RIVAS
Railway Induced Vibration Abatement Solutions
Collaborative project

DESIGN GUIDE AND TECHNOLOGY ASSESSMENT OF THE TRACK MITIGATION MEASURES

Deliverable D3.13

Submission Date: 31/12/2013

Project coordinator:
Wolfgang BEHR
International Union of Railways (UIC)
ext.behr@uic.org

Title	Del 3.13: DESIGN GUIDE AND TECHNOLOGY ASSESSMENT OF THE TRACK MITIGATION MEASURES
Domain	**WP 3 task 5**
Date	**31 December 2013**
Author/Authors	E. Bongini, R. Müller, R. Garburg, A. Pieringer
Partner	
Document Code	RIVAS_UIC_ WP3_D3_13
Version	V5
Status	Final

Dissemination level: PP

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission) Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document history		
Revision	Date	Description
1	12/11/2013	First Draft
2	13/12/2013	Second draft
3	17/12/2013	Third draft
4	29/12/2013	Final draft
5	31/12/2013	Final

TABLE OF CONTENTS

1. INTRODUCTION

Within the frame of the EU FP7 project 'Railway induced vibration abatement solutions (RIVAS)', abatement measures for ground-borne noise and vibrations for tracks at grade are studied. The aim is to develop innovative measures at the source to reduce the annoyance of lineside residents. Mitigation measures studied apply to rail vehicle design, rolling stock maintenance, track design, track maintenance, sub-grade engineering, and the transmission path within the railway infrastructure.

Work package 3 of RIVAS focuses on railway infrastructure based vibration reduction technologies in the superstructure of the track

This report is intended as a practical design guide for the in-track mitigation measures that have been studied within the frame of RIVAS. The focus goes to the soft under-sleeper pads and soft to very soft fastening systems as these are considered most suited for practical implementation: they do not require a complete track rebuilding as it is the case for ballast mats.

The first type of mitigation measure is soft under-sleeper pads implemented in ballasted track. The impact of soft USP is also considered with different types of sleepers: standard, heavy and wide sleepers. After an extensive numerical study, the USP with different types of sleepers have been characterized in laboratory. The final step has consisted in a scale 1:1 test for which various combination of soft USP and sleeper types have been installed. In the same time, fatigue tests in realistic conditions have been carried out in the track box of Cedex.

In parallel, the soft USP potential mitigation effect has been checked for curve sections of track. Their installation in a real curve has also allowed checking their effect on track lateral stability.

The second type of mitigation measure is very soft fastening systems. A same numerical parametric simulation than the one performed for USP has allowed assessing their potential mitigation effect as well as the influence of external parameters on this effect (ground conditions, wheelset mass…). Laboratory tests have been carried out both for certification purpose (that allows this system to be installed in a real track) and for a precise assessment of the real fastening system (the one that will be installed in track) dynamic performances. Finally, in-track installation has been done, on a freight commercial track in France, to check the impact on ground vibration as well as the serviceability of the system.

The third type of mitigation measure is soft under-sleeper pads in slab track system such as GETRAC® A3 system. Same process has been followed: first the potential effect of such mitigation system has been checked with numerical simulation and, after laboratory characterization, the newly designed GETRAC A3.1 system with soft USP has been installed on a scale 1:1 test rig to be tested.

The outline of the design guide is as follows. First, general recommendations are given for the assessment and the design of vibration mitigation measures. This includes the assessment for a need for vibration mitigation as well as a discussion of geotechnical and geophysical tests required for the design of the mitigation measure. Second, a general discussion of the three types of mitigation measures is given. Since costs and effects of vibration mitigation are highly depending on track conditions, these are only discussed in general terms in this section. Third, in the annexes, for each mitigation measure, a case study is discussed. These case studies relate the field tests carried out in RIVAS.

2. RAILWAY APPLICATION OF VIBRATION MITIGATION MEASURES IN THE TRACK

2.1 GENERAL RECOMMENDATIONS

General recommended procedure for assessment and design of vibration mitigation measures.

The following procedures are based on the requirements of the ISO 14837-1 [1] and ISO 2017-2) standards

STEP 1 - First assessment to check the need for vibration mitigation measure

<table>
<tr><th>No</th><th>Train Induced Vibrations</th><th>Remarks</th></tr>
<tr><td>1</td><td>Risk assessment for vibration problems
• Construction of new railway lines
o Assessment of possible vibration problems for construction of new houses close to the newly planned railway.
▪ Restriction on construction of new houses close to the railway line in case required vibration mitigation measures (at track or at building) are not economically acceptable.
o Vibration risk assessment for existing houses close to the newly planned railway.
▪ Reconsidering railway line position in case required vibration mitigation measures are not economically acceptable.
o Guidance on the prediction of ground-borne noise and vibration for newly planned railway lines is provided in ISO 14837-1 [1]. Depending on the stage of development of the line, a distinction is made between scoping (earliest stage), environmental assessment (planning process) and detailed design models (part of construction and design).
• Existing railway lines
o Assessment of possible vibration problems for construction of new houses close to an existing railway line.
▪ Restriction on construction of new houses close to the railway line in case required</td><td>Railway administration
+
Vibration risk expertise</td></tr>
</table>

No	Train Induced Vibrations	Remarks
	vibration mitigation measures (at building or at track) are not economically acceptable. o Assessment of vibration levels for existing houses close to an existing railway line. ▪ Collect and investigate vibration complaints, assessment of vibration levels by means of measurements. o Existing houses close to the existing railway line with new operation conditions (additional track, new turnout, higher speed or/and higher axle loads, etc.) ▪ Vibration risk assessment similar as for new lines.	

In case there is a risk for excessive railway induced environmental vibrations according to limit values valid for the country, the following procedure is recommended:

STEP 2 - Geotechnical investigations and vibration measurements (see also some reports of WP1.3)

1	**Collection of all available documents and existing vibration records** The first step involves a study of archive records like geological maps, results of previous geotechnical and geophysical tests and vibration measurements: • documentation, drawings, reports, geological maps; • previous geotechnical and geophysical investigations, laboratory tests and in situ tests; • vibration measurements for existing railway lines.	***Railway administration***
2	**Complementary geotechnical investigations–assessment of dynamic soil characteristics and vibration propagation** In a second step, more detailed information is gathered from additional laboratory and in situ tests. A first set of tests is intended for soil classification and determination of classical soil mechanics parameters required for the geotechnical design of mitigation measures on the transmission path. It is not required when mitigation measures on track are foreseen. These tests include: • Classical soil mechanics laboratory tests o Index properties of soils ▪ Water content ▪ Bulk and dry density of intact soil	***Geotechnical and geophysical competence***

	▪ Soil particles density, particles unit weight and specific gravity of soil solids ▪ Void ratio, porosity and relative density ▪ Grain size distribution ▪ Plasticity of soils, Atterberg limits, consistency and plasticity index ▪ Overconsolidation ratio o Strength of soils ▪ Unconfined compression test ▪ Unconsolidated undrained triaxial compression test ▪ Consolidated drained triaxial compression test ▪ Consolidated undrained triaxial compression test ▪ Direct shear box test o Compressibility and deformation of soils/ oedometer testing ▪ Consolidation ▪ Swelling and swelling pressure • Classical soil mechanics in situ tests o Cone penetration and piezocone penetration test (CPT, CPTU) o Standard penetration test (SPT) o Other national applicable test In order to assess the efficiency of vibration mitigation measures by means of numerical simulations, a second set of tests allowing for the identification of the dynamic soil properties is required, for all kind of mitigation measures foreseen. Assuming the soil is composed of isotropic and homogeneous elastic layers, parameters to be determined for each layer include shear wave velocity $C_{s,}$ dilatational wave velocity C_p, hysteretic material damping ratios $ß_s$ and $ß_p$ in shear and dilatational deformation, and soil density. The dynamic soil characteristics need to be determined up to a depth that depends on the frequency range of interest and the stiffness of the soil. • In situ seismic tests allow exploring a representative volume of soil in natural stress and compaction conditions at small strain levels and include: o Seismic refraction	

<table>
<tr><td></td><td>

Down-hole testing
Up-hole testing
Cross-hole testing
Seismic cone penetration test (SCPT)
Suspension PS logging
Spectral Analysis of Surface Waves (SASW)
Seismic tomography

Laboratory tests on undisturbed samples may be used to determine the strain dependency of the shear modulus and material damping ratio and include:

Resonant column test
Bender element test
Cyclic simple shear test
Cyclic triaxial test

Test procedures for the determination of the dynamic soil characteristics within the frame of the RIVAS project are defined in deliverable D1.1 [2].
</td><td></td></tr>
<tr><td>3</td><td>
Vibration measurements
New or complementary vibrations measurements may be made in order to study:

Response of the track (rails, sleepers, embankment) and soil in the immediate vicinity of the source.
Propagation of vibration from the track into the free field.
Building response, including amplification in walls and floors compared to free field level next to the building and foundation level.
Response at specific locations inside the building, i.e. near sensitive equipment.

The aim of this study is to specify and quantify the need for vibration reduction.
</td><td>Vibration measurements competence</td></tr>
</table>

In case geotechnical investigations and vibration measurements show clear need for installation of vibration mitigation measures the following procedure is recommended (this procedure is usable for mitigation measures on the rolling stock, in the track as well as on the propagation path):

STEP 3 - Design of vibration mitigation measures

<table>
<tr><td>1</td><td>Assessment of suitable vibration mitigation methods
Define an actual area where vibration mitigation is needed (see STEP 2)
Detailed overview of critical area
Required effect of vibration mitigation
Required lifetime
Installation limits (environment, space)
Risk analysis for particular houses
Social issues (for example public information about expected effect of mitigation measure)
Study of different vibration mitigation methods
Preliminary evaluation of costs
Suggestion for several suitable/acceptable mitigation methods</td><td>Railway administration</td></tr>
<tr><td>2</td><td>Advanced computer simulations and modelling
Choice of suitable numerical model and software, able to deal with simulation of 2D and 3D dynamic soil-structure interaction problems.
Design of different models – geometries, structures and transport operations
Assessment of input parameters for numeric simulations
Numeric simulations and parametric studies
Evaluation, conclusion and selection of the most (cost-) effective mitigation method</td><td>Theoretical and practical competence</td></tr>
<tr><td>3</td><td>Final design of vibration mitigation
Decision on the most effective, economically and social acceptable mitigation method
Detailed construction design
Construction costs and estimation of maintenance costs
Installation procedure, limits on train operations and track possession costs, and evaluation of impact on surroundings
Time schedule for installation</td><td>Railway administration and

Vibration mitigation design competence</td></tr>
</table>

2.2 VIBRATION MITIGATION MEASURES IN THE TRACK – METHODS OF INTEREST

The mitigation measures that could be installed in track have been studied within RIVAS considering the different track configurations that could be encountered: ballasted straight line, curves, turnouts and slab tracks.

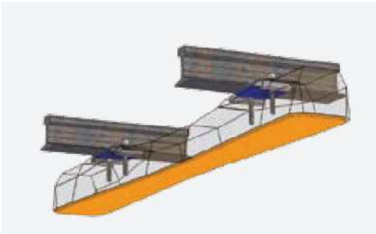
For the straight ballasted track, 2 different mitigation measures have been tested: soft under-sleeper pads coupled with heavy sleepers reported in the table 2.2.1, soft USP in 2.2.2 and soft to very soft rail fastening systems reported in the table 2.2.3.

For the curves, soft under sleeper pads have been installed in different curves. The special case of USP in curves is reported in table 2.2.1 – 8

For the switch configuration, the USP installation and performance assessment have rapidly highlighted a very complex situation. The section 2.2.4 is dedicated to conclusions obtained concerning ground borne vibrations induced by switches.

For the slab track, soft under sleeper pads have been installed in the existing GETRAC A3 system. The results of this combination are reported in table 2.2.3.

2.2.1 Under sleeper pads with heavy sleepers in ballasted straight line

1	**Description of method** Under sleeper pads consist of an elastic layer underneath the sleeper. In the context of ground borne vibration reduction, this elastic layer should be soft to very soft.   *Source: GETZNER-USP ©* *Source: RailOne ©* The lower the dynamic stiffness of the USP, the lower the vehicle on track resonance frequency above which USP allow positive and high insertion loss to be observed. The combination of soft USP with heavy sleeper allows minimizing the rail deflection, even with very soft USP.	
2	**Condition in which the method is applicable** • **Trains, traffic (speed, axle loads):** A detailed study for USP's field of application is given in the UIC leaflet "under sleeper pads: recommendation for use" [3]. A priori, USP could be used for any kind of traffic and trains. Nevertheless, it has to be noticed that most of the elastic component / resilient elements are non-linear with the pre-load applied: the USP stiffness is highly dependent on the quasi-static pre-load (axle load) applied to the track, as shown in the annex A, figure A1. The higher the pre-load, the higher the stiffness. • **Frequency range** Soft USP allow ground vibration to be tackled for frequency range above 40Hz. It also have to be noticed that soft USP have a positive impact (reduction) on the parametric excitation which is dominating the ground vibration generation above 10Hz and below 40Hz for standard rolling stock speeds. • **Track** Soft USP can be installed on ballasted track. To improve their lifecycle, they can be coupled with PRA (hard USP) or another type of load distribution ballast contact layer (LDL) that ensure an improved contact surface area between the USP and the ballast and reduce the long-term USP damage.	***Railway infrastructure manager***

	Installation of USP in curved tracks is a specific issue detailed in row 8 of this table • **Geotechnical conditions** Numerical parametric studies have shown that the ground properties have minor impact on the USP insertion loss. However, it is useful for USP optimization, to take into account the ground dynamic properties: depending on which frequency range is preferentially transmitted by the ground, USP stiffness can be designed to reduce vibration energy in this specific frequency range. • **Distance between track and dwellings / Construction of houses** Soft USP acts only on the track mobility and the wheel/rail interaction force. Therefore, there is no limitation about USP installation considering risk or damage of surrounding buildings. However, as for the geotechnical conditions, it is useful to optimize the under sleeper pads with respect to the parameters which influence the vibrations transmitted to the buildings as well as with respect to the building(s) structure itself.	
3	**Effect of vibration mitigation – expected mitigation result** USP combined with wide sleepers will present an important insertion loss above the vehicle on track resonance frequency that means above 30 Hz to 40 Hz, depending on the chosen USP stiffness. Numerical simulations predict an insertion loss from 10 to 20 dB in the 60 − 125 Hz range, see [4]. At the resonance frequency, numerical simulations predict an amplification of ground vibration up to 10dB. However, the in-site measurements that have been performed within RIVAS never presented such a high amplification effect and sometimes no amplification effect is noticed. From the measurement campaign carried out in the RIVAS project [15], it can be said that: - The vehicle-track resonance frequencies (measurements in unconsolidated track, no trains) of the isolated tracks are observed between 32 and 63 Hz, the resonance frequencies of the un-isolated reference tracks are at 80 - 84 Hz. - The positive insertion losses are found above 55 Hz, maximum insertion loss values of 8 to 20 dB have been measured in test track for the different isolated tracks for the frequencies of 80 and 100 Hz (see 4.1 Annex A and [15]). - The best insertion losses have been achieved for the wide sleepers on soft under sleeper pads, where the highest insertion losses have been	

	observed for the softest under sleeper pads. - The benefit of the heavy sleeper B90.2 could not be demonstrated in this measuring campaign. The results are less significant than for the wide sleepers, and the advantages compared to the normal sleeper B70 are relatively small, each equipped with same USP type. All these results are measured on an unconsolidated track. Some improvements are expected for a consolidated track. These results highlight that soft USP can present a real efficiency for reducing ground vibrations. The use of very soft USPs on heavier sleepers (with normal size footprint: 2.6 x 0.3 m) do not show any significant effect compared to normal soft USP. It has also been observed that wide sleepers can have a noticeable positive impact on this efficiency. Rail pads in ballast often have resiliencies > 300 kN/mm. The application of rail pads with a softer stiffness of approx. 40 kN/mm together with the use of USPs did not show any vibration abatement effect in the measurement frequency range, but unveil a clear decrease of positive insertion loss at higher frequencies in simulations (double resonance effect). Impacts of soft USP coupled with wide sleeper for typical hotspot situations as defined in the RIVAS deliverable 1.5 [16] are assessed in the RIVAS deliverable 1.9 [17]. It is obvious that feelable vibrations, i.e. vibrations for frequency range between 10 Hz and 60 / 70 Hz, are hardly reduced with soft USP installation because their effectiveness range is above 50Hz. On the other hand, soft USP can have a positive impact on ground borne noise, that means for frequencies above 70 Hz. However, it has to be noticed that simulations and/or artificial excitation do not consider the effect of USP holistically. In particular, they do not consider the effect of USP on ground vibration generation, at the wheel-rail contact. This effect may have an impact on the feelable vibrations frequency range.	
4	**Need for geotechnical investigation and vibration measurements as an input for design** As said before, numerical simulations have shown that ground conditions have a small influence on the {USP + heavy sleeper} mitigation impact [4]. However, the USP stiffness can be reasonably chosen considering the ground dynamic properties, in combination with the building dynamic response as well as the railway traffic (mean unsprung mass).	***Geodynamics competence***
5	**Need for computer simulation as a bases to determine mitigation impact** Numerical simulations allow a first approximation of soft USP mitigation impact to be assessed. In RIVAS, it has allowed checking the impact of coupling heavy sleeper with soft USP, particularly on the rail head deflection [4]. However, the comparison between numerical simulations results and	***Numerical simulation competence***

	the measurement results have shown that in the numerical simulations commonly used for ground vibration assessment, some input parameters are very difficult to be determined (such as ballast stiffness or subgrade stiffness) whereas they should have an influence on ground vibration generation and propagation, as they contribute to track dynamic behaviour and to the propagative medium. Their influence on the USP mitigation impact is not fully demonstrated (it has only been demonstrated that the soil and subsoil stiffness has a small impact on the USP mitigation impact). This comparison tends also to demonstrate that the excitation phenomena taken into account in the most common software neglect some important contributions such as the parametric excitation and therefore they also neglect the effect of soft USP on this excitation phenomenon.	
6	**Recommendation for USP installation** The UIC leaflet [3] presents all the technical recommendations for the implementation of USP in ballasted track. Particularly, a chapter is dedicated to the issue of lateral track resistance where it is said that "*the global effect of USP on the lateral track resistance is difficult to prove in all situations based on previous phenomena".* The measurements on test track in Herne showed all over a positive impact of soft and very soft USP on the LTR values of a track with different kind of sleepers with USP. *According to the actual state of knowledge and experience of DB, ÖBB and SNCF the lateral resistance is similar to standard sleepers unless ballast flowing occurs.* *So in most cases sleepers with stiff and medium USP-types* can be used in the same conditions of CWR as standard sleepers.* *For soft USP there is not sufficient knowledge and experience to come to such a general conclusion*" *for USP stiffness classification, please refer to the following table extracted from [3]	***Railway infrastructure manager***

USP type	*Bedding modulus C_{stat}*
Stiff	*0,25 N/mm^3 – 0,35 N/mm^3*
Medium	*0,15 N/mm^3 – 0,25 N/mm^3*
Soft	*0,10 N/mm^3 – 0,15 N/mm^3*
Very soft (not part of this leaflet)	*Less than 0,10 N/mm^3*

For the specific question of USP impact on ground vibration and noise, it can be said that:

- Special care has to be taken regarding the frequency range where vibration problems occur is in accordance with the USP insertion loss spectrum.

	- To take into account the pre-load (axle loads) on the studied track and check the non-linear behaviour of the product to be used. - Beware of the possible noise increase with USP installation, particularly for frequency range where sleeper noise is dominating i.e. between 200Hz and 400Hz. However, within the RIVAS project, calculations carried out with TWINS software have shown that USP installation does not imply any significant effect on the emitted noise (increase lower than 1dB) see [15]. However, it has to be noticed that the presented spectra take into account a unit roughness on the overall wavelength range, and not a typical rail roughness (typical roughness emphasizes the part of noise around 700Hz where rail contribution is dominating but not sleeper radiation).	
7	**Installation procedure, requirements and recommendations** USP installation requires the sleepers to be removed from the track (during a track renewal operation for example) and to be equipped with USP. Again, the UIC leaflet [3] provides a complete overview on the USP handling.	***Railway infrastructure manager***
8	**Specific issue of USP installation in curves** The installation of soft USP has yield two different results in RIVAS in terms of the lateral track resistance (LTR): on the one hand, the measurement of track lateral stability performed by SBB within RIVAS on a curve equipped with soft USP has shown a decrease of 40 to 43 % of the track lateral resistance compare to straight track nominal lateral resistance. On the other hand, the test track for vibration attenuation in Herne has been installed in straight line, but the LTR measurements on all soft and very soft USPs did not show any problems on lateral forces or track stability and even an increase on LTR of more than 27% was observed. Tracks in curve are introducing a certain load shift from one rail to the other due to unbalanced centrifugal force, which creates a certain shift of contact pressure from a rectangular shape to a rectangular plus triangular shape underneath of the sleepers (with USP) plus a lateral load on the track panel. The change of USP contact pressure is increasing the static preload on one side of USP on the sleeper and decreasing the preload on the other half of the sleeper. Enhanced preload has a tendency for a decreasing effect, less preload an increasing effect on vibration attenuation; the unbalanced lateral forces are expected to be beard by LTR as measured in straight track. The issue of lateral resistance modification with USP is still an open question: the difference results of LTR impact by USP installation may be derived from different test procedures. This issue is tackled in the UIC leaflet [3]. The measurement carried out within RIVAS has demonstrated a real impact of soft USP for vibration mitigation in curve situation [10]. Positive insertion losses are observed above 63Hz, up to 10dB.	***Railway infrastructure manager***
9	**Monitoring and control system** If the system is certified, there is no need of a specific monitoring. However, the track behaviour equipped with USP can of course be	***Vibration measurement***

	controlled, particularly in terms of longitudinal defects growth because we believe that USP will have a positive effect on this defect growth.	***s competence***
10	**Quality control** Certification of new elements is always required when you want to put it in a track. The reference standard for USP qualification is in the DIN 45673 (that should be turned into EN standard within the next years, dependent on the European inquiry from the TC 256 WI 597). The heavy sleepers have been checked according to the EN 13230.	***Track component characterization competence***
11	**Risk assessment** No risk is noticeable, except of a potential for the lateral track stability for very soft USP and for curved track (see row 7bis). This issue will be tackled in the on-coming UIC project.	
12	**Service life and ultimate limit states / lifetime** Vibrogir tests shall be carried out in the certification process of every new USP product to be put in a track [9]. These tests allow demonstrating the service life and durability of the product. Moreover, the life time of a soft USP can be improved with load distribution layer (LDL) material glued on it. On the other hand, USP should have a positive impact on the track lifetime by reducing the wheel-rail contact force and improving the contact area with the ballast (even more if it is coupled with LDL). Austrian experiences showed a lengthening of tamping intervals for tracks of sleepers with USP.	
13	**Costs** 70 - 90 EUR/m for new lines, (quite a big range for material costs between ~25 Euro until ~70 Euro), this may depends on the volume of estimation basis (this is only difference to standard track) 250 EUR/m for upgraded lines (costs for sleeper dismantling included) Maintenance relative costs compared to a reference track: The UIC leaflet [3] gives all the details concerning the impact of USP installation in the life cycle cost (LCC) of the track in concern. The following parameters are quoted as the main important one when dealing with USP influence on the track LCC: " • *The production cost of sleepers will depend a lot on the type of USP used, the industrialisation of the USP-sleeper production and thus on the number of sleepers produced. The additional cost of USP-sleepers is typically 25 to 50 % compared to the standard sleepers.* • *As USP will influence the maintenance needs, it is important to use correct data for the different maintenance operations such as costs for tamping and grinding. In some situations not only average costs should be considered as these may vary on the length of the section considered. Maintenance costs as well as labour costs can considerably vary over Europe.* • *The lifespan of the track is one of the main parameters*	

	influencing the results of LCC. It is therefore important to recognise the degradation mechanisms behind track degradation. In certain situations ballast degradation may increase. As USP have a very positive effect on ballast degradation, this shall be considered. This will depend on the line characteristics, products used (sleeper type, ballast quality, formation quality, etc.). • *The maintenance and renewal works have a big impact on the hindrance and availability of the line. The operational hindrance costs shall be considered in the LCC calculation. Again these costs will vary with the line category considered.* " An example is also given concerning the insertion of hard USP in the ÖBB network.	
14	**Social aspects** Mitigation measures in track are positively perceived by the neighbourhood as there is no intervention on their surrounding environment.	

2.2.2 Very soft rail fastening systems on ballasted straight line

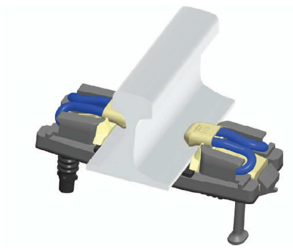
<table>
<tr>
<td>1</td>
<td>
Description of method

Very soft fastening systems consist in rail fastening systems that allow very low stiffness to be observed between the rail and the sleeper. It can consist in:

- One layer fastening system (FastClip from Pandrol or W14 from Vossloh for example) with very soft railpads, which presents, at best, an equivalent vertical dynamic stiffness of 37 kN/mm:

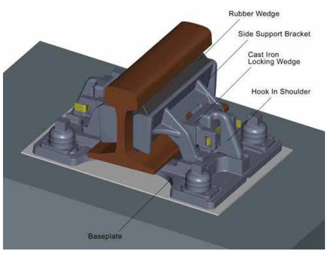
Source: Pandrol FastClip ©

- Multi-layer systems (with baseplate pads and railpads) such as DFC VALIANT from Pandrol for example, which presents, at best, an equivalent vertical dynamic stiffness of 24 kN/mm:



Source: Pandrol DFC Valiant ©

- Unusual fastening system as the VANGUARD system by Pandrol, specifically designed for reducing the transmitted vibration, which presents, at best, an equivalent vertical dynamic stiffness of 6 kN/mm. In VANGUARD, the rail is supported under the head and in the web with rubber assemblies, leaving the foot of the rail suspended



Source: Pandrol VANGUARD ©

The lower the stiffness, the lower the vehicle on track resonance frequency above which these systems present positive and high insertion loss.
</td>
<td></td>
</tr>
</table>

2	**Condition in which the method is applicable** • **Trains, traffic (speed, axle loads)** Very soft fastening systems could be used for any kind of traffic and trains. Some restriction can be advocated to limit the rail deflection at the contact point. Beware that most of the elastic component / resilient elements, such as railpads or/and under baseplate pads that can be used in these systems, are non-linear with the pre-load applied: the pads stiffness is highly dependent on the quasi-static pre-load (axle load) applied to the track. The higher the pre-load, the higher the stiffness. Nevertheless, this effect is counterbalance by the fact that very soft fastening systems allow the force due to wheel-rail contact to be spread over a larger number of sleepers (the sleeper just underneath the contact point is subjected to 32 % to 24 % of the global force with very soft fastening systems, instead of 47% with classic systems such as FastClip installed with classic railpads of 120 kN/mm stiffness) [7] • **Frequency range** Very soft fastening systems allow ground vibration to be tackled for frequency range above 60Hz. It also have to be noticed that very soft fastening systems have a positive impact (reduction) on the parametric excitation which is dominating the ground vibration generation above 10Hz and below 30Hz (depending on the speed of the rolling stock) • **Track** Very soft fastening systems are commonly installed on slab track. The RIVAS project has also shown that it can be installed on ballasted track preferentially on straight line to avoid any problems on track lateral stability and gauge keeping that can appear in curves. • **Geotechnical conditions** Numerical parametric studies have shown that the ground properties have minor impact on the very soft fastening systems insertion loss. However, it is useful for fastening system optimization (stiffness of the pads in concern), to take into account the ground dynamic properties: depending on which frequency range is preferentially transmitted by the ground, the system stiffness can be designed to reduce vibration energy in this specific frequency range. • **Distance between track and dwellings / Construction of houses** Very soft fastening systems acts only on the track mobility and the wheel/rail interaction force. Therefore, there is no limitation about very soft railpads installation considering risk	

	or damage of surrounding buildings, except the increase of noise that could be induced by the installation of very soft railpads (up to 3 dB) However, as for the geotechnical conditions, it is always useful to optimize these systems stiffness considering the parameters that influence the vibrations transmitted to the neighbourhood such as the building(s) structure itself.	
3	**Effect of vibration mitigation – expected mitigation result** Very soft fastening systems will present an important insertion loss after the vehicle-track resonance frequency that means after 60 Hz, depending on the fastening stiffness. Numerical simulations predict an insertion loss from 10 to 20 dB in the 60 − 125 Hz range [6]. Moreover, very soft fastening system will also have a benefit effect on the parametric excitation by reducing the track stiffness variation along the track. This will mainly induce reduction of vibration around the dominant frequency of the parametric excitation. At the resonance frequency, numerical simulations predict an amplification of ground vibration up to 10dB. From the measurement campaign carried out in the RIVAS project [12], we can confirm that the lower the stiffness, the lower the resonance frequency above which positive insertion losses arise. For DFC 3, insertion loss can reach 10dB for frequencies above 50Hz, see Annex B. An amplification occurs at the resonance frequency up to 3dB for the DFC3 (and 4dB for the DFC2) compared to DFC0. When comparing to the reference site, it can reach 5dB but in that case, we do not fully control the effect of the ground discrepancy between the 2 sites. This is less than the amplification effect predicted with numerical simulation. Apparently, there is an effect of very soft fastening systems on the parametric excitation: reduction of the vibrations around 20Hz. Impacts of very soft railpads for typical hotspot situations as defined in the RIVAS deliverable 1.5 [16] are assessed in the RIVAS deliverable 1.9 [17]. It has to be noticed that the insertion loss used in deliverable 1.9 corresponds to numerical simulation results carried out with laboratory characterization of the DFC system; there are not the in-site test results. It is obvious that feelable vibrations are hardly reduced with very soft fastening systems installation because their effectiveness range is above 60Hz. On the other hand, very soft fastening systems can have a positive impact on ground borne noise.	
4	**Need for geotechnical investigation and vibration measurements as an input for design** As said before, numerical simulations have shown that ground conditions have a small influence on the very soft fastening system mitigation impact. However, the system stiffness can be judiciously chosen considering the ground dynamic properties, in combination	***Geodynamics competence***

	with the building dynamic response, the railway traffic.	
5	**Need for computer simulation as a bases to define mitigation impact** Numerical simulations allow a first approximation of very soft fastening system mitigation impact to be assessed. In RIVAS, it has allowed showing that these systems mainly reduce the wheel-rail interaction force (by increasing the track compliance), and have a little impact on the track mobility itself. However, the comparison between numerical simulations results and the measurement results have shown that in the numerical simulations commonly used for ground vibration assessment, some input parameters are very difficult to be determined (such as ballast stiffness or subgrade stiffness) whereas they should have an influence on ground vibration generation and propagation, as they contribute to track dynamic behaviour and to the propagative medium. Their influence on the mitigation impact is not fully demonstrated (it has only been demonstrated that the soil and subsoil stiffness has a small impact on the mitigation impact). This comparison tends also to demonstrate that the excitation phenomena taken into account in the most common software neglect some important contributions such as the parametric excitation and therefore they also neglect the impact of very soft fastening systems on this excitation phenomenon.	***Numerical simulation competence***
6	**Recommendation for very soft rail fastening system installation** Be sure that the frequency range where vibration problem occur is in accordance with the very soft fastening system insertion loss spectrum. Considering the non-linearity of most of elastic/resilient components, with regard to the pre-load (axle load), systems that allows multi-elastic-layers such as DFC with an under-rail pad coupled with an under-baseplate pad. Otherwise, systems such as VANGUARD where the elastic elements work in shear deformations present a quasi-linear behaviour with regards to load. Beware of the possible increase of noise with very soft fastening systems: numerical simulations carried out with TWINS within RIVAS predict an increase of max. +1 dB(A) between reference fastening system of 300 N/mm vertical stiffness and a very soft version of 25 kN/mm vertical stiffness. Indeed, very soft fastening system could decrease the track decay rate in some frequency range, compared to classic railpads. It has to be noticed that the presented spectra take into account a unit roughness on the overall wavelength range, and not a typical rail roughness which could imply a higher increase of noise due to soft railpads (typical roughness emphasizes the part of noise around 700Hz where rail contribution is dominating). On the other hand, some studies have already shown the positive impact of very soft fastening system on roughness growth: after a year of very soft fastening system installation, the Belgium Railways have measured a decrease of rail roughness growth of about 2dB.	***Railway infrastructure manager***

7	**Installation procedure, requirements and recommendations** If a new rail fastening system is required, this could imply a modification of the supporting sleepers [7]. Therefore, a change of sleeper (during a track renewal operation for example) might be required.	***Railway infrastructure manager***
8	**Monitoring and control system** If the system is certified, there is no need of a specific monitoring. However, the track behaviour equipped with soft fastening systems can of course be controlled, particularly in terms of longitudinal defects growth. Experience shows that softening the fastening systems - at least to soft apparent railpad stiffness i.e. 40kN/mm - will have a positive effect on this defect growth as it reduces the wheel-rail interaction force and distributes the wheel load onto more sleepers around the contact point.	***Vibration measurement s competence***
9	**Quality control** Certification of new elements is always required when you want to put it in a track [7]. The reference standards for fastening system qualification are the EN 13146 and EN 13481	***Track component characterization competence***
10	**Risk assessment** No risk is noticeable, except on the lateral track stability for very soft fastening systems in curved ballasted track except if a high lateral stiffness can be kept whereas a low vertical stiffness is reached.	
11	**Service life and ultimate limit states** Fatigue tests shall be carried out for any certification process for new products to be put in a track. These tests allow demonstrating the service life and durability of the product. On the other hand, very soft fastening systems should have a positive impact on the track lifetime by reducing the wheel-rail contact force, and spreading over a larger number of sleepers the effort transmitted to the track by the wheel.	
12	**Costs** Installation costs: DFC Valiant on new track: 80 EUR/m DFC Valiant for upgraded lines (costs for sleeper change included): 250 EUR/m VANGUARD on new track:120 EUR/m VANGUARD for upgraded lines (costs for sleeper change included): 300 EUR/m Maintenance relative costs compared to a reference track: As for the USP implementation, there are several parameters that have to be considered when assessing the impact of soft to very soft fastening system on the life cycle cost of the equipped track: • The production cost of sleepers equipped with the dedicated	

	fastening system will depend a lot on the type of fastening system used, as indicated above. • As very soft fastening system will influence the maintenance needs, it is important to use correct data for the different maintenance operations such as costs for tamping and grinding. In some situations not only average costs should be considered as these may vary on the length of the section considered. Maintenance costs as well as labour costs can considerably vary over Europe. • The lifespan of the track is one of the main parameters influencing the results of LCC. It is therefore important to recognise the degradation mechanisms behind track degradation. In certain situations ballast degradation may increase. As very soft fastening systems reduce the wheel-rail contact force and distribute the wheel load onto more sleepers around the contact point than the stiff systems, their use could reduce the ballast degradation mechanisms. This will depend on the line characteristics, products used (sleeper type, ballast quality, formation quality, etc.). • The maintenance and renewal works have a big impact on the hindrance and availability of the line. The operational hindrance costs shall be considered in the LCC calculation. Again these costs will vary with the line category considered. No quantitative assessment could therefore be given concerning the impact of very soft fastening system on the LCC of the track. Considering the mechanisms in action, it can be said that a positive impact is expected.	
13	**Social aspects** Mitigation measures in track are positively perceived by the neighbourhood as there is no intervention on their surrounding environment.	

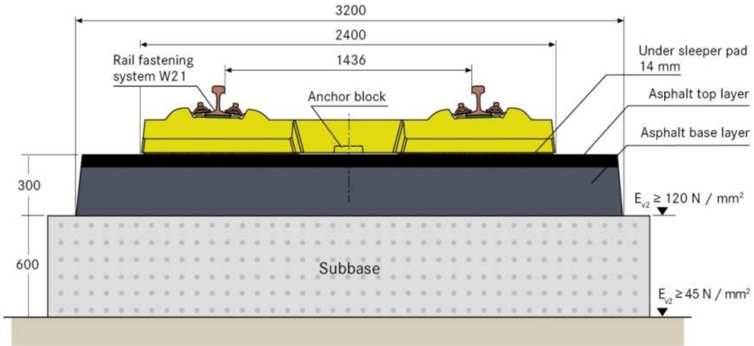
2.2.3 Under sleeper pads in GETRAC® slab track system

<table>
<tr><td>1</td><td>

Description of method

Various designs of slab track co-exist, with a large range of performances in terms of ground vibrations reduction. By itself, the choice of slab track design is a determining factor when ground vibrations have to be tackled.

In case of an existing system such as the GETRAC® A3 system designed by RAILONE, a mitigation solution for ground vibrations consists in adding under sleeper pads in the system itself, giving the system GETRAC A3.1.



This USP installation can be coupled with the use of wide and heavy sleepers, so that rail deflection is minimized, even for very soft USP.

</td><td></td></tr>
<tr><td>2</td><td>

Condition in which the method is applicable

- **Trains, traffic (speed, axle loads)**

  As for USP in ballasted track, USP for slab track can be used for any kind of traffic and trains. Again, note that most of the elastic component / resilient elements are non-linear with the pre-load applied: the USP stiffness is dependent on the quasi-static pre-load (axle load) applied to the track as presented in the Annex C and the deliverable 3.9 [11]. The higher the pre-load, the higher the stiffness. USP can therefore be less efficient with high axle loads as the one frequently encountered with freight trains.

- **Frequency range**

  Soft USP in slab track allow ground vibration to be tackled for frequency range above 40Hz. For a USP with stiffness equal to 50 kN/mm, numerical simulations show insertion loss up to 25dB at 80Hz. At the resonance frequency, numerical simulations predict amplification effect, between 5 and 10 dB.

- **Track**

  Soft to very soft under sleeper pads can be installed in GETRAC system, coupled with heavy sleepers, even in

</td><td></td></tr>
</table>

	curves. • **Geotechnical conditions** Numerical parametric studies have shown that the ground properties have minor impact on the USP insertion loss in a GETRAC A3.1 system. However, it is useful for the mitigation system optimization, to take into account the ground dynamic properties: depending on which frequency range is preferentially transmitted by the ground, USP stiffness can be designed to reduce vibration energy in this specific frequency range. • **Distance between track and dwellings / Construction of houses** Soft USP acts on the track mobility and the wheel/rail interaction force. Therefore, there is no limitation about USP installation considering risk or damage of surrounding buildings. However, as for the geotechnical conditions, it is useful to optimize the under sleeper pads with respect to the parameters which influence the vibrations transmitted to the buildings as well as with respect to the building(s) structure itself.	
3	**Effect of vibration mitigation – expected mitigation result** Numerical simulations have shown that a positive insertion loss can be observed with USP + heavy sleepers in a GETRAC A3 system for frequencies above 40Hz. These same simulations predict an IL up to 25dB for frequency range around 80Hz. Within RIVAS, The GETRAC A3.1 system which is a derivation of a well-known asphalt slab system GETRAC A3 in Germany by equipping the used wide sleeper with a new Under Sleeper Pad (USP) type V02 and the use of a hard Rail Pad (RP) in the same time has been tested. The USP type V02 (see Annex C for more details on the USP used) has been chosen tailor-made both on vibration abatement and track-compatibility requirements. The nominal static stiffness was chosen to 0.085 N/mm³, giving a total spring stiffness of 86 kN/mm per each wide sleeper. The deflection was measured in Eiffage test track to 1.1 – 1.6 mm and has some additional potential for a softer design within usual track compatibility limits. From the measurement campaign carried out in the RIVAS project [14], it can be said that the abatement performance of the slab track system was measured in a comparable range of abatement than the very soft USPs (0.05 and 0.03 N/mm³) on ballast. The GETRAC A3.1 system achieved a positive insertion loss above of 60 Hz and a reduction of up to 16 dB @ 80 Hz. The similar result of actually stiffer USP than for the ballast sections is based on a less stiffening of USP V02 material under preload compared to the USPs used for the	

	ballasted tracks. Impacts of soft USP within GETRAC A3 system for typical hotspot situations as defined in the RIVAS deliverable 1.5 [16] are assessed in the RIVAS deliverable 1.9 [17]. It is obvious that feelable vibrations, i.e. vibrations for frequency range between 10 Hz and 60 Hz, are hardly reduced with soft USP installation because their effectiveness range is above 60Hz. On the other hand, soft USP can have a positive impact on ground borne noise that means for frequencies above 60 Hz. However, it has to be noticed that simulations and/or artificial excitation do not consider the effect of USP holistically. In particular, they do not consider the effect of USP on ground vibration generation, at the wheel-rail contact which unveiled positive insertion losses at 5 Hz to 20 Hz and at 40 Hz under real train pass-by due to diminishing the parametric excitation. This effect has a positive impact on the feelable vibrations frequency range.	
4	**Need for geotechnical investigation and vibration measurements as an input for design** As said before, numerical simulations have shown that ground conditions have a small influence on the {USP + heavy sleeper} - in GETRAC A3.1 system - mitigation impact [5]. However, the USP stiffness can be reasonably chosen considering the ground dynamic properties, in combination with the building dynamic response, the railway traffic.	***Geodynamics competence***
5	**Need for computer simulation as a bases to final design Effect of vibration mitigation** Numerical simulations allow a first approximation of soft USP mitigation impact to be assessed. In RIVAS, it has allowed checking the impact of coupling heavy sleeper with soft USP, particularly on the rail head deflection [5]. However, the comparison between numerical simulations results and the measurement results have shown that in the numerical simulations commonly used for ground vibration assessment, some input parameters are very difficult to be determined (such as subgrade stiffness) whereas they should have an influence on ground vibration generation and propagation, as they contribute to track dynamic behaviour and to the propagative medium. Their influence on the USP mitigation impact is not fully demonstrated (it has only been demonstrated that the soil and subsoil stiffness has a small impact on the USP mitigation impact). This comparison tends also to demonstrate that the excitation phenomena taken into account in the most common software neglect some important contributions such as the parametric excitation and therefore they also neglect the effect of soft USP on this excitation phenomenon for the low frequency range.	***Numerical simulation competence***
6	**Recommendation for USP installation in slab track** - To be planed from the conception phase - Be sure that the frequency range where vibration problem occur is	***Railway infrastructure manager***

	in accordance with the {USP+heavy sleeper} insertion loss spectrum. - Take into account the pre-load (axle loads) on the studied track and check the non-linear behaviour of resilient products to be used. - Beware of the possible noise increase with USP installation, particularly for frequency range where sleeper noise is dominating i.e. between 200Hz and 400Hz. The noise impact of the modified GETRAC A3.1 system have been checked by TWINS simulation and determined to only 1 dB increase due to hard rail pads used on sleeper fastening by simultaneously employment of soft USP underneath of sleeper [13]. This increase is acoustically negligible. Again, in these simulations a unit roughness on the whole wavelength spectrum has been used, minimizing the influence of the rail radiation on the global noise level.	
7	**Installation procedure, requirements and recommendations** Installation of USP coupled with heavy sleeper in a GETRAC A3.1 system shall be planed from the track conception phase.	***Railway infrastructure manager***
8	**Monitoring and control system** If the system is certified, there is no need of a specific monitoring. However, the slab track behaviour equipped with USP and heavy sleepers can of course be controlled, particularly in terms of longitudinal rail defects growth because experiences showed that USP will have a positive effect on this defect growth.	***Vibration measurements competence***
9	**Quality control** Certification of new elements is always required when you want to put it in a track (see [11]). The reference standard for USP qualification is the DIN 45673 (that should be turned into EN standard within the next years, dependent on the European inquiry from the TC 256 WI 597) with a certain adaption for plain load bearing plates compared to standard ballast plates for ballasted under sleeper pads. The heavy sleepers have been checked according to the EN 13230.	***Track component characterization competence***
10	**Risk assessment** No risk is noticeable	
11	**Service life and ultimate limit states** Conventional vibrogear or ballast trough fatigue tests are not necessary for modified GETRAC A3.1 sleepers since the sub-base contact area of USP on asphalt sub-base is multiple as much as effective contact area of USP on a ballast bed (no penetration effect to be expected). Even so fatigue tests on a GETRAC A3.1 system have been performed on an even sub-base in lab test for certification [11]. These tests allow demonstrating the service life and durability of the product. The area of the used USP on BBS 3.1 sleeper is approx. 20 times higher compared to conventional RP´s, insofar is the fatigue loading of an USP under a sleeper on asphalt layer	

	uncritical. On the other hand, USP should have a positive impact on the track lifetime by reducing the wheel-rail contact force.	
12	**Costs** Installation costs USP in GETRAC A3 system (supplies the GETRAC A3.1 system): 52 EUR/m for new lines, Maintenance relative costs compared to reference track: Same remarks can be drawn than the ones detailed for the USP in ballasted track. Apart of these arguments slab tracks provide a more defined bedding conditions and constant track alignment as well as higher accuracy expecting to have a positive impact on the long-term durability of the system and the maintenance costs	
13	**Social aspects** Mitigation measures in track are positively perceived by the neighbourhood as there is no intervention on their surrounding environment	

2.2.4 Ballasted turnout configuration

Ballasted turnout configuration is a special case because the mitigation measures really tested within RIVAS - stiff under sleeper pads - on the turnout have not proven a satisfactory efficiency [8]. Insertion loss results are not consistent and depend on the turnout condition and its subgrade parameters.

Additional studies have therefore been carried out within RIVAS, see [13], to:

- identify the different sources of vibrations within a turnout

- propose a methodology to optimize the geometry of main parts of a turnout i.e. the nose and the switch panel.

The main sources of ground vibration have been identified from measurement results. The crossing panel is generally the most critical part in terms of ground vibration generation in a turnout, because of the impact load at the transfer of charge.

This source could be diminished by soft track components, such as very soft railpads, very soft USP and under ballast mats.

Another source of ground vibration in a turnout is the variation of the apparent global stiffness of the track (apparent from the wheel), which can induce an increase of vibration. This global stiffness varies because of change of track component along the turnout. For the tested turnout in the RIVAS project, the rolling noise increased up to 3dB at the switch panel due to a reduction of the apparent global stiffness of the track (see [13]). On the other hand, also due to this decrease of stiffness, ground vibrations were lower in front of the switch compared to the other part of the turnout. These results are specific to the measured turnout: variation of stiffness shall be checked on every turnout for which mitigation measures have to be installed. Considering these results, ground vibration reduction for a turnout configuration can be obtained by smoothing the global stiffness of the track along the turnout (which can vary a lot) and therefore the track compliance by optimizing the railpads depends on the switch panel considered (see [13]).

In fact, the optimization of the nose design/geometry carried out by simulations to minimize the impact between wheel and the different parts of the nose (by minimizing contact forces between the wheel and the rail) suffers too many constraints to be effective. To reduce the impact load specifically at the nose panel it is therefore recommended smoothing the railpads used on this panel.

3. REFERENCES

[1] I. O. f. Standardization, “ISO 14837-1:2005 Mechanical vibration - Ground-borne noise and vibration arising from rail systems - Part 1: General guidance”. 2005.

[2] J. Houbrechts, M. Schevenels, G. Lombaert, G. Degrande, W. Rücker, V. Cuellar and A. Smekal, “Test procedures for the determination of the dynamic soil characteristics. RIVAS project SCP0-GA-2010-265754, Deliverable D1.1, Report to the EC,” December 2011.RIVAS D1.2:Protocol for free field measurements of mitigation effects in the RIVAS project

[3] UIC Leaflet; Under Sleeper Pads (USP) – Recommendations for Use, to be published

[4] B. Faure, E. Bongini, L. Auersh, G. Lombaert, & al. : Results of the parameter studies and prioritisation for prototype construction for ballasted track, RIVAS project SCP0-GA-2010-265754, Deliverable D3.2, Report to the EC,” 2013

[5] L. Auersch & al.: Results of the parameter studies and prioritisation for prototype construction for slab track, RIVAS project SCP0-GA-2010-265754, Deliverable D3.3, Report to the EC,” 2013

[6] B. Faure, E. Bongini, B. Nelain, G. Lombaert, C. Petit, D. Herron: Optimisation of the fastening system and the sleeper: numerical and test bench results, RIVAS project SCP0-GA-2010-265754, Deliverable D3.4, Report to the EC,” 2013

[7] B. Faure, E. Bongini, D. Herron: Mitigation measures installed on commercial track, RIVAS project SCP0-GA-2010-265754, Deliverable D3.5, Report to the EC,” 2013

[8] R. Müller, B. Nelain, J. Nielsen, S. Said, W. Rücker, E. Bongini: Description of vibration generation mechanism of switches and the development of cost effective solution, RIVAS project SCP0-GA-2010-265754, Deliverable D3.6, Report to the EC,” 2013

[9] E. Knothe, V. Cuellar: Results of laboratory tests for ballasted track mitigation measures, RIVAS project SCP0-GA-2010-265754, Deliverable D3.7, Report to the EC,” 2013

[10] R. Mueller, Y. Brechbühl: Measurement report about a new undersleeper test track in curve, RIVAS project SCP0-GA-2010-265754, Deliverable D3.8, Report to the EC,” 2013

[11] E. Knothe: Results of laboratory tests of slab track mitigation measures, RIVAS project SCP0-GA-2010-265754, Deliverable D3.9, Report to the EC,” 2013

[12] B. Faure, E. Bongini: optimisation of the fastening system and the sleeper: results of the measurement campaign on commercial track, RIVAS project SCP0-GA-2010-265754, Deliverable D3.10, Report to the EC,” 2013

[13] R. Müller, B. Faure, E. Bongini, A. Zemp J. Nielsen, B. Pålsson: “Ground vibration from turnouts: numerical and experimental tests for identification of the main influencing sources/factors.” RIVAS project SCP0-GA-2010-265754, Deliverable D3.12, Report to the EC,” 2013

[14] A.Pieringer, L.Auersch, R.Garburg, S.Schwieger: results of field test of slab track mitigation measures, RIVAS project SCP0-GA-2010-265754, Deliverable D3.14, Report to the EC,” 2013

[15] A.Pieringer, L.Auersch, R.Garburg, S.Schwieger: results of field test for ballasted track mitigation measures, RIVAS project SCP0-GA-2010-265754, Deliverable D3.15, Report to the EC,” 2013

[16] Dorothé Stiebel, Roger Müller, Estelle Bongini, Alf Ekblad, Guillaume Coquel, Álvaro Andrés Alguacil, Definition of reference cases typical for hot-spots in Europe with

existing vibration problems, RIVAS project SCP0-GA-2010-265754, Deliverable D1.5, Report to the EC," 2013

[17] M. Villot, S. Bailhache, Evaluating the mitigation measures developed in WP2-5 in terms of decrease of exposure and annoyance, RIVAS project SCP0-GA-2010-265754, Deliverable D1.9, Report to the EC," 2013

4. APPENDICES

4.1 ANNEX A: SOFT USP TESTS WITHIN RIVAS

1	**Principles** Several soft USP have been investigated within RIVAS project, coupled with heavy sleepers and wide sleepers. The conclusions from numerical parametric study carried out in the first step of the project were that the main parameters that influence the reduction of ground vibration are the stiffness of the under sleeper pad, the mass and the width of the sleeper. The softest sleeper pad yields the best reduction of the ground vibration. A strong increase of the sleeper mass, for example the double mass of the standard sleeper, can improve the reduction effect. The influence of other parameters has been examined. The stiffness of the rail pads, the bending stiffness of the track, the stiffness of the ballast, the sub-soil and soil configurations and layering. According to the results of this numerical parametric study, it has been decided to test several combinations of soft USP with standard sleepers, heavy sleepers and wide sleepers. In a first step, laboratory tests have allowed assessing the performance of resilient material in terms of vibration mitigation but also for fatigue strength, bond strength, shear strength and the freeze-thaw resistance. The new heavy sleepers have also been characterized with lab tests and the results are presented in [9]. A test on the track box of CEDEX has been performed to assess the performance of heavy sleeper equipped with soft USP with regards to fatigue tests. Several load situations were simulated, quasi-static for passenger and freight train as well as coupling of quasi-static and dynamic load corresponding to freight train pass-by. Finally, several combinations of soft USP with standard, heavy and wide sleepers have been installed on the ER test rig in Herne to be tested with a dedicated devices (Butterfly devices).
2	**Laboratory tests: characterization of the USP** The tests for under sleeper pads have been performed in accordance with DIN 45673-6 – Mechanical vibration – Resilient elements used in railway tracks – Part 6: Laboratory test procedures for under sleeper pads of concrete sleepers. The tests for the sleepers have been performed in accordance with DIN EN 13230-2 – Railway applications – Track – Concrete sleepers and bearers – Part 2: Prestressed monoblock sleepers. They are fully described in [9]. Three different types of under sleeper pads (SLN1010, SLN0613 and SLN0315) and one new sleeper type (B90.2) were investigated. For the examination of the under sleeper pads for ballasted tracks tests for the static and dynamic bedding modulus, fatigue strength, bond strength, shear strength and the freeze-thaw resistance were carried out in lab tests beforehand. Here are presented only the static and dynamic bedding modulus results for the 3 samples of soft USP tested. To get more details on these tests, please refer to [9].

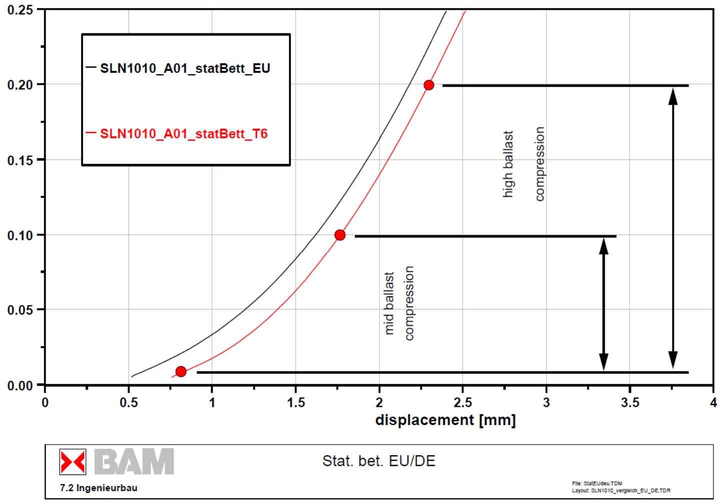


Figure A.1: stress versus displacement, for static test, for 1 sample of USP, SLN1010

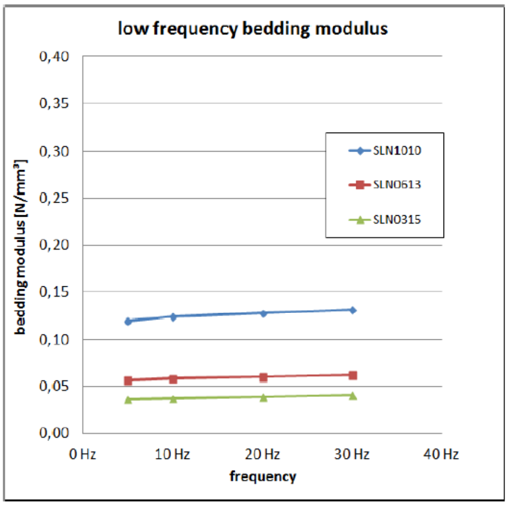


Figure A.2: low frequency bedding modulus

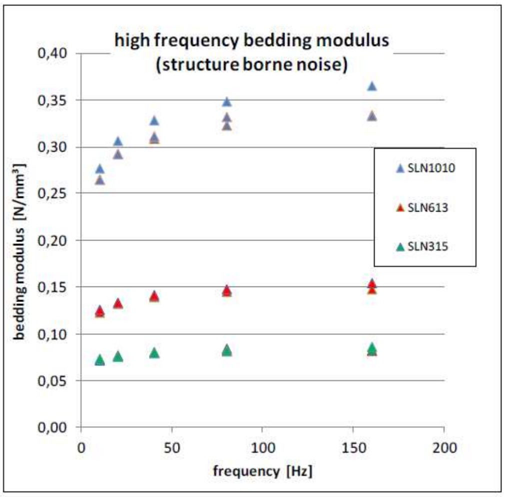


Figure A.3: high frequency bedding modulus

3	**Tests scale 1 – Track box**

CEDEX track box measurements have been carried out to assess the performances over time of a set of USP + heavy sleepers.

A prototype sleeper provided with hard rail pads and a soft under-sleeper pad has been manufactured and delivered by RAILONE to CEDEX to be tested in its big dimension track box under realistic conditions (i.e. realistic traffic scenarios with different speeds). The new sleeper is a mono-bloc concrete pre-stressed B90.2 model having a mass of 610 kg and approximately the same dimensions than standard mono-bloc sleepers.

Figure A.4: Track box devices with heavy sleepers installation

Tests performed:

- After tamping and stabilization of the track, several quasi static passenger and freight train pass-by have been simulated
- 12195 quasi static pass-by of freight train simulated, corresponding to 2Mio axle loads
- Track receptances are measured
- Track quasi static behaviour is checked regularly during the tests: during the load cycles, static tests have been performed to check the track behaviour

Measurement device:

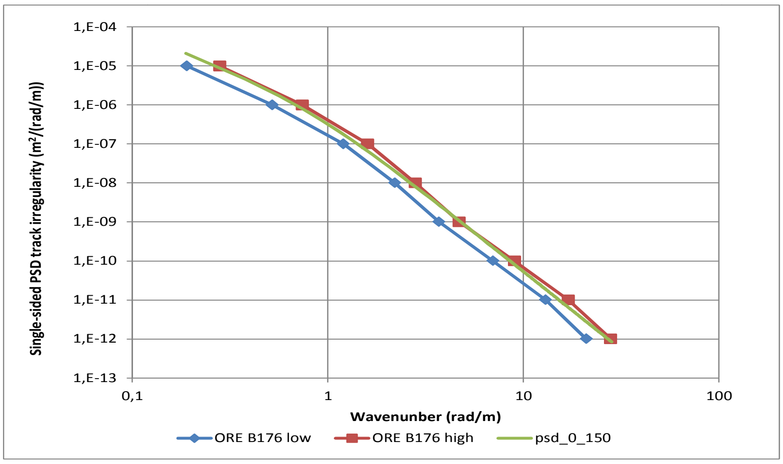
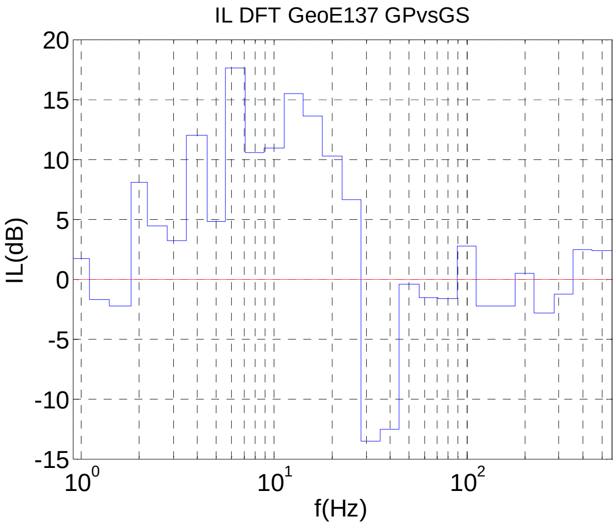
- 124 sensors are available in track box: sleeper geophones, rail accelerometers, sublayer geophones, displacement gauge (for fatigue tests), + 2 geophones on the foundations of the box

Train parameters:

the pass-by of 2 types of train are simulated

- Passenger trains: load equal to 165kN per axle; Quasi-static loading: excitation below 30Hz
- Freight trains: load equal to 225kN/axle; quasi-static excitation below 20Hz

The frequency content reproduces the geometric parameters of the train (axle/bogie distances)

	The track box devices have allowed carrying out simulation of train passage over a medium class track (i.e. with longitudinal track defects) and simulation of vertical irregularities according to the transfer function established between the geometric irregularities and the corresponding dynamic load (with a given track stiffness and damping), in the frequency domain.  Figure A.5: Adopted PSD versus ORE PSD's functions Insertion loss have been measured for different kind of excitation (quasi-static and quasi-static+dynamic)  Figure A.6 : Freight vehicle dynamic velocity insertion loss
4	**Test scale 1:1 - Rig test in Herne** Soft USP with standard, heavy and wide sleepers have been installed on a test rig, scale 1:1 together with a reference track of standard sleepers without USP. It has allowed measurement of the USP performances in terms of vehicle-track resonance frequencies and insertion losses at the soil measurement points at 12m and 16m distance from the track.

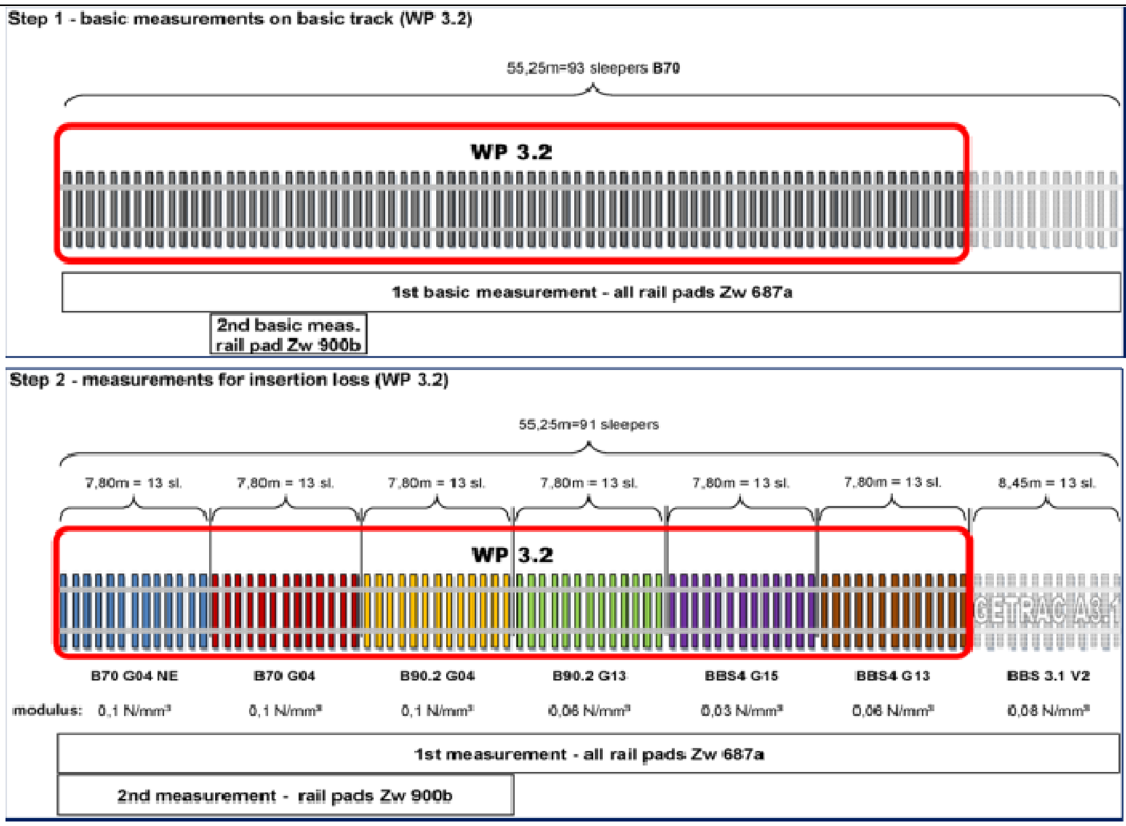


Figure A.7: Test rig in Herne

section [-]	sleeper /USP type [-]	Supply name [-]	nominal static USP modulus [N/mm²]	total USP area, consolid ** [cm²]	USP Contact Area, Tamped *** [cm²]	calc. stat. tot. spring stiffness /sleeper consolid. [kN/mm]	calc. stat. spring stiffness /sleeper tamp. [kN/mm]	Diffe-rence [%]	Elastic length tamp. [mm]	result. Stat. Rail seat load 20t tamp [kN]	stat. ballast-contact pressure tamp. [N/mm²]
ME 11	BBS3.1 V02	-	0,085*****	10.080	-	85,7	-	-			
ME 12	BBS4 G13	SLN 0613	0,046	11.820	8.640	54	40	27%	938	32	0,07
ME 13	BBS4 G15	SLN 0316	0,029	11.820	8.640	35	25****	27%	1049	29	0,07
ME 14	B90.2 G13	SLN 0613	0,046	7.122	6.016	33	28****	16%	1027	29	0,10
ME 15	B90.2 G04	SLN 1010	0,096	7.122	6.016	68	58	16%	855	35	0,12
ME 16	B70 GO4	SLN 1010	0,096	5.900	4.940	56	47	16%	898	33	0,14
ME 17	B70 GO4 NE*	SLN 1010	0,096	6.391	5.341	61	51	16%	881	34	0,13

Figure A.8: Sleeper + USP (types, area, stiffness, rail seat load, contact pressure) in test track of Eiffage Rail workshop in Herne

The different combinations of soft USP with standard/heavy or wide sleepers were tested with a dedicated set-up, presented in [14], that allows applying realistic static pre-load and dynamic loading.

Several measurements have been performed such as track receptance, unsprung mass mobility on the loading device, and insertion loss and rail deflection under realistic load of 20 t single axle and lateral track resistance (LTR) measurements.

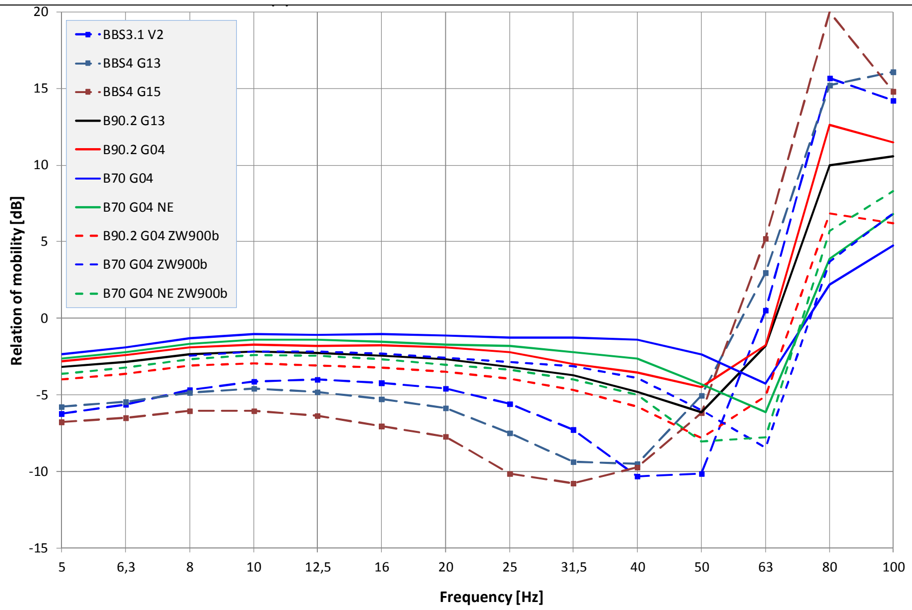


Figure A.9 : Relation of unsprung mass mobility (with the static preload case LC 2) of all investigated track systems

According to these tests, the vehicle-track resonance frequencies of the isolated tracks are observed between 32 and 63 Hz, the resonance frequencies of the un-isolated reference tracks are at 80 - 84 Hz. The positive insertion losses are found above 55 Hz, maximum insertion loss values of 8 to 20 dB have been established for the different isolated tracks for the frequencies of 80 and 100 Hz. The best insertion losses have been achieved for the wide sleepers on soft under sleeper pads, where the higher insertion losses have been observed for the softest under sleeper pads. The benefit of the heavy sleeper B90.2 could not be demonstrated in this measuring campaign. The results are less significant than for the wide sleepers, and the advantages compared to the normal sleeper B70 are relatively small, each equipped with same USP type. Therefore, the effect of increased sleeper mass can only be shown by the results of the wide sleeper BBS 4 which has a similar mass of about 600 kg as the B90.2 sleeper.

4.2 ANNEX B: VERY SOFT RAILPAD SYSTEM TEST WITHIN RIVAS

1	**Principle** A dedicated subtask was focused on rail fastening systems that allow very soft pads under the rail to be installed, on ballasted straight lines. Numerical simulations previously carried out in the WP3 [4] have shown that such systems can induce a positive insertion loss up to 20 dB, after the vehicle-on-track resonance frequency (i.e. above 40Hz to 50Hz). Therefore, two systems have been specifically designed by PANDROL in order to be tested on a ballasted track: the DFC set-up which consists in a double layer of pads (under rail pad and under base-plate pad) that allows a various range of fastening system to be obtained by varying the combination between the 2 pads, and the VANGUARD set-up that induces to clip the rail on its web with rubber assemblies so that vertical stiffness of the fastening system is reduced to its minimum. Only the DFC system has finally been fully tested within RIVAS. The installation of this system on a ballasted track required a dedicated sleeper to be designed: the SATEBA M260-DFC monobloc concrete sleeper. Once these components are designed and before they can be installed on a real commercial track, a string of tests have to be carried out to verify that they fulfil the required degree of reliability and safety, particularly for freight traffic conditions. Laboratory tests for track component certification have been done according to the EN 13146 standard. DFC in various configurations has passed these tests (different combination of under rail pad and under base-plate pad: from DFC 0 with an equivalent stiffness close to 75 MN/m to the DFC 3 with an equivalent stiffness equal to 25 MN/m). In parallel to the certification process, installation of this innovative system into a real track has been organized. The last step before installing and testing the system consisted in designing the in-situ measurement campaign: track and ground dynamic characterization, free-field vibration measurement, rolling noise assessment. The DFC is installed since September 2013 into the DFC3 configuration in the East of France. Several measurements have allowed assessing its performances in terms of ground vibration mitigation.
2	**Dedicated lab tests** As a first step, before testing the mitigation measures in situ, laboratory measurements have been carried out by CSTB at SATEBA premises. Six different fastening systems were tested: 4 classical FASTCLIP systems with 4 different pads, the DFC system and the VANGUARD system. The idea was to design and to use an experimental set-up able to reproduce track conditions as realistic as possible. The two objectives that where aimed by the laboratory measurements are the following: - the estimation of the insertion loss in terms of ground vibrations for each system, - the estimation of a realistic dynamic stiffness for the tested systems. A full report has been written on these specific tests in [6] appendix B.

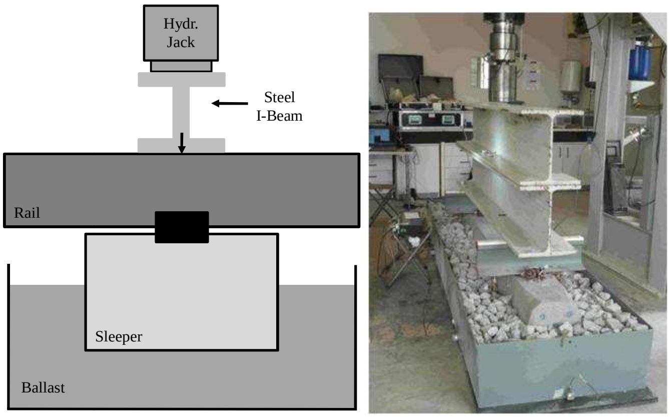


Figure B.1: Test bench set-up for the high amplitude dynamic tests

The assessment of the realistic dynamic stiffness performed with these tests has allowed numerical simulations to be carried out in order to assess the insertion losses that could be expected with both systems. With the VANGUARD system, an IL of 10 dB above around 60 Hz and about 20 dB above 90 Hz can be reached, with a DFC system an insertion loss of nearly 10 dB can be reached above 90 Hz. This very positive impact is counter-balanced by an amplification effect in the very low frequency range, as already mentioned in the deliverable [4]. However, it is mentioned that the numerical study carried out take into account only unevenness excitation phenomena and not parametric excitation.

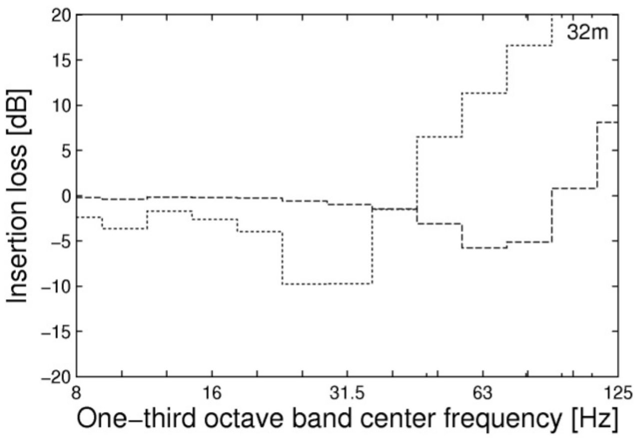


Figure B.2: Insertion loss of the free field velocity at 32m for the DFC system (dashed line) and the VANGUARD system (dotted line) when compared to the standard SNCF pads, IL simulated with TRAFFIC © with pads dynamic stiffness assessed with lab tests

3 **Certification tests**

The DFC system, chosen to be installed in real track, has to pass the SNCF certification tests to be used in in-service configuration (commercial freight traffic).

The sleeper M260 DFC, specifically designed to support the DFC systems, has also passed the SNCF certification tests as it should be able to be let indefinitely on the test site. It has therefore been submitted to wrenching tests and resistance tests.

The global system M260 DFC sleeper equipped with DFC fastening system, has been submitted to:

- Rail pad thickness before and after repeated loads
- Static stiffness before and after repeated loads
- Dynamic stiffness before and after repeated loads
- Clamping force before and after repeated loads
- Creep resistance before and after repeated loads
- Clamping torque
- Impact load attenuation
- Fatigue tests (repeated loads)
- Electrical resistance
- Exposure to hard environmental conditions

All the results of these tests are detailed in [7]

We focus here on the dynamic stiffness of the DFC system in 2 different configurations: the stiffest (DFC0) one and the softest (DFC3) one.

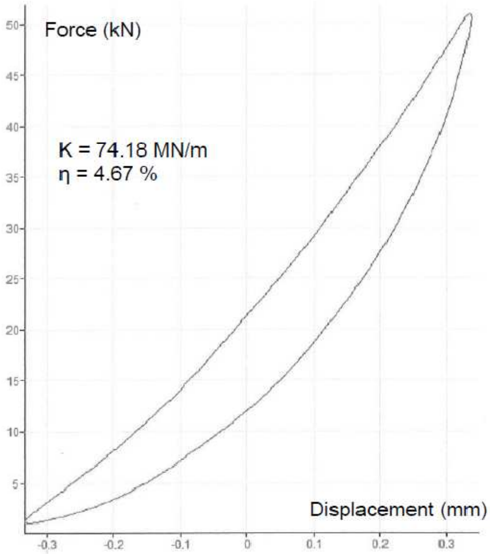


Figure B.3: Vertical dynamic stiffness for DFC 0, after fatigue tests

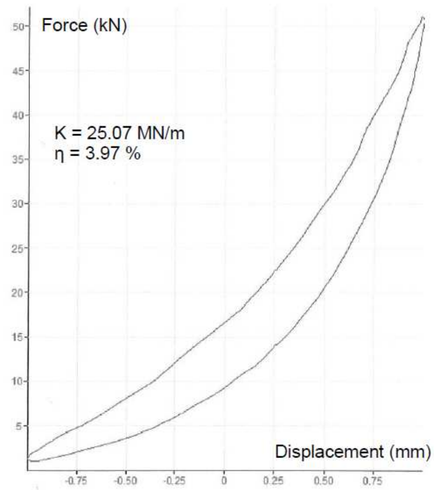


Figure B.4: Vertical dynamic stiffness for DFC 3, after fatigue tests

From previous graphs, it is clear that the DFC systems have a non linear stiffness with respect to the load (progressive spring characteristic). This behaviour which is well known for rail pads seems to be more important for the DFC systems, and also more important for the softest systems.

4 **In site test: installation in commercial track**

The site for the field tests has been selected considering the following requirements:

- Try to install the M260-DFC sleepers within a track renewing operation (at least sleeper renewing) in order to minimize the installation costs.
- Track in alignment including two sections of 100m circulated by the same trains: a reference zone and a test zone.
- Track with UIC 60 rail (DFC and VANGUARD are designed for this type of rail).
- Line with freight traffic.
- Easy access around the test and the reference sections (sensors placement and equipment conveyance).
- Allowing measurements at an appropriate date i.e. after the sleepers and the system are produced and soon enough before the end of the project.

Under these requirements, only 1 site was eligible. It is located in the North-East of France, on the line 204000 between the kilometre marker 272 and 273 near the city of Florange.

Figure B.5: DFC systems installed in track

The stiffness of the fastening system will vary from 120 MN/m in regular track (FASTCLIP system directly installed on the sleeper) to 25 MN/m in the test section equipped with DFC 3. If a running train would experience such a gap in the track stiffness, it would lead to high wheel/rail interaction forces which are potentially damageable for the rail and the track foundation (ballast). In order to avoid this risk, the stiffness variation from stiff track to soft track is achieved using transition zones with intermediate stiffness (see RIVAS deliverable 3.4 [6] for more details).

The following table gives an overview of the different configurations that have been sequentially installed on each zone of the tests section, including the Under Rail Pad type (URP) and the Under Base-plate Pad type (UBP).

Config.	Sleeper	M450	M450	M260	M260	M260	M450	M450
	Length	20m	20m	25m	100m	25m	20m	20m
DFC 0	URP	120 MN/m	120 MN/m	120 MN/m	120 MN/m	120 MN/m	120 MN/m	120 MN/m
	UBP			270 MN/m	270 MN/m	270 MN/m		
DFC 2	URP	60 MN/m	40 MN/m	40 MN/m	40 MN/m	40 MN/m	40 MN/m	60 MN/m
	UBP			270 MN/m	270 MN/m	270 MN/m		
DFC 3	URP	60 MN/m	40 MN/m	120 MN/m	120 MN/m	120 MN/m	40 MN/m	60 MN/m
	UBP			64 MN/m	64 MN/m	64 MN/m		

A reference site has also been identified, at 400m from the test site.

The following measurements for characterizing the 2 different sites have been performed:

Reference section			Test section		
AEF			AEF		
Nature	**When ?**	**Description**	**Nature**	**When ?**	**Description**
Low frequency track receptance	Before and after the tests	Excitation with large hammer, on the rail, at mid-span and above a sleeper, 10 impacts	Low frequency track receptance	DFC 0 DFC 2 DFC 3	Excitation with large hammer, on the rail, at mid-span and above a sleeper, 10 impacts
High frequency track receptance	Before and after the tests	Excitation with small hammer, on the rail, at mid-span and above a sleeper, 10 impacts	High frequency track receptance	DFC 0 DFC 2 DFC 3	Excitation with small hammer, on the rail, at mid-span and above a sleeper, 10 impacts
Soil to soil mobility	Before the tests	Excitation with large hammer on a steel plate close to the track, 70 impacts	Soil to soil mobility	Before the tests	Excitation with large hammer on a steel plate close to the track, 70 impacts
Rail to soil mobility	Before and after the tests	Excitation with large hammer, on the rail, at mid-span and above a sleeper, 70 impacts	Rail to soil mobility	DFC 0 DFC 2 DFC 3	Excitation with large hammer, on the rail, at mid-span and above a sleeper, 70 impacts
Rail Roughness	No specification	Following EN 15610	Rail Roughness	No Specification	Following EN 15610
VIBRATEC			VIBRATEC		
			Rail to soil mobility along the Rail	DFC 0 DFC 3	Excitation with large hammer on the rail, each 1 m, over 17 m, Ground vibration sensor.

	Sleeper to soil mobility	DFC 0 DFC 3	Excitation with large hammer on 1 sleeper, on both sides of the rail

The following track-free field mobilities have been found on both sites, at 8m from the track:

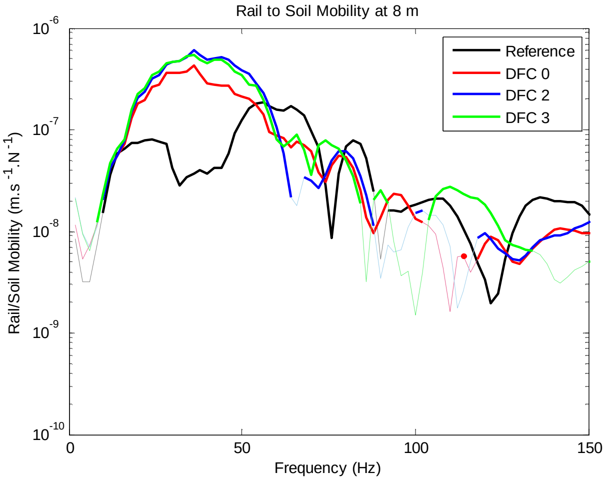


Figure B.6: mobilities between the track and the free-field receptor at 8m for the reference site and the different DFC configurations on the test site

At 8 m and 16 m to the track, there is a wide frequency range below 50 Hz for which high mobility is observed at the test section. This high mobility concerns the three DFC configurations and is therefore related to the track section and not to the stiffness of the fastening system. The following track receptances on both sites have been found:

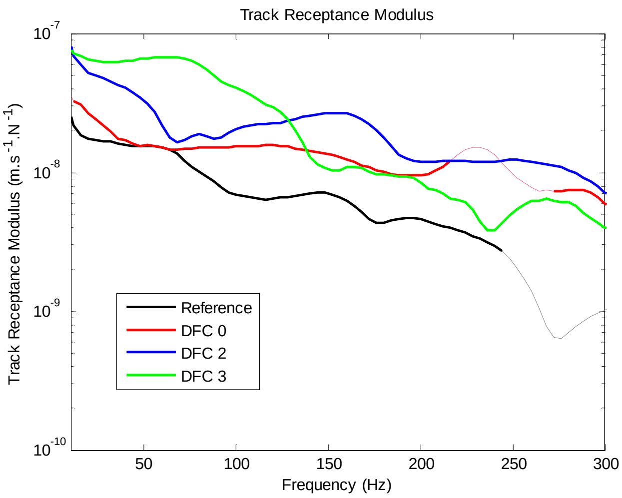


Figure B.7 : track receptance at the reference site and the test site for the different DC configurations

According to the deliverable 3.10 [12], the following conclusions can be drawn from the track and soil characterization:

First, despite the efforts that have been made to choose a test site that fulfils the RIVAS recommendations, the track characterization measurements highlighted important differences in the transmission path between the track and the free field depending on the track section considered. However, the complete measurements that were performed and that lead to this conclusion will help to interpret further results (pass-by measurements) with care and give also the possibility to carefully correct some of them.

Secondly, the analysis of the track receptance pointed out some expected features concerning the stiffness of the different fastening systems. The vibration isolation of the rail from the rest of the track is confirmed for all the systems and is close to what is expected from laboratory measurements.

In addition, ground vibrations (+ rail vibrations and sleeper vertical vibrations) have been measured, during several freight and passenger train pass-by, for each DFC configuration, at test site and reference site, as described in the following table.

Reference section		**Test section**	
AEF		**AEF**	
Nature	**Description**	**Nature**	**Description**
Vertical Ground Vibration	Accelerometers at 8 m (3 times), 16 m and 32 m to the track.	Vertical Ground Vibration	Accelerometers at 8 m (3 times), 16 m and 32 m to the track.
Vertical Rail Vibration	Accelerometer under the rail foot at midspan.	Vertical Rail Vibration	Accelerometer under the rail foot at midspan.
Vertical Sleeper Vibration	2 accelerometers on both sides of the rail.	Vertical Sleeper Vibration	2 accelerometers on both sides of the rail.
Pass-by Noise	1 microphone at 7,5 m to the track, at 1,2 m height.	Pass-by Noise	1 microphone at 7,5 m to the track, at 1,2 m height.
Train Speed and Axles Detection	2 electromagnetic detection pedals at one section's end.	Train Speed and Axles Detection	2 electromagnetic detection pedals at one section's end.
VIBRATEC		**VIBRATEC (only DFC 0 and DFC 3 tested)**	
		Rail/Sleeper Vertical Relative Displacement	2 displacement sensors on 7 consecutive sleepers.
		Vertical Sleeper Vibration	2 accelerometers on both sides of the rail, for these 7 sleepers.
		Low Frequency Vertical Sleeper Vibration	1 accelerometer with mechanical low-pass filter on 5 of the 7 sleepers.

Several trains have been measured with various speeds. A categorization of the results according to the speed of trains has been performed within the deliverable 3.10 [12]. The results for speeds between 70 km/h and 85 km/h are presented below (this speed range gathers the maximum number of recorded pass-by). The following insertion losses between the reference site and the test site have been found, for the different DFC configurations that have been tested:

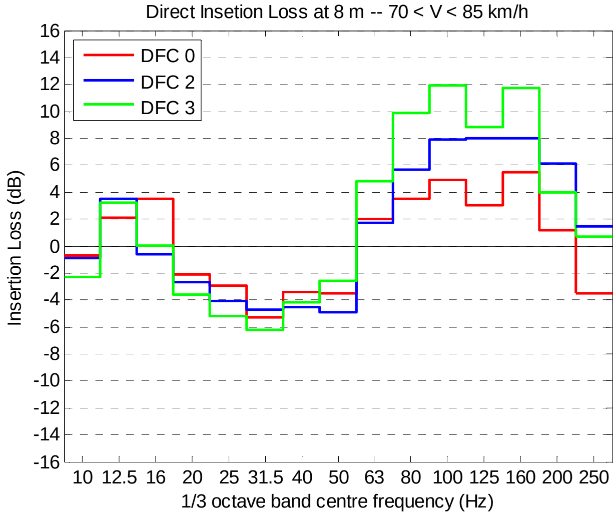


Figure B.8: insertion losses between the reference site and the test site, for the different DFC configurations

Insertion losses between the different configurations of DFC have also been computed, taking as reference the configuration DFC0. This allows releasing the results from the ground and site effect.

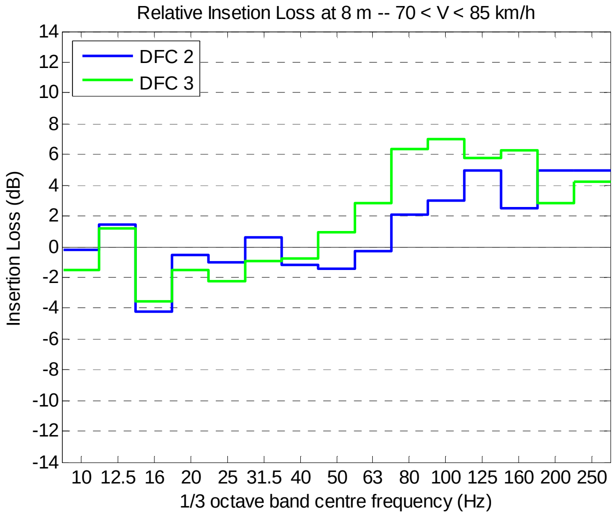


Figure B.9: indirect insertion losses at the test site

The lower the stiffness, the lower the resonance frequency above which positive IL arise. For DFC3, a insertion loss up to 10 dB can be reached for frequencies above 50 Hz.

Amplification occurs at the resonance frequency up to 3dB for the DFC3 (and 4dB for the DFC2) compared to DFC0. When comparing to the reference site, it can reach 5dB but in that case, we do not fully control the effect of the ground discrepancy between the 2 sites.

Apparently, we do have an effect of very soft fastening systems on the parametric excitation: reduction of the vibrations around 20Hz.

4.3 ANNEX C: SOFT USP INSTALLED IN GETRAC A3 SYSTEM

1 **Principle**

A parameter study has been carried out on a particular slab track, the GETRAC® A3.1 system, equipped with under-sleeper pads, in order to determine the most promising design in terms of vibration mitigation. This study is described in detail in the RIVAS D3.3 [5]. It has been shown that the main parameters that influence the reduction of ground vibration are the stiffness of the under sleeper pad, the mass and the width of the sleeper. The softest sleeper pad yields the best reduction of the ground vibration. A strong increase of the sleeper mass, for example the double mass of the standard sleeper, can improve the reduction effect. The influence of other parameters has been examined. The stiffness of the rail pads, the bending stiffness of the track, the sub-soil, and the soil, and the layering of the soil. All these parameters show no or only a minor influence on the mitigation effect in simulations.

As the standard isolated track, a track with an under sleeper pad of a stiffness of k_S = 50.10^6 N/m has been chosen, which can also be expressed as a stiffness per area of $k_{S''}$ = 0.050 N/mm3 yields a vehicle-track resonance frequency of 32 Hz, whereas the vibration at this frequency are amplified, levels at higher frequencies are reduced. The insertion loss of this solution is up to 25 dB at 80 Hz for the ground vibrations in comparison to the reference slab track system (GETRAC A3 system without under sleeper pads but with soft rail pads with a total nominal dynamic stiffness per sleeper of ks = 80.10^6 N/m).

According to these results, it has been decided to test at scale one the insertion of soft USP in a GETRAC A3.1 system.

To do so, laboratory tests were performed to assess the performance of the USP material and their potential performance when inserting in a GETRAC system. Then, a GETRAC system with USP has been fully constructed at the test rig of Eiffage Rail in Herne and its mitigation impact has been assessed, with regard to standard ballasted track.

2 **Laboratory tests**

The tests for under sleeper pads have been performed in accordance with DIN 45673-6 – Mechanical vibration – Resilient elements used in railway tracks – Part 6: Laboratory test procedures for under sleeper pads of concrete sleepers. They are fully described in [11]. The tests for the sleepers have been performed in accordance with DIN EN 13230-2 – Railway applications – Track – Concrete sleepers and bearers – Part 2: Prestressed monoblock sleepers. For some tests, a test specification was used which takes into account the 1.6 times larger contact area from the wide sleeper compared to a standard sleeper (B70) each with USP, by the same load.
Two different types of under sleeper pads (V01 and V02) and one sleeper type (BBS3.1) were investigated.

Type	Material	Fleece / felt	Thickness [mm] target	Static bedding modulus [N/mm³] target
V01	EPDM	Polyester based	13 mm ≤ x ≤ 15 mm	0,04
V02	EPDM	Polyester based, hardened by water jet	13 mm ≤ x ≤ 15 mm	0.08

For the examination of the under sleeper pads for slab track laboratory tests for the static and dynamic bedding modulus, bond strength, shear strength and the freeze-thaw resistance were carried out. For the sleepers static tests, dynamic tests and fatigue tests were carried out. The fatigue strength of the whole system was determined by a so called system test.

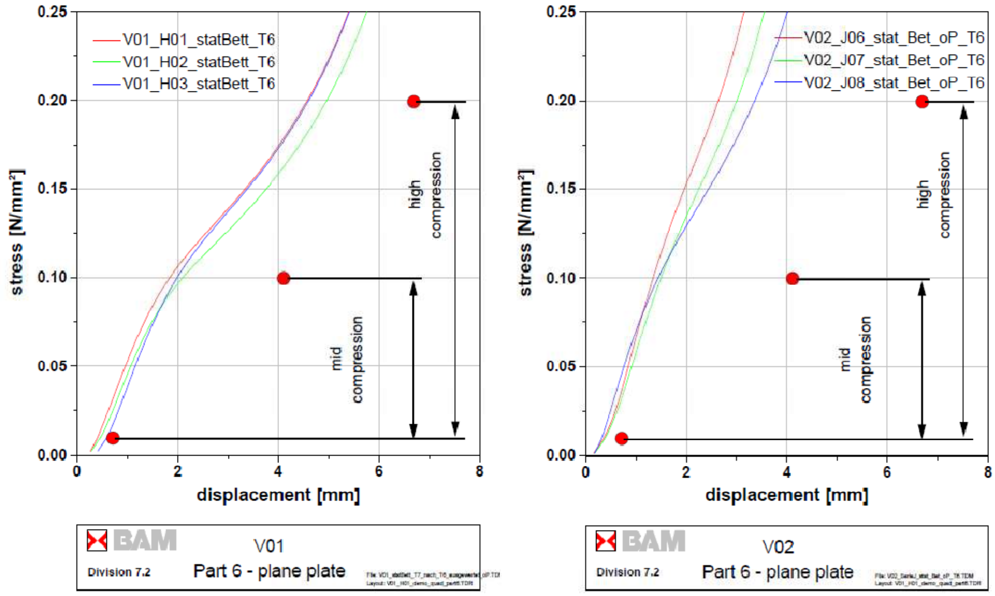


Figure C.1: static bedding modulus DIN 45673-6 plane loading plate

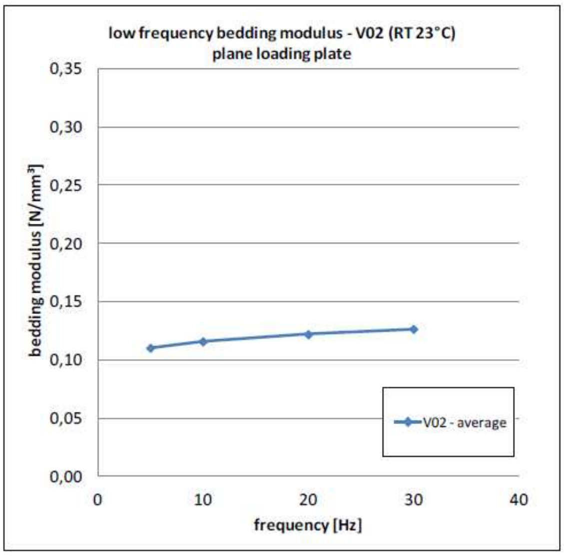


Figure C.2: low bedding modulus DIN 45673-6 plane loading plate

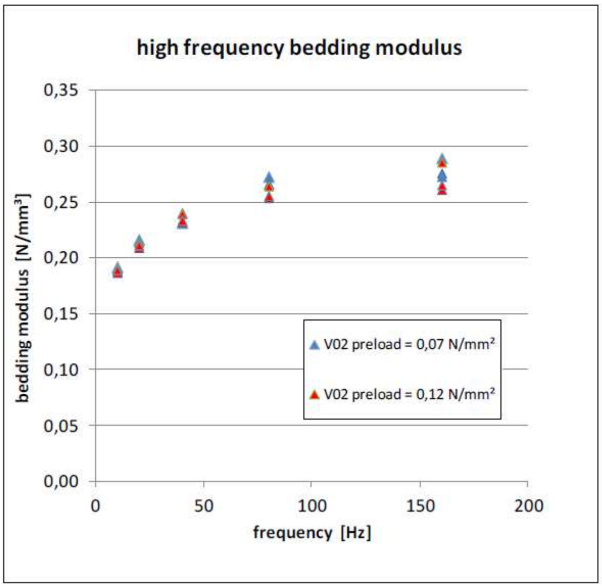


Figure C.3: high frequency bedding modulus for VO2 sample of USP

The static displacement under a static service load of USP V01 was more than 2.5 mm for the maximum load in the system test. Therefore USP V02 with the higher stiffness but the lower mitigation potential was chosen and installed in a test track for further tests.

3 **Scale 1:1 test rig implementation**

The GETRAC A3.1 system with USP type V02 has been installed on the same test rig than the different combinations of USP +standard/heavy or wide sleepers on ballast, presented in the Annex A. It corresponds to the test section ME11.

Measuring section ID	**Short name**	**Sleeper**		**Under sleeper pad (USP)**				**Rail pad**
		Type	weight *incl. USP & fastener* [kg]	type	Supply name	Nominal static modulus [N/mm³]	Total area [cm²]	
ME11	BBS3.1 V2	BBS 3.1	577	V-02	-	0,085	10,080	Zw 687a

The same loading set-up has been used (Butterfly system) as described in the report [14] that reproduces realistic static pre-laod and dynamic load.

Several measurements have been performed such as track receptance, unsprung mass mobility on the loading device, insertion loss and rail deflection under realistic load.

Figure C.4 : Insertion loss at the 12m - measuring points

Three load cases LC 1 to LC 3 has been performed, where only LC 1 and LC 2 are close to reality because of the simulated static preload.

The abatement performance of the slab track system was measured in a comparable range of abatement than the very soft USPs (0.05 and 0.03 N/mm³) on ballast. The GETRAC A3.1 system achieved a positive insertion loss above of 60 Hz and a reduction of up to 16 dB @ 80 Hz. The similar result of actually stiffer USP than for the ballast sections is based on a less stiffening of USP V02 material under preload compared to the USPs used for the ballasted tracks.