Case studies & non-highway applications; Success and failure from real practice

Influence of bituminous sublayer on high speed line structure behaviour: Case study Brittany-Loire HSL

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Abstract

Feedback on the use of a bituminous sublayer in the trackbed of the Brittany-Loire (BPL) high-speed line (HSL) is presented in this paper. This ballasted HSL has 105km of innovative trackbed with bituminous sublayer (GB), and 77km of conventional unbound granular material (UGM) trackbed. In order to monitor the behaviour of the innovative track, three sections of the GB zone were instrumented with multiple sensors such as accelerometers, extensometers, anchored displacement sensors and temperature and humidity probes. A section of the UGM zone was also instrumented to serve as reference. The sensors were placed during the track construction at different positions and depths in order to monitor the behaviour of each component of the track, from the sleepers to the soil. This paper presents the acceleration (on sleepers and sublayer) and strain (in GB layer) measurements for train circulations at speeds ranging from 160 to 352 km/h. The comparison with the measurements from the reference section shows a clear reduction of the vertical accelerations of the track components with the use of a bituminous sublayer. This would lead to lower ballast deterioration induced by dynamic loads. Additionally, the magnitude of the strain measurements at the bottom of the bituminous layer was found to be compatible with the track structure dimensioning hypothesis, which validates the design. Moreover, the strain levels were observed to be very low, compared to typical values observed in conventional highway structures, which might lead to slow fatigue damage of the bituminous mixture. These observations suggest that the trackbed design and the used materials are compatible with the 100 years lifetime required for the HSL structure.

This paper was first published in 2020 in version 1.0 of the proceedings of the 7th E&E Congress. This second edition (version 1.1.) of the proceedings is published in June 2021. The content of this paper has not changed, but the author(s) may have provided additional information in the form of an annex.

1. INTRODUCTION

The challenges facing the development of railway transportation include allowing higher circulation speeds, heavier freight trains and increased traffic volume, while assuring high availability of the infrastructure to maximise its profitability. In order to achieve this, the time allocated to maintenance operations that occupy the tracks must be reduced as much as possible, in spite of the more aggressive traffic conditions.

A way to address the mentioned challenges is to propose an improved track structure that is less prone to degradations. In the case of ballasted tracks, ballast settlement is one of the main issues for which heavy and periodic maintenance operations are required. The main cause of these settlements is the degradation of the ballast grains under dynamic loads. There is a known relation between high accelerations in the ballast layer and settlements, which is specially observed in high-speed lines (HSL) [1]–[3].

The platform quality plays an important role in the dynamic stresses generated in the ballast layer. Water infiltration, poor compaction, inadequate material nature, amongst others, might lead to poor bearing capacities and to a poor stress transmission from the ballast to the underlayment. Fine particles might also migrate to the ballast layer, filling up the voids and acting as a lubricant that affects the friction between the grains lowering the capacity of the ballast to maintain the track in place.

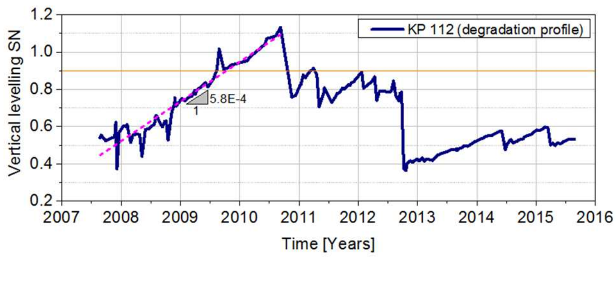
As an alternative to conventional unbound granular material (UGM) underlayments, rail authorities in the United States, and European and Asian countries, have been actively involved with the construction of bituminous subballast layers for more than fifty years. In spite of the different approaches towards the use of bituminous sublayers, all countries have observed a reduction of the maintenance needs of tracks with bituminous underlayment compared to UGM conventional ones [4], [5].

The SNCF allowed the use of bituminous sublayers on four recent HSL projects in France, including the Brittany-Loire (BPL) HSL which was built with this technique in over more than half of its length. The BPL HSL is indeed the first large-scale application of a bituminous sublayer in France. During the construction, four zones where instrumented by the IFSTTAR in the frame of a collaborative project named "Monitoring of BPL HSL" (Railenium, Eiffage, SNCF, SETEC, IFSTTAR and University of Lille). Data acquisition started during the train circulation tests of the line in 2016 and continues still, providing a rich source of information on the behaviour of both conventional and bituminous HSL tracks.

2. FRENCH HSL TRACK STRUCTURES AND INSTRUMENTED SECTIONS

French track structures consist on a layered system and the design method aims to optimize the thickness of each layer depending on the traffic conditions and on the quality of the subgrade. The ballast layer thickness depends mostly on the type of sleeper. The standard for HSLs is to use 30cm under the sleeper.

The first track section with a bituminous subballast layer in France was the East-European HSL trial section, which used a GB3 mixture (*grave bitume* class 3 according to the European Standard NF EN 13108-1-2007). The bearing capacity of the subgrade under the bituminous mixture is higher than 120 MPa. More information on this trail section can be found in [6]. One of the most interesting observations from the feedback on the EE HSL test section concerns maintenance needs. In service since June 2007, it has needed few maintenance operations compared to neighbouring equivalent conventional track sections. Moreover, the efficiency of the tamping operations in readjusting the track's geometry is also increased with respect to the zones with UGM platforms, as seen in Figure 1. The bituminous subballast in the EE HSL test section allowed reducing the amount of tamping per year by a factor 2.



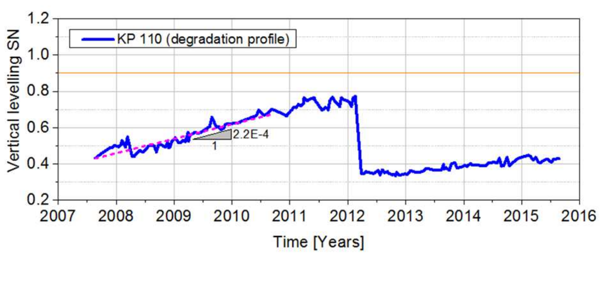


Figure 1 Vertical levelling evolution (bold line) over time: track section with UGM platform (left) and track section with GB3 platform (right)

Track geometry degradation is described by an unfavourable evolution of the position of the running plane. The indicator of such an evolution in France is the standard deviation of the vertical levelling. An increase of this indicator

can then be interpreted as a degradation of the geometry of the track in the vertical plane [7], [8]. For HSL, maintenance operations are mandatory when a threshold value of 0.9 is reached.
Even though track geometry degradation is mostly related to ballast wear, a poor evenness of the platform can create track geometry problems from the opening of the track to traffic. In France, there are no specific requirements for evenness of the platform, whether it is granular or bituminous. During the construction, the SNCF standard prescribes a ±3cm tolerance for the vertical position of the top of the subballast layer, and a ±10% tolerance of its thickness with respect to the design. These tolerances are very large compared to those applied for road structures, which are of the order of some millimetres. Paver finishers allow laying bituminous mixture layers high thickness precisions. Therefore, evenness requirements were easily respected.

The BPL HSL track design is shown in Figure 1. A GB4 mixture was used, which is a better performing material than the GB3. Commonly used as highway base-course material, a GB4 has a |E*| modulus higher than 11GPa and a fatigue resistance value ε_6 higher than 110µm/m (NF EN 13108-1-2007). The GB4 layer has a transversal slope of 2.5% compared to the standard 4% for UGM layers. The GB4 layer lays on an adjustment UGM layer (to compensate for the transversal slope difference), which lays on top of a subgrade that was treated with lime and a hydraulic binder to achieve a minimum EV2 modulus (plate test) of the platform of 80MPa.

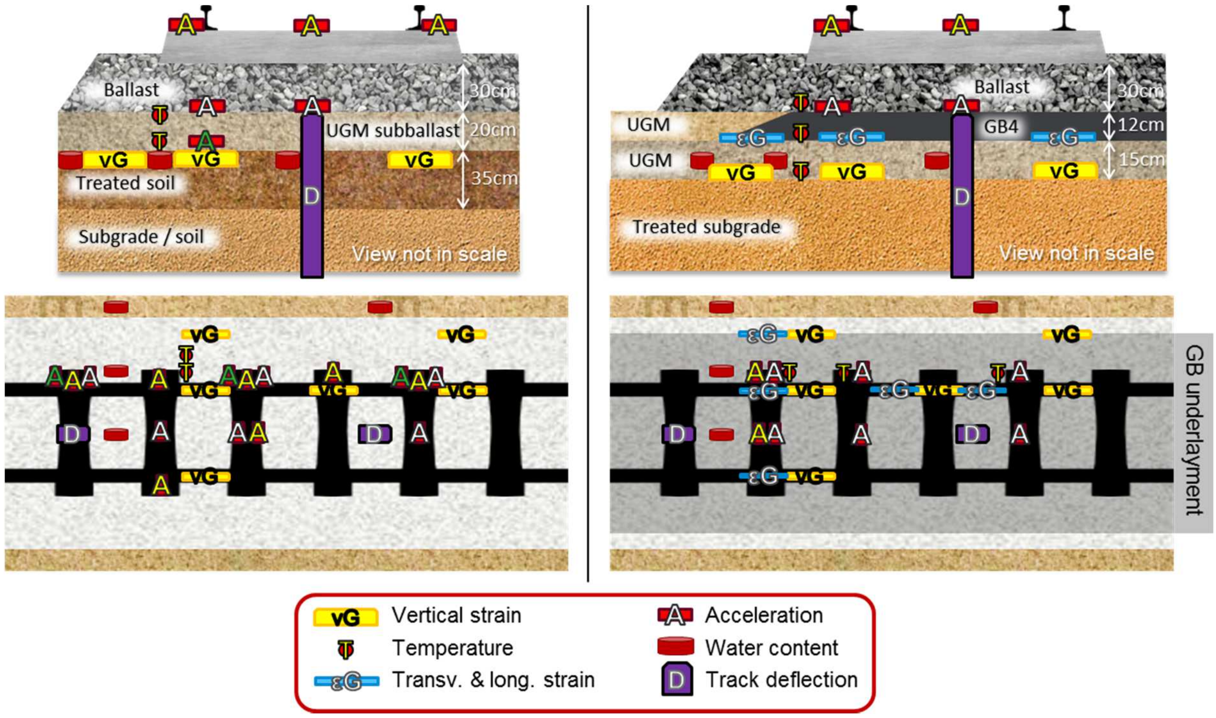


Figure 2 Scheme of the track structures and instrumentation of the BPL HSL: Instrumented section 2 in conventional UGM structure (left) and Instrumented section 4 with bituminous underlayment (right) [9]

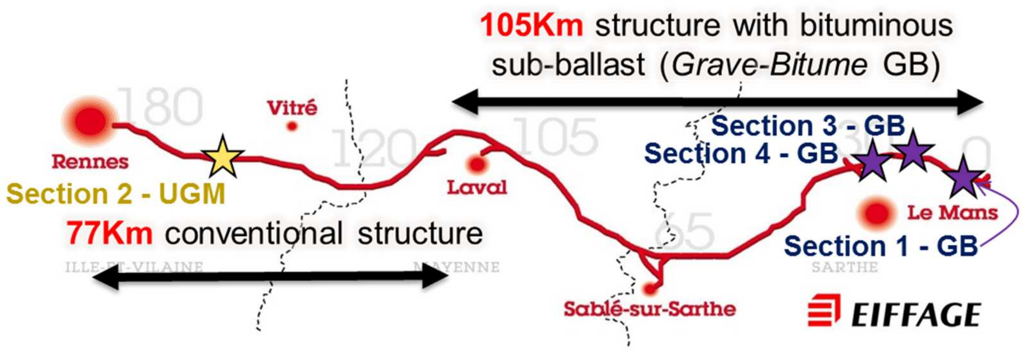


Figure 3 Overview of the BPL HSL and indicative location of the instrumented sections

The instrumentation of the BPL HSL is the most extensive one in France at the moment. Sections 2 and 4 are each instrumented with [10]:
- A weather station to monitor environmental conditions.
- Accelerometers to measure the vertical accelerations at different track levels: on the sleepers, at the top and at the bottom of the bituminous and granular subballast.
- Strain gages to measure vertical, longitudinal and transverse strains.
- Temperature probes.
- Moisture content probes to quantify seasonal water content variations. These measures are also used to calculate the deformations due to moisture content variations of the subgrade.
- Anchored displacement sensors to measure the structure's total displacement under the ballast (total deflection between the top of the subballast and a reference point located 6m deep below the track).
- A PEGASE data acquisition system that transfers the measurements to a cloud storage and that can be programmed remotely to change the data acquisition parameters [11].

This paper focuses on the comparison between instrumented zones 2 (UGM) and 4 (GB4) (cf. Figures 2 and 3). The instrumentation of these zones is as follows:
- Section 2 (PK 156+950): 6 vertical strain gages, 16 accelerometers, 4 moisture content probes, 2 temperature sensors, 2 anchored displacement sensors and a weather station.
- Section 4 (PK 27+850): 6 vertical strain gages, 10 extensometers (5 longitudinal and 5 transversal horizontal strain gauges) in the asphalt layer, 8 accelerometers, 4 moisture content probes, 3 temperature sensors, 2 anchored displacement sensors and a weather station.

3. BPL HSL DATA ACQUISITION AND TREATMENT

Two types of measurements are recorded at each instrumented section of the BPL HSL. On the one hand, the so-called "slow" ones are registered continuously (every 15 minutes) and comprise temperature, soil moisture content, track deflexion and weather conditions. On the other hand, the "fast" measurements are recorded by the accelerometers, extensometers and vertical strain gauges when triggered by the approach of a train.

The data acquisition started with the first circulations on the BPL HSL in November 2016. These first circulations where part of the speed-up trials of the new HSL, using one single train at different speeds to test the integrity of the track. The trains were French TGV type trains with 2 motor locomotives, and 8 passenger cars. Each train has 13 bogies with axle loads of 17ton for the locomotive, and about 14.5ton for passenger cars. The wheelbase of these bogies is 3m. The fact that the same train type was used during this speed-up phase facilitate the analysis of the measurements since the load is known and constant. The speed of the train varied from 160 to 352km/h. In this paper, only the results from this speed-up test phase are presented.

Once obtained, the data was treated using an automate signal processing protocol created using the SciLab software. More than 50 data files are treated per train passage. The SciLab protocol is as follows:
- Scale the measurements of the sensors installed
- Register the date and time, and calculate the speed of the train using the time offset between the same measure taken by different sensors (distance between sensors known)
- Filter the signals using a low pass filter
- Plot the signal of the selected sensors for a selected lapse of time [12]

The measurements presented in this paper correspond to the mean signal of the carrying (passenger cars) bogies. The motor bogies are excluded. Figure 4 presents an example of a filtered acceleration signal of a train passing at 320km/h. The figure presents the signal that is used to analyse the track's behaviour. For each signal of every sensor, the signals of each carrying bogie are extracted, then superimposed and statistically treated to calculate the mean curve and the curves corresponding to +/- one standard deviation. Figure 5 presents an example of superimposed vertical displacement signals. Acceleration and vertical displacement measures were verified by comparing the measured acceleration to the double derivation of the displacement.

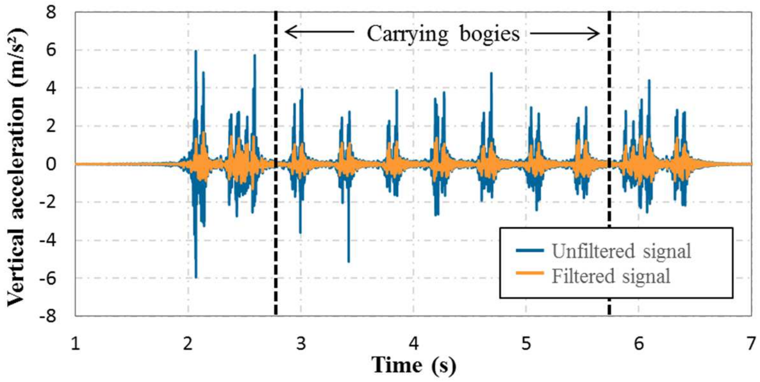


Figure 4 Filtered acceleration signal for a train passage (speed 160km/h) [9]

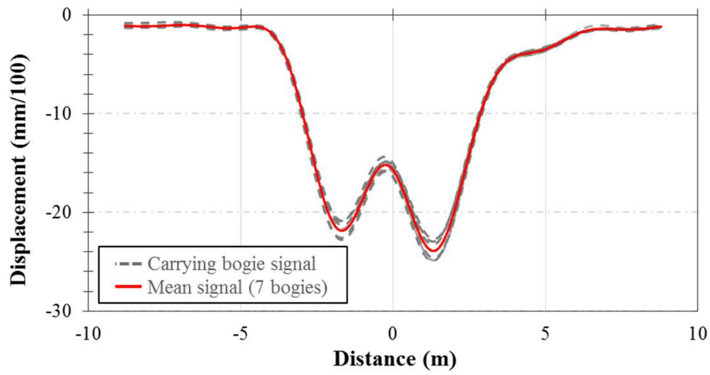


Figure 5 Superimposed displacement signals of seven carrier bogies and mean displacement signal [13]

4. EFFECT OF THE BITUMINOUS SUBBALLAST ON TRACK BEHAVIOUR

Two principal measures allow comparing the behaviour of the bituminous and conventional UGM tracks: deflection and vertical acceleration. Temperature variations during the speed-up trial period (November 2016 to January 2017) were very small (Max. 10°C and Min. 2°C). Under these conditions, the bituminous mixture presents a stiff behaviour and the modulus variations can be neglected.

Figure 6 presents the mean deflexion signal for sections 2 (UGM) and 4 (GB4) for a single train passing at 320km/h. The signals from each pair of displacement sensors are very similar, showing that the measurements are repeatable. The deflection signal on the bituminous track presents a lower elastic return than that of the UGM structure. Moreover both structures present similar maximum displacement values. This indicates that the bituminous layer smoothens the displacements making them less aggressive for the track.

Maximum vertical deflection values are presented in Figure 7 for both sections 2 (UGM) and 4 (GB4) as a function of the train speed. It is observed that both structures present similar track deflection values of the order of 25mm/100. These low and stable defection values are probably related to the high bearing capacity of the treated subgrade or soil layer beneath the subballast. It is important to note that the soil treatment, which was done on the whole BPL line, was very effective and most EV2 measures were over 250MPa. Moreover, no significant effect on track deflection of the train speed is observed. These observations lead to allowing the direct comparison between the two structures in terms of acceleration and strain.

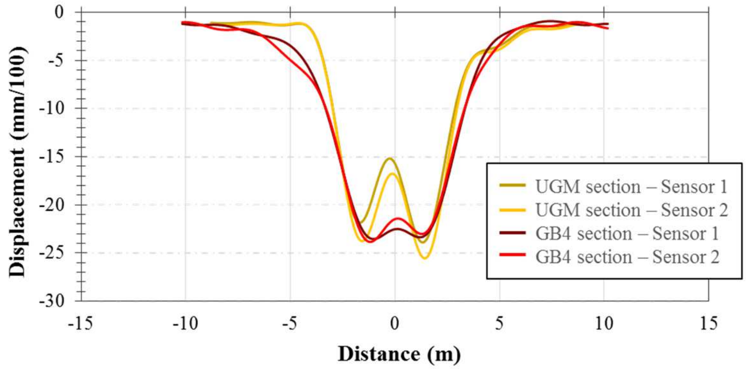


Figure 6 Mean signals of anchored displacement sensors on Section 2 (UGM) and Section 4 (GB4) - Train speed = 320 km/h [13]

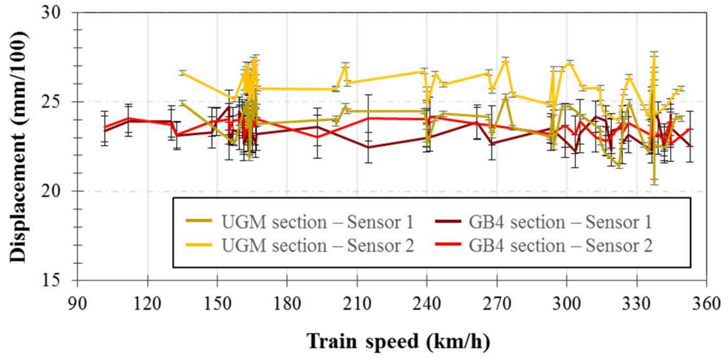


Figure 7 Track deflection measures – Section 2 (UGM) and Section 4 (GB4) BPL HSL [13]

Vertical deflection is an indicator of the track vertical stiffness: the lesser the displacements, the stiffer the track. Vertical track stiffness is an important design parameter for railway tracks. Previous studies, based on the EE HSL test section, found that the bituminous track to be less than 10% stiffer than the conventional UGM [6], [14]. The study by [14] identified a clear correlation between vertical stiffness variations along the track and track degradation. As for the BPL HSL data, the maximum track deflection values on the EE HSL did not show significant differences between the conventional and bituminous tracks. However, the vertical stiffness standard deviation along the bituminous section length was found to be 40% less than that of the UGM sections. Considering the hypothesis of a perfectly elastic track, this stiffness homogeneity would mean a substantial reduction of the differential settlements of the bituminous track under dynamic loading at the specific used EWM test conditions. Given the viscoelastic behaviour of the bituminous layer, different standard deviation values can be obtained at higher loading frequencies and different temperatures. Nonetheless, the study by [14], and the correspondence between the EE HSL and BPL HSL deflection measurements, highlight the beneficent effect of the bituminous layer in terms of track stiffness.

The acceleration levels measured on the sleepers and at the top of the subballast layer (under the sleepers) are presented. Acceleration levels at the interface between subballast and ballast layers are in direct relation with ballast wear and deformation. For each train passing and for each accelerometer, the maximum positive accelerations (oriented upwards) and the minimum negative accelerations (oriented downwards) were obtained from the mean signals of the seven carrying bogies to reduce variability. The standard deviation is presented.

As for the acceleration measured on the sleepers, there is no evident difference between the bituminous and UGM tracks (Figure 8). However, the acceleration values measured on the track with bituminous underlayment are in the lower end of the measured values presented, especially for train speeds below 300km/h. At speeds higher than 300km/h, the acceleration values are more scattered which can be due to a stability loss at the top of the structure when loaded at very high frequencies. These observations are in concordance with the measures from the EE HSL [15].

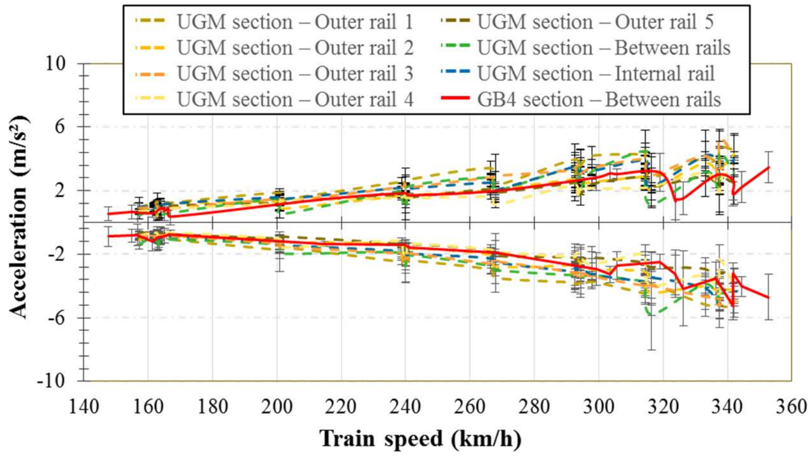


Figure 8 Maximum upwards and downwards acceleration values on the sleeper – Section 2 (UGM) and Section 4 (GB4) BPL HSL [13]

Figures 9 and 10 present the maximum and minimum acceleration values at the axis of the track and under the outer rail, respectively. For both figures, the full lines represent the bituminous track (Section 4) and the dotted lines represent the conventional UGM track (Section 2).

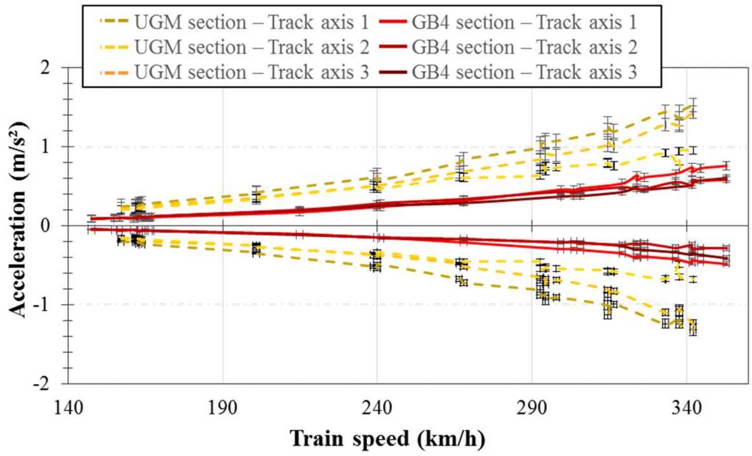


Figure 9 Maximum upwards and downwards acceleration values at the top of the subballast layer at the axis of the track – Section 2 (UGM) and Section 4 (GB4) BPL HSL [13]

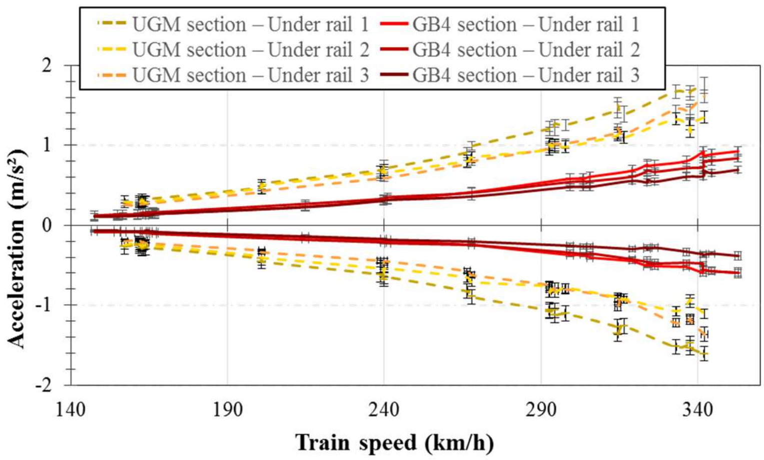


Figure 10 Maximum upwards and downwards acceleration values at the top of the subballast layer under the outer rail – Section 2 (UGM) and Section 4 (GB4) BPL HSL [13]

According to previous studies, the most damaging effect on the ballast layer is generated by the downwards-oriented accelerations which reduce the apparent weight of the grains and, therefore, reduce the inter-granular friction forces [16], [17]. It is observed that both upwards and downwards-oriented acceleration maximal values are much lower in the bituminous track section than in the conventional UGM one. The ratio between the acceleration at the top of the subballast layer between the bituminous track and the UGM one can be estimated at 60%. Moreover, for the bituminous track, the acceleration measured at the axis is lower than that measured under the outer rail, which is not observed for the UGM track.

These lower acceleration values might explain the lower maintenance needs observed in ballasted tracks with bituminous underlayment (both high-speed and classical), compared to conventional UGM tracks [5], [18].

5. LOADING CONDITIONS OF THE BITUMINOUS SUBBALLAST LAYER

The bituminous subballast layer was designed accordingly to the French design method for asphalt pavements. This method imposes a minimum thickness for each layer of the pavement structure in order to limit vertical deformations and premature fatigue failure.

In order to validate and to monitor the evolution of the strain levels at the bottom of the bituminous subballast, horizontal extensometers (strain gauges) were placed in 2 instrumented bituminous track sections (1 and 4), on both transversal and longitudinal directions.

Figure 11 presents an example of a filtered signal for the 3 extensometers in section 4 (GB) placed under the outer rail for a train circulating at 320km/h.

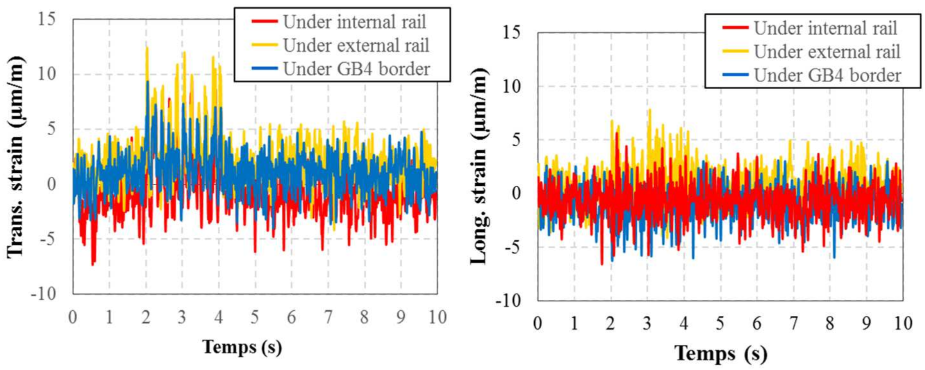


Figure 11 Transversal (left) and longitudinal (right) strain filtered signals at the bottom of the bituminous subballast of Section 4 (GB4) - Train speed = 320 km/h [9]

The measured strain values at the bottom of the bituminous subballast of the HSL BPL are very small (lower than 15µm/m) compared to typical strain levels observed in road pavements which range between 30µm/m and 40 µm/m. The same order of magnitude was observed in the test section of the EE HSL [6]. The signals recorded by the extensometers did not allow the identification of the bogies due to the low levels recorded which are very close to the noise amplitude. Therefore, only the maximum value of the filtered signal was analysed for each train passing.

The research held by [19] studied the strain created by a 13 ton/axle truck at different depths of the pavement structure. The truck circulation speed varied from 20 km/h to 90 km/h. The strain gauges were placed at various depths within the pavement structure, with the deepest ones at 19cm from the road surface. In comparison, the strain gauges of the BPL HSL were placed at (at least) 70cm from the top of the rail. The position of the bottom of the bituminous layer with respect to the effort application (wheel) is then very different from a road to a ballasted track. This means that the effort transmitted to the bituminous mixture is very different between both structures. Moreover, [20] found that the beam action of the rail, which distributed the wheel loads over several sleepers and then to the well confined stiff ballast layer, effectively reduces the axle loadings effect on the bituminous layer which acts also as a beam when transmitting the load to the subgrade. They concluded that the pressures applied at the sub-ballast bituminous layer are only a fraction in magnitude of the typical pressures applied by road traffic at the surface of a highway pavement. They further concluded that the sub-ballast bituminous layer should have extremely long fatigue life given the low load-induced pressure levels.

Table 1 shows the mean maximal strain levels at the bottom of the bituminous subballast with the train speed. It is observed that, indeed, the strain level is low (<10µm/m) for all train speeds. Table 2 compares the vertical strain at the top of the structural layer beneath the subballast of the UGM and bituminous structures. The two structures are submitted to very low vertical strain levels which can be related to the highly efficient treatment of the soils with hydraulic binders. However, it is observed that the bituminous subballast reduces the vertical strain, for all train speeds.

Table 1 Maximum horizontal strain values at the bottom of the bituminous subballast layer under the outer rail – Section 4 (GB4) BPL HSL [9]

Train speed (km/h)	Mean maximum strain value (µm/m)	
	Transversal	Longitudinal
160	11,5	12,2
320	8,4	14,6

Table 2 Maximum vertical strain values at the top of the capping layer under the outer rail – Comparison section 2 (UGM – top of added treated soil layer) and section 4 (GB4 – top of treated in-situ subgrade) BPL HSL [9]

Train speed (km/h)	Mean maximum strain value (µm/m)	
	Section 2 - UGM	Section 4 – GB4
160	18	12
320	20	12

The study by [19] highlighted a significant reduction of the strain with the increase of the speed. They observed strain levels going from 25µm/m, for a truck circulating at 12 km/h, to 9µm/m for the same truck at 70km/h. These observations, even if they do not correspond to the circulation of a high-speed train on a HSL, serve as reference to validate the order of magnitude of the experimental measurements at the BPL HSL bituminous track.

Given such low strain levels, the good fatigue resistance properties of the used GB4 mixture and the layer thickness of 12cm, the bituminous subballast of the BPL HSL should present a very long fatigue lifetime according to the French design method for asphalt pavements. This is in accordance to the conclusions of the study by [20].

6. DISCUSSION AND CONCLUSION

The use of a bituminous subballast layer was proposed to reduce the acceleration levels in French HSLs, which are one of the main causes of ballast settlement and wear. The measurements obtained from the instrumented sections of the recently built Brittany-Loire HSL allowed observing the effect of this innovative technology on the HSL track behaviour, compared to a conventional track with only unbound granular materials.

The reliability of the measures obtained from the BPL HSL instrumentation has been proven by evaluating the repeatability of the measurements during the speed-up test phase of the line. This instrumentation provides a rich source of information on the behaviour of ballasted high-speed tracks.

Concerning vertical displacements, both conventional UGM and bituminous track structures present similar maximal values, for all train circulation speeds. This validates the direct comparison of both structures in terms of acceleration.

Acceleration levels on the sleepers and at the top of the subballast layer were observed to be significantly lower when a bituminous subballast is present, for all train circulation speeds. This is beneficial for the ballast integrity and for the general stability of the track. These observations can be related to the confirmed lower maintenance needs of ballasted tracks with bituminous subballast in France and other countries in Europe, Asia and America.

Concerning the working conditions of the bituminous material as a subballast layer, compared to its more common use in road pavements, the strain levels observed at the bottom of the layer were found to be very small. This suggests that the bituminous mixtures should have a very long fatigue life as subballast as long as they lay on good quality subgrades and are not damaged by railway maintenance operations, water infiltration.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the FEREC association and Railenium Research Institute for financing this project.

REFERENCES

[1] A. L. Pita, P. F. Teixeira, and F. Robuste, “High speed and track deterioration: The role of vertical stiffness of the track,” *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 218, no. 1, pp. 31–40, Jan. 2004.

[2] J. C. Quezada, “Mécanismes de tassement du ballast et sa variabilité,” 2012.

[3] G. Saussine, “Contribution à la modélisation de granulats tridimensionnels : application au ballast.,” Oct. 2004.

[4] J. G. Rose, “Asphalt Underlayment Railway Trackbeds : Designs , Applications , and Long-Term Performance Evaluations,” National University Rail Center - NURail US DOT OST-R Tier 1 University Transportation Center, 2017.

[5] D. Ramirez Cardona, H. Di Benedetto, C. Sauzeat, N. Calon, and J. G. Rose, “Designs, application and performances of asphalt trackbeds in European and Asian countries,” in *Railway Engineering 2019*, 2019, pp. 1–11.

[6] D. Ramirez Cardona, “Characterisation of thermomechanical properties of bituminous mixtures used for railway infrastructures,” Ecole Nationale des travaux publics de l’état (ENTPE), University of Lyon, 2016.

[7] L. F. Caetano and P. F. Teixeira, “Optimisation model to schedule railway track renewal operations: a life-cycle cost approach,” *Struct. Infrastruct. Eng.*, vol. 11, no. 11, pp. 1524–1536, Nov. 2015.

[8] International Union of Railways, *Best practice guide for optimum track geometry durability*. Paris, France, 2008.

[9] D. Khairallah, “Analyse et modélisation du comportement mécanique des structures de voies ferrées avec sous-couche bitumineuse,” Ecole Centrale de Nantes, 2019.

[10] D. Khairallah *et al.*, “Monitoring of railway structure with bituminous underlayment,” in *Georail 2017*, 2017.

[11] V. Le Cam, L. Lemarchand, W. Martin, and N. Bonnec, “Improving wireless sensor behavior by means of generic strategies,” in *Structural health monitoring 2010 : proceedings of the fifth European Workshop*, M. Giordana and F. Casciati, Eds. Naples, Italy, 2010, pp. 696–703.

[12] D. Khairallah *et al.*, “Monitoring of railway structures HSL BPL with bituminous layer,” in *Proceedings of the 7th Transport Research Arena TRA 2018*, 2018.

[13] D. Khairallah *et al.*, “Monitoring of railway structures of the high speed line BPL with bituminous and granular sublayers,” *Constr. Build. Mater.*, vol. 211, pp. 337–348, Jun. 2019.

[14] 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*, 2014, pp. 99–108.

[15] D. A. Ramirez Cardona *et al.*, “High-speed ballasted track behavior with sub-ballast bituminous layer,” in *Proceedings of the 2nd international symposium on railway geotechnical engineering - Georail 2014*, 2014, pp. 139–148.

[16] O. Chupin, A. Martin, J.-M. Piau, and P.-Y. Hicher, “Calculation of the dynamic response of a viscoelastic railway structure based on a quasi-stationary approach,” *Int. J. Solids Struct.*, vol. 51, no. 13, pp. 2297–2307, Jun. 2014.

[17] O. Chupin and J.-M. Piau, “Modeling of the dynamic response of ballast in high-speed train structures,” in *8th International Conference on Structural Dynamics - EURODYN 2011*, 2011, pp. 712–718.

[18] D. Ramirez Cardona, H. Di Benedetto, C. Sauzeat, N. Calon, and G. Saussine, “Use of a bituminous mixture layer in high-speed line trackbeds,” *Constr. Build. Mater.*, vol. 125, pp. 398–407, 2016.

[19] P. Gaborit, C. Sauzéat, H. Di Benedetto, S. Pouget, F. Olard, and A. Claude, “Investigation of highway pavements using in-situ strain sensors,” in *Sustainability, Eco-efficiency, and Conservation in Transportation Infrastructure Asset Management*, Massimo Losa and Tom Papagiannakis, Ed. London, UK: CRC Press, 2014, pp. 331–337.

[20] J. G. Rose, D. Li, and L. Walker, “Test measurements and performance evaluations of in-Service railway asphalt trackbeds,” in *Proceedings of the AREMA 2002 annual Conference*, 2002, p. 30.