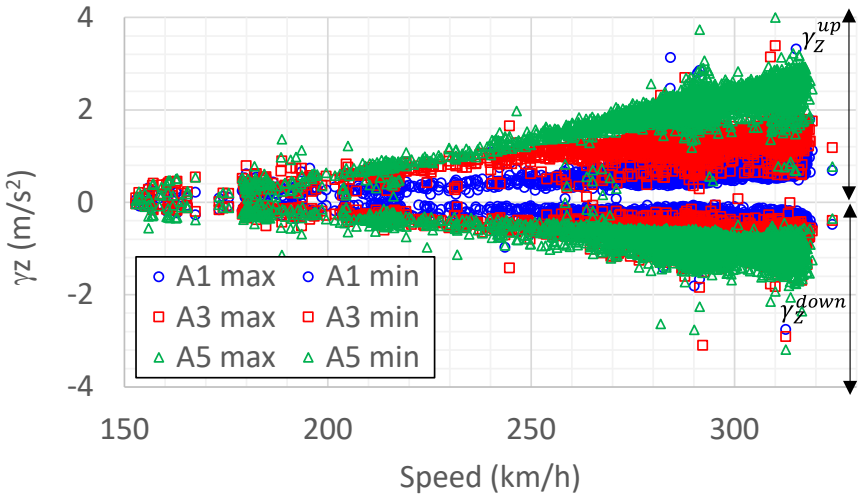

Figure 16. Acceleration under the signal second peak recorded for 26 bogie-trains on Section 4 (with bituminous sub-layer) by accelerometers A1, A3 and A5 (located below the outer rail) from July 2017 to July 2021, as a function of speed

Figure 17 compare positive and negative vertical acceleration changes at the top of the GB layer recorded by accelerometers A1, A3 and A5 (located below the outer rail) from July 2017 to June 2021 for 26 bogie-trains running at a speed within the range of 280-300 km/h (most common speed) as a function of time. Regarding signal processing, the comparison considers the second peak of the filtered signal referring to the motor bogie of the trains. All values remain constant over the four-year measurement period, with the exception of accelerometer A3 for a short period of time in April 2021 (positive and negative accelerations decrease and eventually return to the initial level). The negative acceleration recorded by accelerometer A5 appears to be decreasing over the four-year measurement periods. At present, no explanation can be given.

However, no significant increase in the positive or negative acceleration values (which may reflect the deterioration of the track) is noticed during the 4-year follow-up. This observation is confirmed by the results displayed in Table 5.

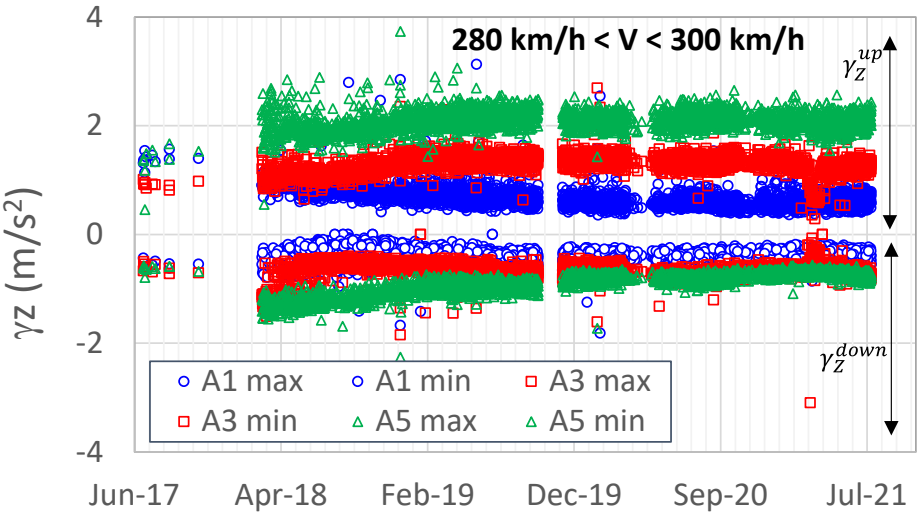

Figure 17. Acceleration under the signal second peak recorded on Section 4 (with bituminous sub-layer) by accelerometers A1, A3 and A5 (located under the outer rail) from July 2017 to July 2021 for 26 bogie-trains and a speed within the range of 280-300 km/h as a function of time

Table 5 presents the vertical acceleration average values (and standard deviation in percent) recorded on Section 4 (with bituminous sub-layer) from August 1 to July 31 over the 4-year measurement period for trains with 26 bogies and a speed ranging from 280 to 300 km/h. Accelerometers A1 and A2, A3 and A4 and A5 and A6 are placed in the same transverse position (c.f. Figure 3). Values from A1 and A2 decrease slightly each year. Values from A3 and A4 and A5 and A6 increase slightly during the first three year and eventually decrease during the fourth year of measurement. There are no significant changes in the acceleration values over the four-year measurement period. In addition, the accelerations remain at a relatively low level.

For this bituminous section, it can also be concluded that accelerations recorded between rails are lower than those measured under the outer rail. This is a logical outcome considering that accelerometers located under the outer rail are directly subject to train loading.

Table 5. Average value of vertical acceleration (and standard deviation in percent) recorded on Section 4 (with bituminous sub-layer) from August 1 to July 31 during the four-year measurement period for 26 bogie-trains and a speed within the range of 280-300 km/h

	TOP GB ACCELERATION (Section 4)					
	Top GB – out rails (m/s²)			Top GB – between rails (m/s²)		
	A1	A3	A5	A2	A4	A6
Aug. 2017 – Jul. 2018	0.88(16%)	1.1(13%)	1.95(13%)	0.81(20%)	1.13(12%)	1.59(9%)
Aug. 2018 – Jul. 2019	0.73(25%)	1.34(11%)	2.12(8%)	0.7(16%)	1.26(10%)	1.65(8%)
Aug. 2019 – Jul. 2020	0.62(22%)	1.36(8%)	2.13(6%)	0.61(15%)	1.25(8%)	1.62(7%)
Aug. 2020 – Jul. 2021	0.60(20%)	1.27(14%)	2.11(7%)	0.55(14%)	1.19(10%)	1.57(8%)

Section 1, with bituminous sub-layer

Figure 18 and Figure 19 compare positive and negative vertical acceleration changes recorded at the top of the GB layer by accelerometers A2, A4 and A6 (located below the outer rail) from July 2017 to September 2020 versus time and speed (between 280 and 300 km/h only), respectively. Regarding signal processing, the comparison considers the second peak of the filtered signal referring to the motor bogie of the trains.

The measurements summarized in Figure 18 broadly show the same trend: the acceleration follows a non-linear increase with train speed and upward acceleration levels are higher than downward accelerations. The same trend is found for the accelerometers located between the rails.

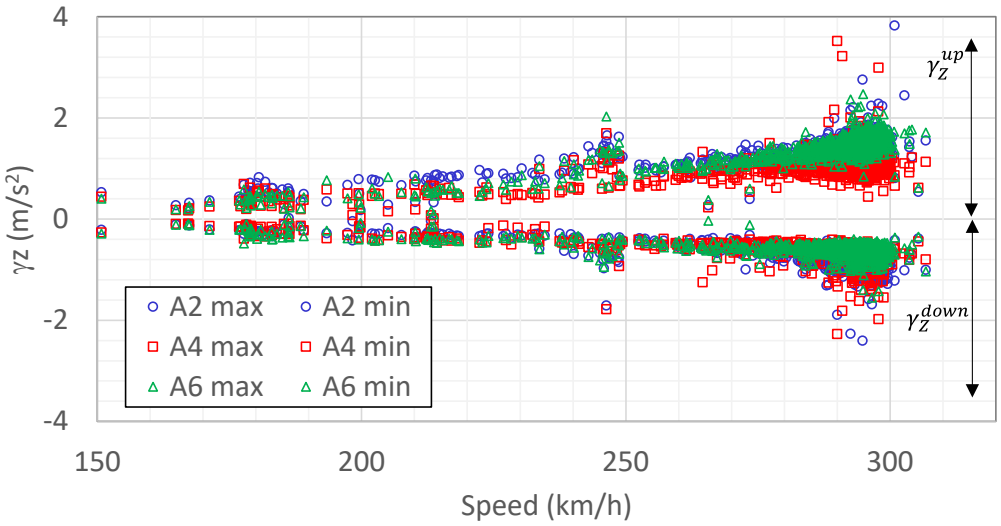

Figure 18. Acceleration under the signal second peak recorded by accelerometers A2, A4 and A6 (located under the outer rail) on Section 1 (with bituminous sub-layer) for 26 bogie-trains from July 2017 to September 2020, as a function of speed

Figure 19 shows that the vertical acceleration measured at the top of the GB layer on Section 1 remains very stable during the first three years of measurements. In September 2017, the acceleration level recorded by accelerometer A6 appears to vary: the positive acceleration increases slightly whereas the negative acceleration decreases also slightly. After this period, the vertical acceleration remains very stable. An explanation is provided at the end of this paper.

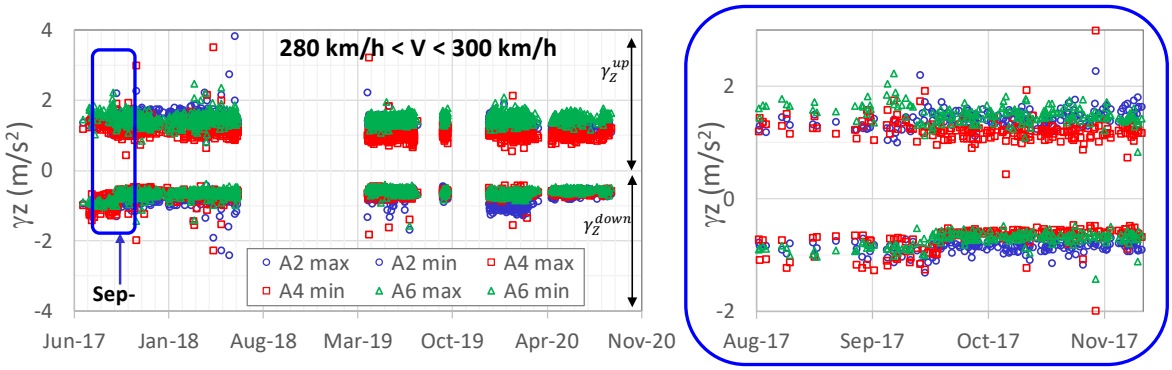

Figure 19. Acceleration under the signal second peak recorded by accelerometers A2, A4 and A6 (located under the outer rail) on Section 1 (with bituminous sub-layer) from July 2017 to September 2020 for 26 bogie-trains and a speed within the range of 280-300 km/h, as a function of time, and zoomed view

Table 6 presents the vertical acceleration average values (and standard deviation in percent) recorded on Section 4 (with bituminous sub-layer) from August 1 to July 31 over the 3-year measurement period for trains with 26 bogies and a speed ranging from 280 to 300 km/h. Table 6 shows that there are no significant changes in the acceleration values over the three-year measurement period. The maximum acceleration levels around 1.6 m/s^2 obtained for this section 1 with a bituminous sub-layer are lower than those of the section 4, also with a bituminous sub-layer. It is probably due to the maximum speed, which is 300 km/h on section 1 and 320 km/h on section 4.

Table 6. Average vertical acceleration values (and standard deviation in percent) recorded on Section 1 (with bituminous sub-layer) from August 1st to July 31th during the first three years of the measurement period for 26 bogie-trains and a train speed ranging from 280 to 300 km/h

	TOP GB ACCELERATION (Section 1)					
	Top GB – out rails (m/s^2)			Top GB – between rails (m/s^2)		
	A2	A4	A6	A1	A3	A5
Aug. 2017 – Jul. 2018	1.47(12%)	1.21(17%)	1.48(12%)	1.80(11%)	1.17(17%)	1.52(11%)
Aug. 2018 – Jul. 2019	1.29(10%)	1.03(16%)	1.46(8%)	-	1.01(15%)	1.55(8%)
Aug. 2019 – Jul. 2020	1.34(10%)	1.06(11%)	1.51(8%)	-	0.90(18%)	1.53(8%)

Section 2, with granular sub-layer

Figure 20 compares the positive and negative vertical acceleration changes recorded using accelerometers AS2, AS4 and AS6 (located under the outer rail) at the top of the UGM layer from July 2017 to July 2021 as a function of speed. Regarding signal processing, the comparison considers the second peak of the filtered signal referring to the motor bogie of the trains. All measurements show the same trend: the acceleration follows a non-linear increase with train speed and upward acceleration levels are higher than downward accelerations. The same trend is found for the accelerometers located between the rails.

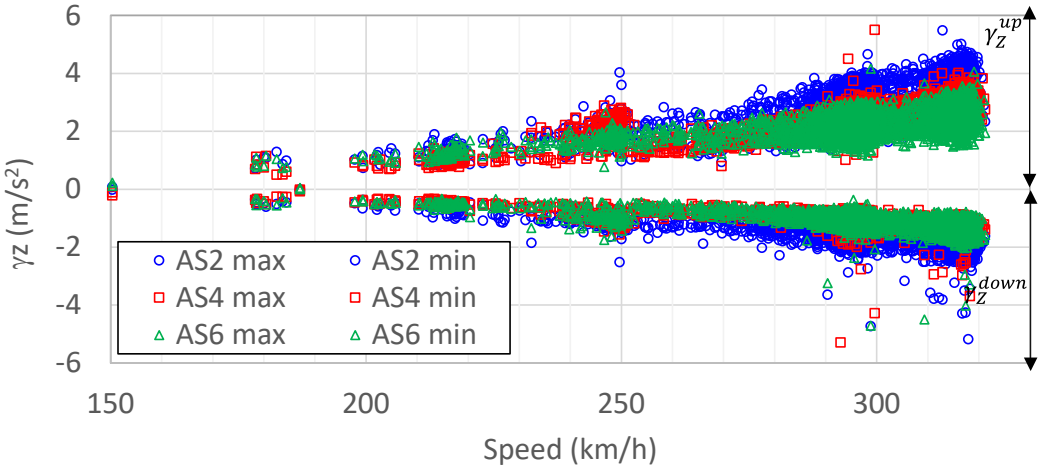

Figure 20. Acceleration under the signal second peak recorded on Section 2 (with granular sub-layer) by accelerometers AS2, AS4 and AS6 at the surface of the UGM layer (located below the outer rail) from July 2017 to July 2021 for 26-bogie trains as a function of speed

Figure 21 and Figure 22 compare positive and negative vertical acceleration changes recorded by accelerometers AS1, AS3 and AS5 at the top of the UGM layer and by accelerometers AF1, AF3 and AF5 at the bottom of the UGM layer, all located below the outer rail, from July 2017 to July 2021 for 26-bogie trains and for a speed within the range 280-300 km/h only as a function of time. Regarding signal processing, the comparison considers the second peak of the filtered signal referring to the motor bogie of the train.

It appears that upward accelerations at the top and at the bottom of the UGM layer, though they vary with seasonal changes, otherwise remain stable. Downward accelerations remain quite stable throughout the measurement period. Acceleration values are higher at the top than at the bottom of the granular layer. Regarding downward and upward acceleration at the top of the UGM layer, the vertical acceleration values recorded using accelerometer AS2 (and accelerometer AS1, c.f. Figure 24) appear to rise over a short period of time in August 2017, shortly after the opening of the track to commercial traffic. After this rise, the vertical acceleration level also starts to change for the measurements from accelerometers AS4, AF1 and AF2, which increase, and AF3, which decrease. An explanation is provided at the end of this paper.

The maximum acceleration levels around 5 m/s^2 obtained for this section with a granular sub-layer are significantly higher than those of the section 4 with a bituminous sub-layer and the same soil. Nevertheless, the accelerations remain at a relatively low level that can be considered as safe with respect to the risk of ballast settlement under the repeated passage of HST.

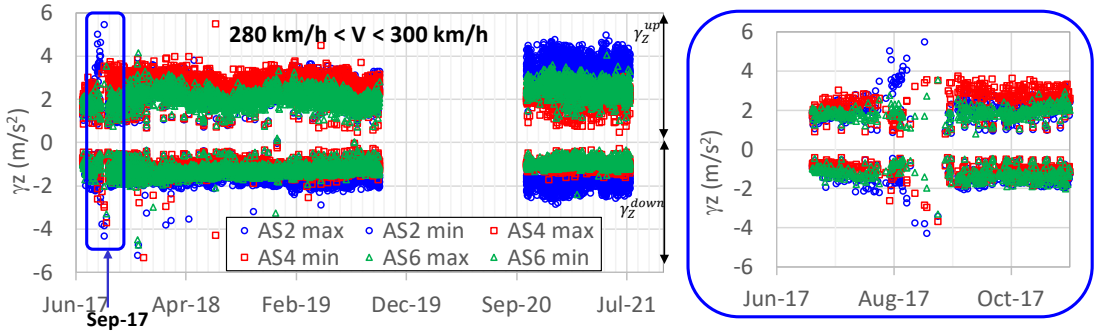

Figure 21. Acceleration under the signal second peak recorded on Section 2 (with granular sub-layer) by accelerometers AS2, AS4 and AS6 at the surface of the UGM layer (located below the outer rail) from July 2017 to July 2021 for 26-bogie trains as a function of time, and zoomed view

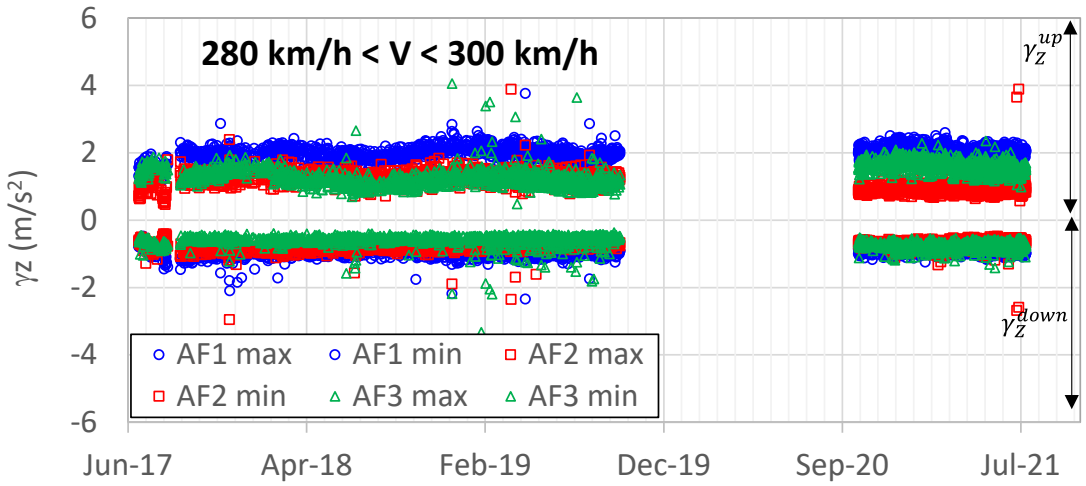

Figure 22. Acceleration under the signal second peak recorded on Section 2 (with granular sub-layer) by accelerometers AF1, AF3 and AF5 at the bottom of the UGM layer (located below the outer rail) from July 2017 to July 2021 for 26-bogie trains as a function of time

Figure 23 compares positive and negative vertical acceleration changes measured on the top of the sleeper using accelerometers AT2, AT3 and AT5 (located close to the outer rail, close to the outer rail but on another sleeper and between the rails on the same sleeper, respectively) from July 2017 to July 2021 as a function of speed. Regarding signal processing, the comparison considers the second peak of the filtered signal referring to the motor bogie of the trains. Upward and downward acceleration values measured on the sleepers remain constant throughout the measurement period, with the exception of a short period of time in August 2017, shortly after the inauguration of the track to commercial traffic, for Accelerometer AT3.

Table 7 shows no significant change in the acceleration level (which may reflect the deterioration of the track) is noticed during the 4-year follow-up.

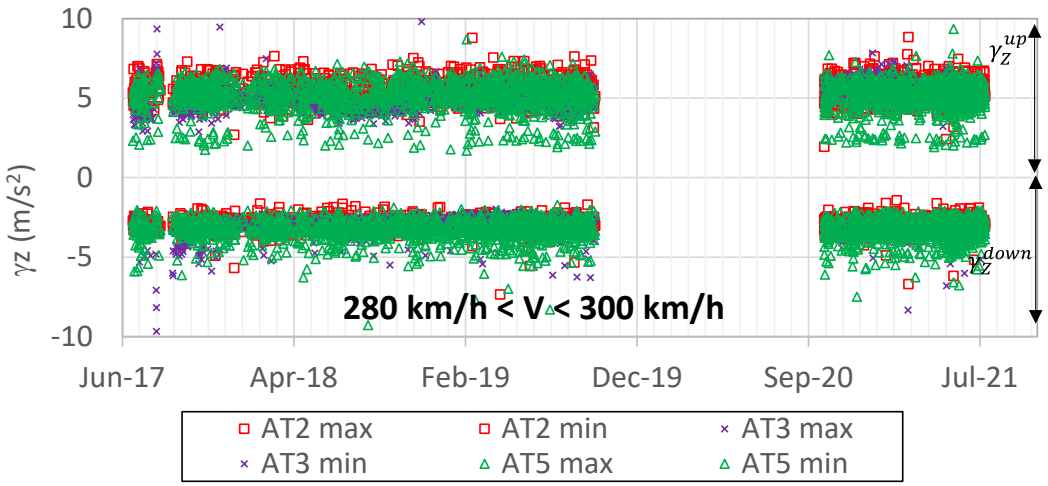

Figure 23. Acceleration under the signal second peak recorded on Section 2 (with granular sub-layer), from accelerometers AT2, AT3 and AT5, located at the top of the sleepers, from July 2017 to July 2021 for 26 bogie-trains and a speed within the range of 280-300 km/h, as a function of time

Table 7. Average vertical acceleration values (and standard deviation in percent) recorded on Section 2 (with granular sub-layer) from August 1st to July 31th during the four-year of the measurement period for 26 bogie-trains and a train speed ranging from 280 to 300 km/h

	TOP UGM ACCELERATION					
	Top UGM – out rails (m/s²)			Top UGM – between rails (m/s²)		
	AS2	AS4	AS6	AS1	AS3	AS5
Aug. 2017 – Jul. 2018	2.29(17%)	2.59(15%)	2.02(15%)	2.21(21%)	3.24(11%)	1.47(14%)
Aug. 2018 – Jul. 2019	2.37(12%)	2.48(10%)	1.93(13%)	2.32(14%)	3.02(8%)	1.32(15%)
Aug. 2019 – Jul. 2020	2.34(8%)	2.34(8%)	1.78(10%)	2.24(12%)	2.79(7%)	1.19(13%)
Aug. 2020 – Jul. 2021	3.26(9%)	1.99(8%)	2.42(11%)	2.85(8%)	2.23(7%)	1.27(12%)
	Bottom UGM acceleration - out rails (m/s²)			Top sleeper acceleration below rail axis (m/s²)		
	AF1	AF2	AF3	AT2	AT3	AT5
Aug. 2017 – Jul. 2018	1.94(9%)	1.26(15%)	1.31(17%)	5.46(46%)	5.02(28%)	5.26(34%)
Aug. 2018 – Jul. 2019	2.02(10%)	1.29(15%)	1.22(23%)	5.30(10%)	4.86(11%)	5.21(13%)
Aug. 2019 – Jul. 2020	1.95(7%)	1.24(10%)	1.14(15%)	5.16(8%)	4.67(9%)	4.81(12%)
Aug. 2020 – Jul. 2021	2.05(8%)	0.91(20%)	1.60(11%)	-	5.57(8%)	5.22(24%)

7. Comparison of acceleration results in the different structures

Lastly, accelerometer measurements obtained on Section 2 with the granular sub-layer and on Section 4 with the bituminous sub-layer during the commercial phase are compared.

Figure 24 and Figure 25 compare the minimum and maximum accelerations for two accelerometers located below the rail axis at the top of the sub-layer: AS1 on Section 2 (with granular sub-layer) and A3 on Section 4 (with a bituminous sub-layer) versus time for Figure 24 and versus speed for Figure 25. The results clearly demonstrate that the acceleration peaks at the top of the bituminous sub-layer are much lower than those achieved at the top of the granular sub-layer, for both upward and

downward acceleration. It can therefore be concluded that, even after four years of use, the presence of the bituminous sub-layer reduces acceleration measured below the ballast by a factor of about 2, as already observed during the speed up test phase [21]. The measured values of accelerations are also less dispersed on the section 4 with bituminous sub-layer.

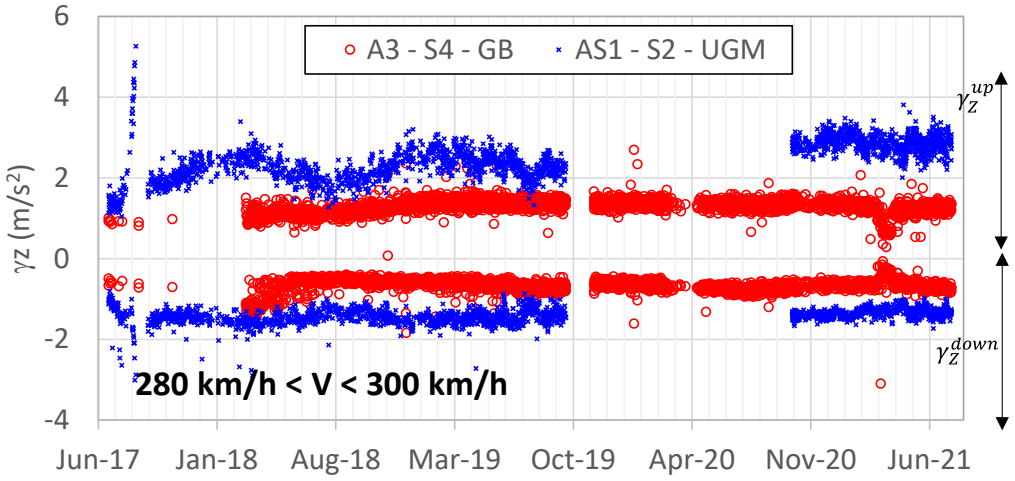

Figure 24. Comparison of positive and negative vertical acceleration peaks, under the signal second peak, recorded on Section 2 (with granular sub-layer) and Section 4 (with bituminous sub-layer) accelerometer AS1 and A3 (both located below the outer rail), respectively, during the commercial phase from July 2017 to July 2021 for 26 bogie-trains and a speed within the range of 280-300 km/h

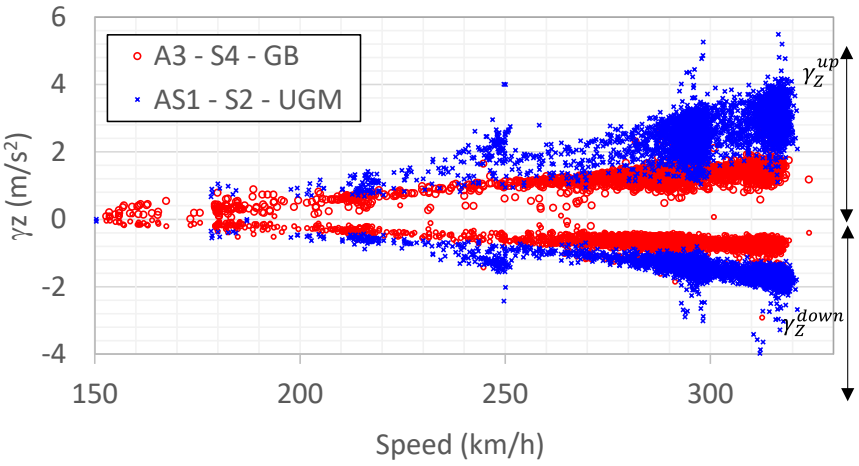

Figure 25. Comparison of positive and negative vertical acceleration peaks, under the signal second peak, recorded on Section 2 (with granular sub-layer) and Section 4 (with bituminous sub-layer) accelerometer AS1 and A3 (both located below the outer rail), respectively, during the commercial phase from July 2017 to July 2021 for 26 bogie-trains as a function of speed

Table 8 summarizes the upward accelerations obtained for all the trains with 26 bogies running on the granular and bituminous structures at the same speed, within the range 280-300 km/h, from July 2017 to July 2021. Regarding signal processing, the comparison considers the second peak of the filtered signal referring to the motor bogie of the trains. The results displayed in Table 8 confirms the previous observation: for a train speed within the range of 280-300 km/h, the estimated ratio of the acceleration

recorded at the surface of the bituminous layer to those recorded at the surface of the UGM layer is around 50%. A similar observation was made during the speed up test phase [21].

Table 8. Vertical acceleration average values (and standard deviation in percent) recorded on Section 4 (with bituminous sub-layer) and on Section 2 (with granular sub-layer) from July 2017 to July 2021 for 26 bogie-trains and a speed ranging from 280 to 300 km/h

TOP GB ACCELERATION (Section 4)						
	Top GB – out rails (m/s^2)			Top GB – between rails (m/s^2)		
	A1	A3	A5	A2	A4	A6
Average	0.67	1.30	2.10	0.64	1.22	1.61
St. dev.	0.17	0.16	0.17	0.13	0.13	0.13
St. dev.(%)	26%	13%	8%	21%	10%	8%
TOP UGM ACCELERATION (Section 2)						
	Top UGM – out rails (m/s^2)			Top UGM – between rails (m/s^2)		
	AS2	AS1	AS3	AS1	AS3	AS5
Average	2.67	2.47	2.74	2.47	2.74	1.33
St. dev.	0.56	0.46	0.49	0.46	0.49	0.20
St. dev. (%)	21%	19%	18%	19%	18%	15%

8. Comparison of the vertical leveling results

Track geometry affects travel comfort and safety. Geometry quality is hence considered as the main trigger for maintenance operations, emergency interventions and material replacement in most countries. Among the many geometry parameters monitored by French railway network (*i.e.* longitudinal level, alignment, cross-level, twist and gauge) to which correspond specific normative thresholds, longitudinal level is the most important one. The longitudinal level is defined, for each rail, in EN 13848 [31], see [32-34] also, as the deviation in millimeters in the vertical direction of the running table levels (contact surface on top of the rail) from a reference line. This ideal line can be considered as a smoothed transformation of the raw signal of vertical measurements. The smoothing parameters reflect the wavelength range of interest for railway dynamics. Such measurements were historically performed on chord measurement systems, which evaluate the vertical displacement of one wheel of a car with respect to the average position of the other wheels on the same car. Modern on-board measurement systems, such as for IRIS 320 HST monitoring train, are otherwise base on IMU[1] and/or optical technologies. French regulations impose a limit threshold for peak-to-average values of longitudinal levels of each to detect and consider track defect. For the monitoring of track temporal deterioration, NL, a synthetized index of quality is systematically used. The NL index is roughly defined, for each 200-meter-long section of a track, as the standard-deviation of both of its two longitudinal levels. An increase in NL in function of time indicates potentially a deterioration in the track geometry, usually combined with mechanical behavior problems [35]. On the other hand, a drop in NL signal would necessarily relate to a maintenance operation.

Figure 26 presents evolutions of the track NL that correspond to 200-meter-long sections, including the three instrumented sections. NL is hence displayed from PK 5+200 to PK 5+400, including Section 1 (PK 5+250), from PK 27+800 to 28+000, including Section 4 (PK27+850), and from PK 156+800 to PK 157+00, including Section 2 (PK156+850).

[1] Inertial Measurement Unit

It should be emphasized also that the measurements are carried out on 200-meter long sections whistle the length of the instrumented sections is approximately 10 meters, which remains very limited.

The dash-dot lines represent tamping or other maintenance operations. Tamping or other maintenance operations can be performed on singular points or on longer deteriorated sections. Tamping operations have been carried out on Section 2 in September 2017 and November 2019 and on Section 1 in September 2017.

These dates correspond to the periods when some accelerometer measurements increase:

- Accelerometers AS2, AS1 and AT3 (c.f. Figure 21, Figure 23 and Figure 24) on Section 2 (with granular sub-layer and clay soil)
- Accelerometer A6 (Figure 19) on Section 1 (with bituminous sub-layer and sandy soil)

It therefore appears that track defect or track deterioration could be observed using accelerometers placed under the ballast layer or on the sleepers. However, the results presented in this article also show that not all the accelerometers record a significant increase in acceleration levels. Furthermore, the precise location of the accelerometers below the ballast as regards the sleepers is not known (some accelerometers are below a sleeper, others between two sleepers). Thus, although initial results appear promising, more work needs to be carried out to improve our understanding of damage detection.

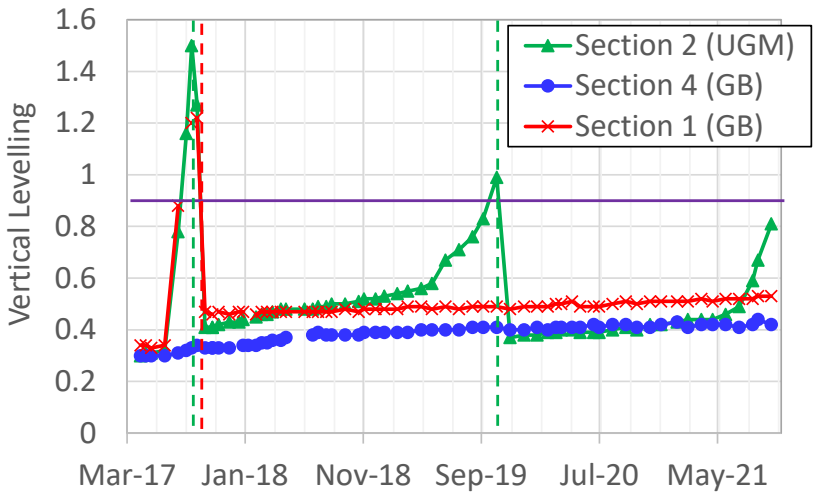

Figure 26. Vertical leveling measured on distances of 200 meters including Sections 2, 1 and 4

9. Conclusion

The BPL HSL consists of two different railway structures including either a granular or a bituminous sub-layer. In order to monitor the response of the two structures, three experimental sections with different sub-layers and subgrades (different type of soils) were instrumented with more than 100 sensors installed during the construction of the track.

More than 60 000 train passages, at different speeds and under different environmental conditions, were analyzed in this study which provides, for the first time, a continuous monitoring over a representative period of time of the behavior of bituminous sub-layers under in-service conditions.

The present paper therefore focuses on the analysis of the data recorded from the instrumented track sections during the commercial traffic phase of the line (from July 2017 to July 2021). The data analysis is based on measurements carried out under real traffic conditions. A method for automatic data processing is proposed, in order to enable the treatment of the large database.

The comparison of the behavior of the two track structures was carried out based on different measures obtained from instrumented Sections 2 (granular sub-ballast) and 4 (bituminous sub-ballast). Both sections have a clay subgrade. Section 1 has a bituminous sub-ballast and sandy subgrade.

Regarding track vertical displacement under a train passage, the deflection levels were observed to be similar on both Sections 2 and 4. However, the deflection level is higher on Section 1. This is most likely due to the difference in soil type, as the sandy subgrade appears to present higher water content changes with the seasons than the clay subgrade.

For similar reasons, the analysis of measured vertical strains reveals some higher levels on Section 1, compared to Sections 2 and 4.

The analysis of measured horizontal strains shows that extension strain values recorded at the bottom of the bituminous layer are very low, compared to commonly observed strain values in road structures. According to these observations, and based on road mechanics, almost no fatigue damage is expected to be induced to the bituminous material by HST traffic on the BPL HSL. The consistent and stable strain levels measured over more than 4 years since the first train travelled on the track structure are in accordance to this conclusion. Regarding the acceleration measured at the bottom of the ballast layer, for the three instrumented sections, the acceleration levels induced by train traffic increase as the train velocity increases. The observations made in this study clearly demonstrate that the presence of a bituminous sub-layer reduces the acceleration levels under the ballast and thus prevents its deterioration since this layer gains in stability, even after 4 years of service.

It is also important to underline the very good overall behavior of the track which presents very low values of deflection, vertical acceleration, vertical strain in the UGM layer and horizontal strains in the GB layer. Regarding these measurements, no significant evolution is noticed over the studied 4-year period. This indicates that the behavior of the track for the three instrumented sections is stable.

For the three instrumented sections, an increase of the vertical leveling also results in an increase of the acceleration levels recorded by some accelerometers. Once appropriate tamping operations or maintenance are carried out to correct the vertical alignment of the track, the acceleration levels get back to their value prior to the damage occurrence. The detection of track failure or track damage using accelerometers placed under the ballast layer or on the sleepers therefore appears possible. However, more work in this direction needs to be carried out.

Monitoring the BPL line has provided a large amount of information about the mechanical response of the track under high speed train loading. Five years after their implementation, most of the sensors are still working properly. Despite some interruptions in the data collection due to modem issues, the acquisition system and data transfer systems are still working too.

Disclosure statement

The authors indicate that there is no potential conflict of interest.

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References

[1] J.G. Rose, L.S. Bryson, Hot mix asphalt railway trackbeds: trackbed materials, performance evaluations, and significant implications. International Conference on Perpetual Pavements, Columbus, Ohio, USA, 2009

[2] J.G. Rose, R. Souleyrette, Hot-Mix Asphalt (Bituminous) Railway Trackbeds: In-Track Tests, Evaluations, and Performances – A Global Perspective – Part I - Introduction to Asphalt Trackbeds and International Applications and Practices, 3rd Int. Conf. Transp. Infrastruct., 2014a

[3] J.G. Rose, R. Souleyrette, Hot-Mix Asphalt (Bituminous) Railway Trackbeds: In-Track Tests, Evaluations, and Performances – A Global Perspective – Part II -United States Asphalt Trackbed Applications and Practices, 3rd Int. Conf. Transp. Infrastruct., 2014b

[4] M. Sol-Sánchez, L. Pirozzolo, F. Moreno-Navarro, M.C. Rubio-Gámez, Advanced characterisation of bituminous sub-ballast for its application in railway tracks: The influence of temperature, Construction and Building Materials, Vol 101, Part 1, 338-346, 2015, https://doi.org/10.1016/j.conbuildmat.2015.10.102

[5] S. Liu, X.H. Chen, Y.W. Ma, J. Yang, D.G. Cai, G.T. Yang, Modelling and in-situ measurement of dynamic behavior of asphalt supporting layer in slab track system, Constr. Build. Mater. 228, 2019, https://doi.org/10.1016/j.conbuildmat.2019.116776 116776

[6] D. Ramirez Cardona, H. Di Benedetto, C. Sauzeat, N. Calon, J.G. Rose, Designs, Application and Performances of Asphalt/Bituminous Trackbeds in European, Asian, and African Countries. Transportation Research Record: Journal of the Transportation Research Board, 2674(11), 245–262, 2020, https://doi.org/10.1177/0361198120945314

[7] J.G. Rose, R. Souleyrette, Asphalt Railway Trackbeds : Recent Designs , Applications and Performances. AREMA, Proceedings of the 2015 AREMA Annual Conference. Minneapolis, MN, 2015

[8] J.G. Rose, P.F. Teixeira, P. Veit, International Design Practices, Applications, and Performances of Asphalt / Bituminous Railway Trackbeds, Georail, 1–23, 2011

[9] A. Buonanno, R. Mele, The use of bituminous mix sub-ballast in the Italian State Railways, Proceedings of the papers submitted for review at the 2nd Eurasphalt and Eurobitume Congress, Barcelona, Spain, September 2000, https://trid.trb.org/view/674000

[10] P. Teixeira, A. Lopez Pita, Viability of Using Bituminous Subballast Layer on High-Speed Ballasted Tracks, Proceedings of the BCRA2005 - International Conference on Bearing Capacity of Roads, Railways and Airfields Conference, Trondheim, Norway, 2005

[11] P. Teixeira, A. Lopez Pita, P. Ferreira, New possibilities to reduce track costs on high-speed lines using a bituminous sub-ballast layer, International Journal of Pavement Engineering, 11, 301–307, 2010 https://doi.org/10.1080/10298431003749733

[12] D. Ramirez Cardona, Characterisation of thermomecanical properties of bituminous mixtures used for railway infrastructures, Université de Lyon (PhD Thesis), 2016

[13] J.G. Rose, Asphalt Underlayment Railway Trackbeds: Designs, Applications, and Long-Term Performance Evaluations, September 2017, trid.trb.org, https://trid.trb.org/view/1716813

[14] M. Sol-Sánchez, G. D'Angelo, Review of the design and maintenance technologies used to decelerate the deterioration of ballasted railway tracks, Construction and Building Materials, Vol 157, 402-415, 2017, https://doi.org/10.1016/j.conbuildmat.2017.09.007

[15] G. Di Mino, M. Di Liberto, C. Maggiore, S. Noto, S, A dynamic model of ballasted rail track with bituminous sub-ballast layer, Procedia-Social and Behavioral Sciences, 53, 366‐378, 2012

[16] P. Veit, Rechenmodell zur wirtschaftlichen Bewertung von Strategien im Bereich Fahrweg, [Calculation model for evaluation of track strategies]. Habilitationsschrift an der Technischen Universität Graz, 1999

[17] Y. Momoya, E. Sekine, Performance based design method for railway asphalt roadbed, Doboku Gakkai Ronbunshuu E, vol. 63, no 4, p. 608-19, 2007, https://doi.org/10.2208/jsceje.63.608

[18] F. Policicchio, Lineamenti di infrastrutture ferroviarie (Firenze University Press), 2017

[19] S.A. Albalat, L.M. Domingo, I.V. Sanchis, J.I.R. Herráiz, A.V. Segarra, Crumb Rubber Modified Bitumen for sub-ballast layer, 2011

[20] A. Robinet, A. Cuccaroni, L'expérience grave bitume de la LGV Est Européenne [A bituminous subballast layer on the Eastern Europen HSL (France)], In Proceedings of the 1st international symposium on railway geotechnical engineering - Georail 2011, pp. 477–484, 2011

[21] D. Khairallah, J. Blanc, L.M. Cottineau, P. Hornych., J.M. Piau, S. Pouget, M. Hosseingholian, A. Ducreau, and F. Savin, Monitoring of railway structures of the high-speed line BPL with bituminous and granular sub-layers. Construction and Building Materials 211, 337–348, 2019 https://doi.org/10.1016/j.conbuildmat.2019.03.084

[22] D. Khairallah, J. Blanc, L.M. Cottineau, P. Hornych, S. Pouget, M. Hosseingholian, A. Ducreau, F. Savin, Monitoring of railway structure with bituminous underlayment. In Proceedings of the 3rd international symposium on railway geotechnical engineering Georail-2017, Paris, 2017

[23] J. G. Rose, D. Li, L. Walker, Test measurements and performance evaluations of in-Service railway asphalt trackbeds. In Proceedings of the AREMA 2002 annual Conference (p. 30). Washington, DC., 2002

[24] V.-N. Trinh, N. Calon, A.M. Tang, Y.J. Cui, J.C. Dupla, J. Canou, A. Robinet, L. Lambert and O. Schoen, Caractérisation hydromécanique des matériaux constitutifs de plates-formes ferroviaires anciennes. In Proceedings of the 1st international symposium on railway geotechnical engineering – Georail 2011, pp. 377–388, 2011

[25] D. Khairallah, J. Blanc, P. Hornych, J.-M. Piau, L.-M. Cottineau, S. Pouget, A. Ducreau, F. Savin, and M. Hosseingholian, Influence of the Bituminous Layer on Temperature and Water Infiltration in

Railway Structures of the Bretagne–Pays de la Loire High-Speed Line, Journal of Testing and Evaluation 48, no. 1, 134–149, 2020a, https://doi.org/10.1520/JTE20180894

[26] O. Chupin, and J.M. Piau, Modeling of the dynamic response of ballast in high-speed train structures. 8th International Conference on Structural Dynamics, Jul 2011, Belgium, 712-718, 2011a

[27] O. Chupin, A. Martin, J.M. Piau, P.Y. Hicher, Calculation of the dynamic response of a viscoelastic railway structure based on a quasi-stationary approach, Int. J. Solids Struct., 51, 2297–2307, 2014

[28] A. Martin, Analyse numérique de la réponse dynamique de structures ferroviaires. Application à la réduction des désordres géométriques induits dans les couches de ballast des Lignes à Grande Vitesse. Ecole Centrale de Nantes, Nantes, PhD Thesis, 2014 (in French)

[29] D. Khairallah, Analyse et modélisation du comportement mécanique de structures de voies ferrées avec sous-couche bitumineuse [Analysis and modeling of the mechanical behavior of railway structures with bituminous underlayment] Ecole Centrale de Nantes, Nantes, PhD Thesis, 2019 (in French)

[30] D. Khairallah, O. Chupin, J. Blanc, P. Hornych, J.M. Piau, D. Ramirez, A. Ducreau, F. Savin, Monitoring and Modeling of Railway Structures of the High Speed Line BPL with Asphalt Concrete Underlayment, Transportation Research Record, Vol. 2674(12) 600–607, 2020b, DOI: 10.1177/0361198120960472

[31] European Norm EN 13848, Railway applications - Track - Track geometry quality - Part 1: Characterisation of track geometry, October 2017

[32] L. Caetano, P. Teixeira, Optimisation model to schedule railway track renewal operations: a life-cycle cost approach, Struct. Infrastruct. Eng.: Main. Manag., Life-Cycle Design Perform, 11 (11) 1524–1536, 2015

[33] H. Guler, Prediction of railway track geometry deterioration using artificial neural networks: a case study for Turkish state railways, Struct. Infrastruct. Eng.: Main. Manag. Life-Cycle Design Perform. 10 (5) 614–626, 2013

[34] D. Ramirez Cardona, H. Di Benedetto, C. Sauzéat, N. Calon, G, Saussine, Use of a bituminous mixture layer in high speed line trackbeds, Construction and Building Materials. 125, 398-407, 2016, http://dx.doi.org/10.1016/j.conbuildmat.2016.07.118

[35] P.E. Laurens, Prise en compte de la raideur de la voie dans la compréhension des mécanismes de dégradation du nivellement [Taking into account the track stiffness in the understanding of the vertical level degradation mechanisms]. In Proceedings of the 2nd international symposium on railway geotechnical engineering - Georail 2014, pp. 99–108, Marne la Vallée, France, 2014