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Railway Induced Vibration Abatement Solutions
Collaborative project

Measurement report about a new under sleeper test track in a curve

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EXECUTIVE SUMMARY

Within the frame of the EU FP7 project 'Railway Induced Vibration Abatement Solutions (RIVAS)', abatement measures for ground-borne noise and vibrations for tracks (Workpackage 3) are studied. Workpackage 3.3 of RIVAS focuses on vibration reduction technologies for curves and turnouts. This report describes the measurements and their result of the under sleeper pad (USP) test in the curve.

With exception of ballast mats, up to now there are no well-established methods to mitigate vibrations in curves of ballasted tracks. In comparison with straight tracks there are much higher lateral forces arising in curves which could destabilize the track. USP may represent another method besides ballast mats with respect to vibration mitigation in curves and was tested at SBB.

The main objectives of this work are (i) to quantify the mitigation effect of different USP materials with respect to vibration mitigation and effects on airborne noise and (ii) to investigate their reliability in terms of track stability parameters. To address these objectives, SBB designed a test-track spanning a curve section as well as a straight section. In each section, three different USP products (i.e. Tiflex, CDM and Getzner) are installed. To further reduce the track stiffness, a soft railpad (C_{stat} = 100 kN/mm) is installed in all sections with USP, whereas the SBB standard railpad (C_{stat} = 700 kN/mm), which is seven times stiffer, is installed in the reference section. Due to the lack of space for another 108 m reference section with soft railpads and as the stiff railpads are installed all over Switzerland, the stiff railpads were chosen for the reference section. At that time SBB did not know that soft railpads lead to a sometimes significant higher airborne noise due to the higher sound radiation from the rail. Noise effects of USP compared to a standard track cannot be truly determined because the railpads of reference and test sections are not equal.

The results of the track characteristics and stability measurement campaign as well as from the noise measurements are presented in Chapter 3. Track deflection measurements reveal a quite highly disturbed track subgrade along the test track. Therefore, the deflections of the USP test site are potentially underestimated to some extent due to considerable differences in ground stiffness. Overall, deflections of about 0.6 to 1.2 mm are observed. The settlement measurements revealed a much more pronounced (up to three times higher values) settlement in the reference section compared with the sections with USP. The lateral force resistance measurements showed that in comparison with the reference section, the lateral force resistance in sections with USP is significantly lower. At a displacement of 2 mm, about 40% to 43% of the lateral force resistance was found in straight track sections with USP compared with the straight reference section. A conclusive interpretation of the lateral force resistance results will be possible after the UIC working group for lateral force resistance will have tested and discussed the SBB measurement method for lateral force resistance. The vibration measurements of the sleepers in the straight line reveal that the highest vibration acceleration (RMS values) arise for the sleeper product Tiflex. The lowest vibration amplitudes is found for the product Getzner (soft and stiff).

The static stiffness was determined in laboratory experiments following the CEN-standard for characterisation of USP stiffness for all the tested USP samples. The measurements reveal a value of about 0.12 N/mm^3. The dynamic stiffness is only around 30% higher, but for the product Tiflex, the dynamic stiffness at 30 Hz is about 20% lower compared to the products Getzner and CDM.

The comparison of the noise measurements of the straight reference section with hard railpads and without USP revealed an increase of 2 dBA to 5 dBA depending on the train type running over the straight and curve sections with soft railpads and USP. Based on experience and physical models, it is assumed that this effect rather arises from railpads than from USP: considering the track decay rate (TDR) measurements and the analysis of the collected TDR spectra, differences of about 2-4 dB are

expected. With a more accurate and frequency dependent evaluation of the noise measurements, it would be possible to verify the contribution of the soft railpads. This additional noise effect potentially could be reduced by the installation of harder rail pads than C_{stat} = 100 kN/mm.

The rail roughness measurements show that the reference section exhibits the highest roughness. This indicates that the additional noise is due to effects such as track component stiffness (such as soft rail-pad which could lead to additional track dynamics in higher frequencies) or measurement conditions, but not due to rail roughness.

The results from the vibration data analysis with respect to the quantification of the mitigation effect of USP on ground vibrations is presented in Chapter 4. Accounting for correction of the influence of the heterogeneous geology, a distinct reduction of vibration can be observed by means of the v_{RMS} values; considering all train categories (i.e. intercity, regional and freight trains), the achieved mitigation effect is in the range of about 10%-40%.

The frequency analysis of the measurements shows that a mitigation effect can be observed above 50 Hz, which reaches about 15 dB at 250 Hz. The scattering within the vibration data for the test sections in comparison to the reference section made it meaningful to apply a correction algorithm by using train pass-bys on the adjacent track to eliminate the biggest differences which occurred probably due to heterogeneous geology. These train pass-bys then serve as a second reference after being transferred to 8 m distance using a suitable transfer function. The corresponding results show that also for lower frequencies (8 Hz - 31.5 Hz) a mitigation effect of around 5 dB is achieved.

The comparison of simulations of deliverable D3.2 with these measurement results for the mitigation effects shows that the observed mean mitigation effect corresponds relatively well to the calculations. However, the high amplification of vibrations at the resonance frequency is much less evident from the measurement results than is expected from simulations.

The inhomogeneity of the measurement conditions did not allow for a further and more precise analysis of the different USP products, since the results scatter too much but the material properties such as C_{dyn} or C_{stat} differ only slightly and would therefore need very precise results for a validation.

The analysis of axle box measurement data indicate that further insight of the excitation mechanisms can be achieved. Such results may help to provide statistically relevant information of mitigation effects for the frequency range of interest.

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1. INTRODUCTION

The scope of WP 3 is to tackle ground vibrations at source by developing and optimising mitigation measures on the track itself. As the track characteristics (pad stiffness, fastening system, sleeper,…) play a major role in the generation of ground vibrations, efficient mitigation measures can be designed to modify the track response with the target of low vibration emission in the ground. USP (under sleeper pads) with C_{stat}=0.1 kN/mm^3 in combination with softer railpads (C_{stat}=100 kN/mm) could be a solution. SBB tested (installation of USP and reference in October 2011) soft USP in combination with softer railpads, in a curve as well as in the straight line to compare it to the standard SBB track with stiff railpads (C_{stat}=700 kN/mm) which are seven times stiffer.

1.1 UIC OVERVIEW OF USP IMPACT ON GROUND VIBRATION

The influence of USP stiffness on vibration mitigation is not yet fully understood and defined in literature, but a first study on this subject was performed by UIC in 2007 [1]. This study was part of a big UIC project on USP initialised in 2004 to investigate if this soft layer could help to have lower LCC for the track. In the course of these projects also vibration reduction related issues have been looked at (stiffness much lower for USP products for vibration mitigation). The most important results concerning vibration questions are summarised hereafter (for details see [1]):

Fig. 1.1 shows the results of vibration measurements taken on open track. Referring to the insertion loss of the emission of ground-borne vibrations, a resonance frequency was observed between 25 and 40 Hz for all the different under-sleeper pads considered. At this frequency, the insertion loss is normally negative (but here only the test site in Nüziders showed a relevant vibration amplification) which indicates that the vibration emission at the test site with USP is higher than the emission at the reference site without under-sleeper pads. According to the theoretical predictions, the resonance frequency shifts to lower frequencies with a softer and thus more dynamic bedding modulus of the under-sleeper pads. It is interesting that for all test sites an improvement from 5-8 dB is observed at 50 Hz already.

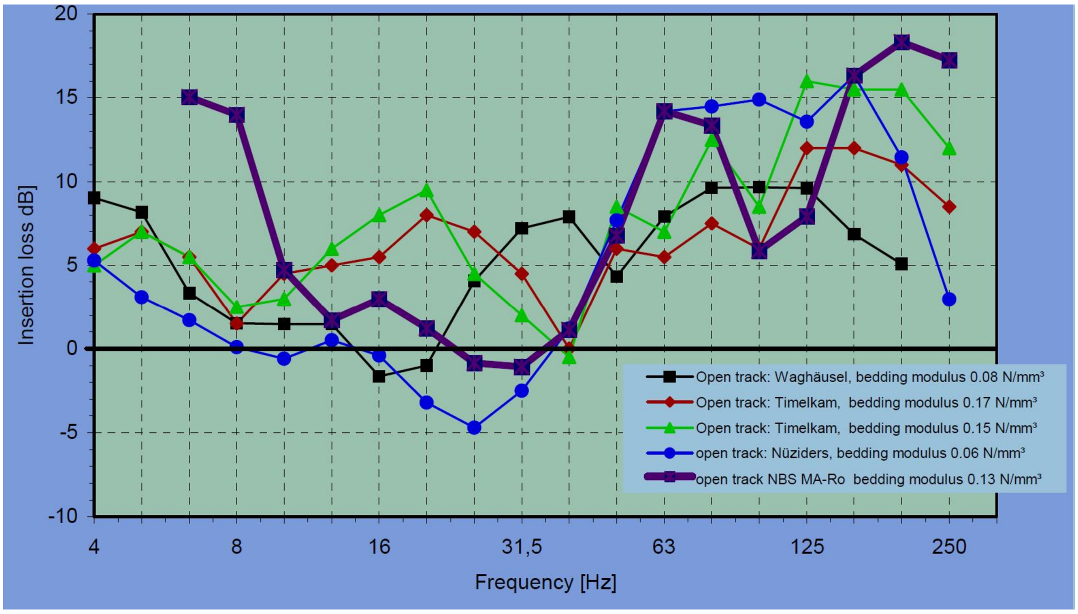


Figure 1.1: Insertion loss of USP from [1], static bedding modulus is shown in legend.

1.2 Scope and objectives

The scope of the hereafter presented project is to characterise the different effects of soft USP installed in a curve.

With exception of ballast mats, up to now there are no well-established methods to mitigate vibrations in curves of ballasted tracks. In comparison with straight tracks there are much higher lateral forces arising in curves which could destabilize the track. USP may represent another method besides ballast mats with respect to vibration mitigation in curves and was tested at SBB.

The main objectives of the present study are (i) to quantify the mitigation effect of different USP materials with respect to vibration mitigation and effects on airborne noise and (ii) to investigate their reliability in terms of track stability parameters.

2. FIELD TEST CAMPAIGN

The field test campaign at Pieterlen is intended to show whether under sleeper pads are a cost effective mitigation measure for curved tracks. To address the objectives of Chapter 1.2, SBB designed a test-track spanning a curve section as well as a straight section. In each section, three different USP products (i.e. Tiflex, CDM and Getzner) are installed. To further reduce the track stiffness, a soft railpad (C_{stat} = 100 kN/mm) is installed in all sections with USP, whereas the SBB standard railpad (C_{stat} = 700 kN/mm) is installed in the reference section.

After an equilibration period of more than 6 months, the track characteristics and stability were observed measuring different parameters (e.g. track deflection, lateral force resistance), the effect on vibration mitigation was determined with a series of vibration measurements. In addition, noise measurements were performed to characterize the effect of USP on the noise level.

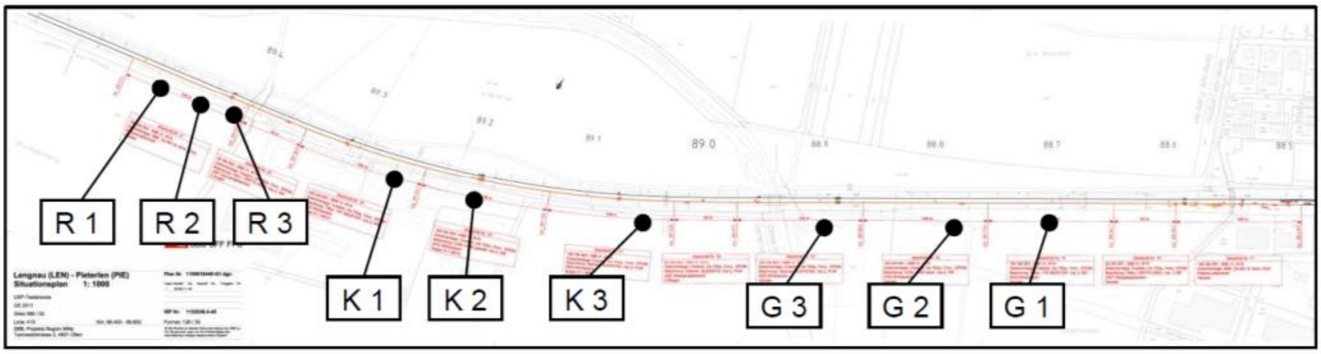
2.1 OVERVIEW OF FIELD TESTS

The ground vibration measurements were performed by Ziegler Consultants, Zurich [2] (16.4.-18.4.2012), to evaluate the mitigation effect due to different types of under sleeper pads. The exact positions of the particular measurement points as well as the instrumental set up is presented in the corresponding report. A further analysis on vibration and noise measurements is presented in the report [3].

Noise measurements were performed by Planteam GHS, Sempach-Station LU [4] (15.4.2013), to determine the noise levels for the test sections in comparison with the reference section. Additional measurements by Müller BBM [5,6] (1.7.-4.7.2013) investigated the TDR and the corrugation of the rails.

A detailed measurement campaign was performed by SBB to test the track behaviour for the USP equipped site [7]. Because of the additional softness of a USP a different behaviour of the sleeper is suspected which can have an impact on track behaviour such as additional deflection, ballast deterioration, lateral force resistance or even sleeper wear which can have an influence on track security or lifecycle costs.

A schematic overview on the setup for the USP test track is presented in Figure 2.1 and the Table 2.1 shows more details on the individual sections. Notice that a reference section in the curve is missing due to the fact that the curve length is small (a little more than 300 m) but it was sufficient for the three USP material installations (3x 108 m).



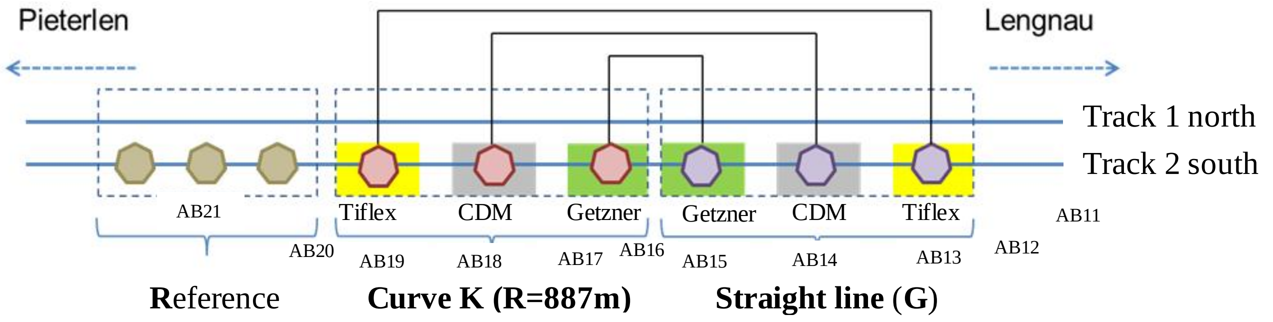


Figure 2.1: Above map and below schematic representation of the test-track with three different types of USP and the reference section where no under sleeper pads are installed.

Section nr (AB)	length	Km from	Km to	Railpad	USP	Track
11 = Ref.	108 m	88.485	88.593	SBB stiff	---	Straight line
12	54 m	88.593	88.647	Vossloh soft	Tiflex stiff	Straight line
13	108 m	88.647	88.755	Vossloh soft	Tiflex soft	Straight line
14	108 m	88.755	88.863	Vossloh soft	CDM soft, flat	Straight line
15	108 m	88.863	88.971	Vossloh soft	Getzner soft	Straight line
16	54 m	88.971	89.025	Vossloh soft	Getzner stiff	Transition curve
17	108 m	89.025	89.133	Vossloh soft	Getzner soft	Curve 887 m
18	108 m	89.133	89.241	Vossloh soft	CDM soft, waves	Curve 887 m
19	108 m	89.241	89.349	Vossloh soft	Tiflex soft	Curve 887 m
20	54m	89.349	89.403	Vossloh soft	Tiflex stiff	Transition curve
21 = Ref.	108 m	89.403	89.511	SBB stiff	---	Straight line
Total	1026m					

Table 2.1: Test and reference sections between Pieterlen and Lengnau.

2.2 Measurement site

The test track between the villages of Lengnau (LEN) and Pieterlen (PIE), see Figure 2.2 and 2.3, is set up on one track (southern) of the double track, which is part of the Jura-Südfuss line (SBB line 410) between the cities of Solothurn and Biel. Intercity-, ICN- (Intercity tilting train), regional- and freight-trains are operated on this section. The average load per day on each track was 58’000 gross registered tons (GRT). The maximum speed of R-class and N-class compositions is 130 km/h and 140 km/h respectively.

The test site was installed within a curve (radius 887 m) and a straight section.

Figure 2.2: Photo of test site USP in curve in Pieterlen, view to the west.

Figure 2.3: Aerial photo representing the situation of the test-track. The under sleeper pads are installed on the southern track on the indicated section of the double track between the villages of Pieterlen (to the left) and Lengnau (to the right). (copyright: Google Maps)

3. CHARACTERIZATION OF TEST SITE

Several measurements (for vibration measurements see Chapter 4) have been performed at the track and a sophisticated noise measurement campaign (9 microphones) and for each place the track decay rate TDR and the corrugation of the rail were measured.

3.1 USP LABORATORY TESTS

The laboratory tests performed by BAM [8] were following Draft CEN/TC 256: Railway applications – Track – Concrete sleepers and bearers – concrete sleepers and bearers with under sleeper pads, 2012-02, see [9].

Normally the USP track characteristics are described by the static stiffness C_{stat} which does not directly influence vibration mitigation but is an important parameter to define track behaviour in terms of security and LCC and can be important for example for track deflection under load. On the other hand, the dynamic stiffness C_{dyn1} (f) defines the dynamic behaviour of the USP and defines e.g. the resonance frequency of the system.

This section describes the measurement of static bedding modulus C_{stat} and low frequency bedding modulus C_{dyn1} (f) for the heaviest track category TC5 for three different under sleeper pads. The tested materials of under sleeper pads are Tiflex TR1 86-GF, CDM USP H400 and Getzner SLN 1510. Detailed measurements can be found in the annex, and further details about the measurements in [8]. The BAM report [8] only documents the results of the laboratory test without any interpretation.

The results of the measurements for the static bedding modulus are documented in detail in stress-displacement diagrams for each specimen (see Annex A). The low frequency bedding modulus is determined for 4 Hz, 10 Hz, 20 Hz and 30 Hz. All tests were carried out only at room temperature.

The static stiffness measurements show that the 3 USP materials have values marginal over 0.1 N/mm^3 and show quite similar values. The Getzner SLN 1510 has about 10% higher stiffness with 0.127 N/mm^3 (see also Table 3.1).

	Tiflex TR1 86 GF	CDM USP H400	Getzner SLN1510
C_{stat}	**0,1139 N/mm³**	**0,1152 N/mm³**	**0,1268 N/mm³**

Table 3.1: Average static and dynamic bedding modulus according to CEN/TC 256 from 3 samples of 3 USP types [8]

The dynamic stiffness measurements show that the 3 USP materials have values not far over the static stiffness. The Tiflex TR1 86 GF shows the lowest dynamic stiffness with 0.129 N/mm^3 (at 30 Hz, see also Table 3.2 and Figure 3.1) and the other two have around 20% higher dynamic stiffness.

Frequency	Tiflex TR1 86 GF	CDM USP H400	Getzner SLN1510
4 Hz	0,1245 N/mm³	0,1431 N/mm³	0,1467 N/mm³
10 Hz	0,1254 N/mm³	0,1504 N/mm³	0,1506 N/mm³
20 Hz	0,1272 N/mm³	0,1572 N/mm³	0,1543 N/mm³
30 Hz	0,1291 N/mm³	0,1615 N/mm³	0,1572 N/mm³

Table 3.2: Average static and dynamic bedding modulus according to CEN/TC 256 from 3 samples of 3 USP materials [8]

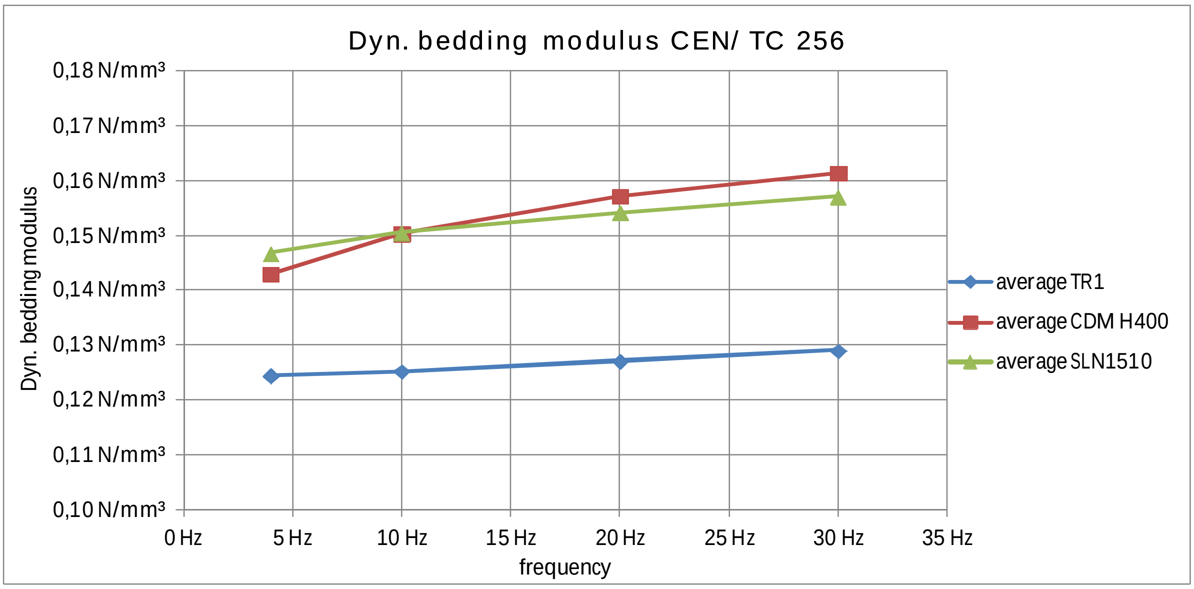


Figure 3.1: Dynamic stiffness measurements of three USP materials.

3.2 Track recording car measurements

Instead of track recording car measurement analysis a special axlebox measurement was performed to better identify dynamic wheel-rail interaction, see Chapter 4.3.

3.3 Track deflection measurements

The deflection of the track for a 20 t axle is for the reference sections without USP about 0.9 to 1.2 mm. In the sections with USP the track deflection increases with decreasing static stiffness of the USP. All sections with soft USP have a deflection of about 2 mm (see Figure 3.2).

The deflection difference (see Figure 3.3) between the test section (track south) and the adjacent track (track north) shows results with higher plausibility for the different sections, since the influence of the subgrade on the measurement results is partly compensated. It can be seen an increase in deflection in the average in comparison to the mean of the two reference sections of 0.2 to 0.4 mm with rigid USP and 0.6 to 1.2 mm with soft USP.

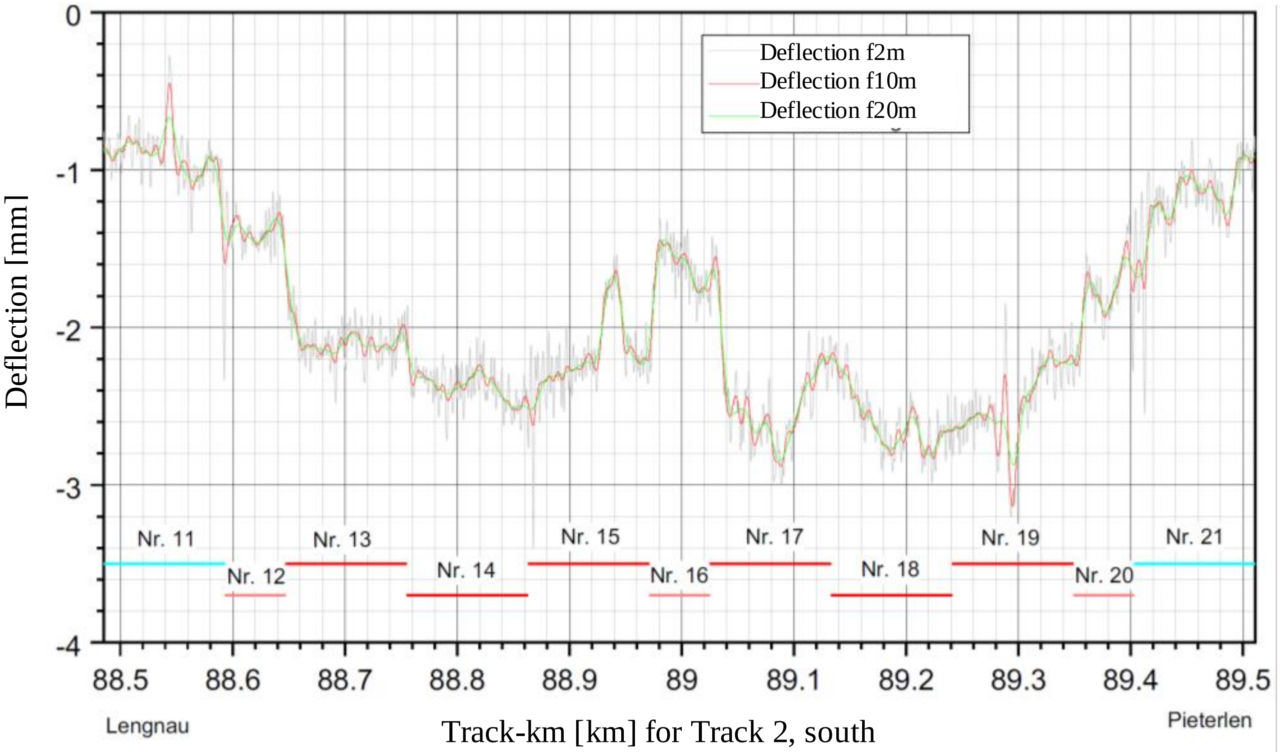


Figure 3.2: Deflection measurements of Track 2, south, over all sections with different low pass filter (no short wavelength) of wavelength 2m, 10m, 20m.

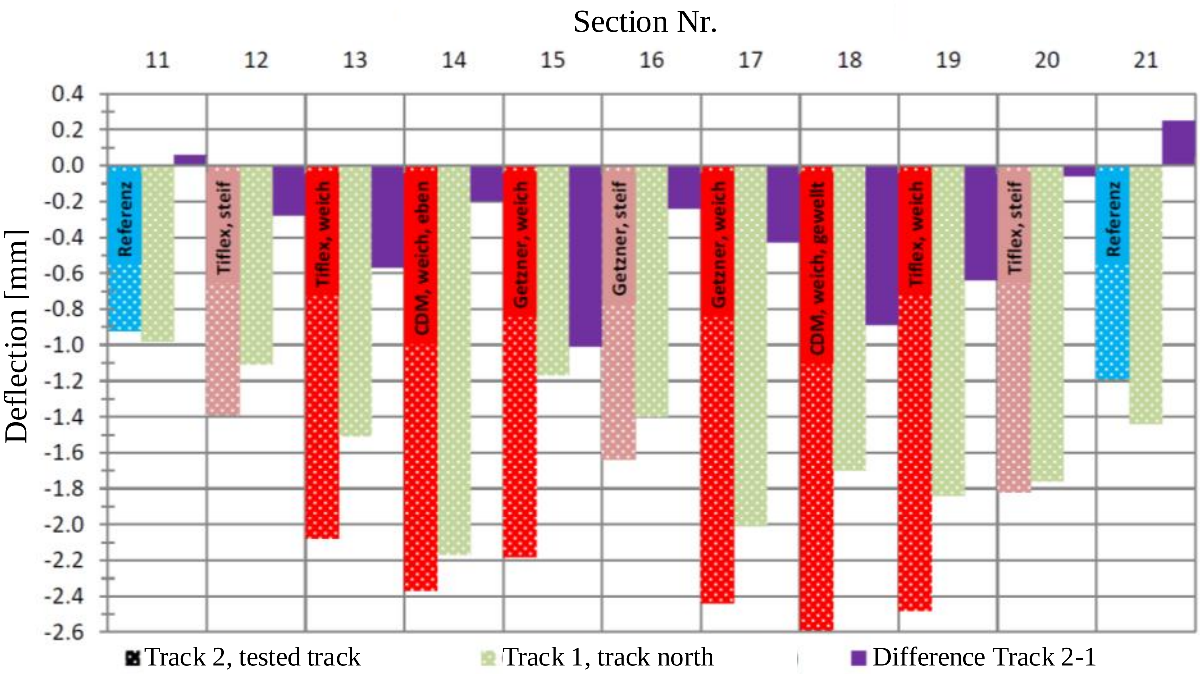


Figure 3.3: Mean deflection for each section and difference of south, track 2 to north, track 1 (filter 2m)

3.4 SETTLEMENT MEASUREMENTS

The measured sections can be sorted in three groups for the settlement measurements:
- AB 13 and 14: Low settlement of approximately 3.5 mm at USP Tiflex soft and CDM soft.
- AB 12 and 15: Mean settlement of 5 mm to 6 mm at USP Getzner soft and Tiflex stiff.
- AB 11 and 16: High settlement of 8 to 9.5 mm at USP Getzner stiff and in the reference section.

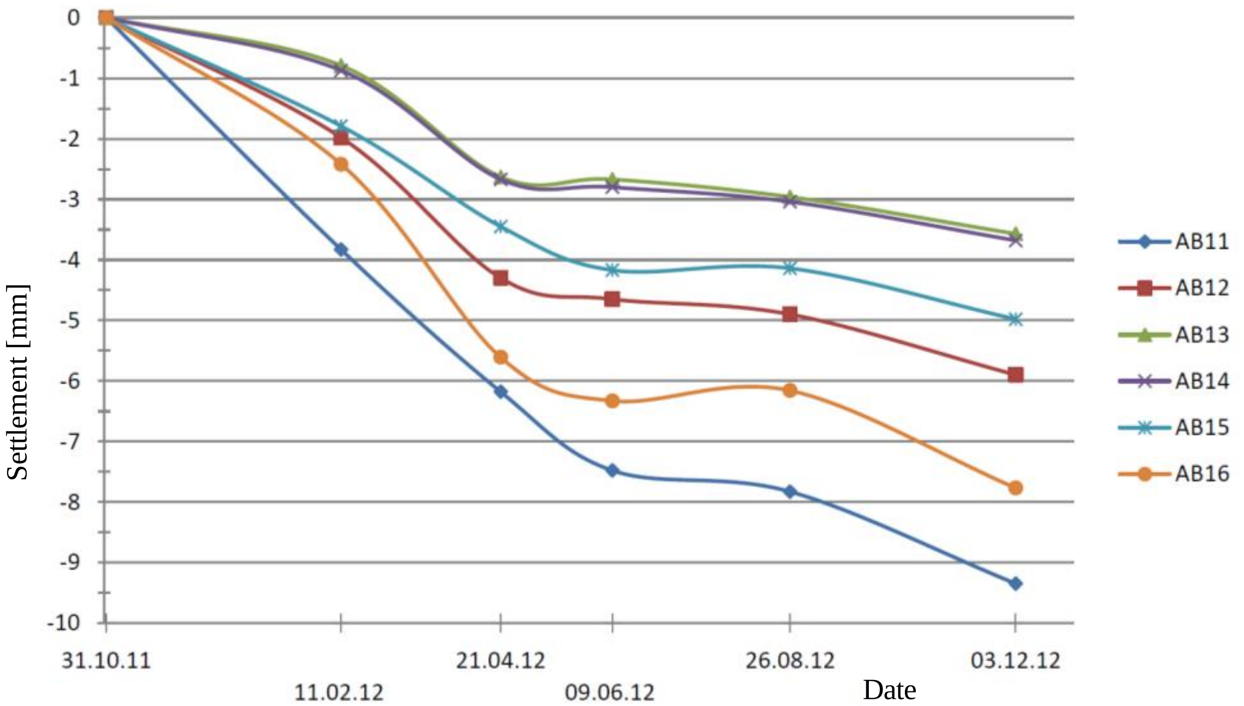


Figure 3.4: Settlement since the start of the test

It can be seen (see Figure 3.4) that the non USP reference section has a high settlement, the sections with stiff USP an intermediate and the sections with soft USP have the lowest settlement behaviour. The reference track shows a higher settlement of almost a factor of three than in sections with soft USP. The settlement of the track has not yet achieved a fully stable state after a year of operation as settlement differences can be identified for all sections between the last two measurements.

3.5 LATERAL FORCE RESISTANCE MEASUREMENTS

The lateral force resistance measurements were performed according to the SBB method []. So far no regulations exist which would define the measurement procedure. A UIC working group will start very soon on this topic.

The sections with soft USP have on average in comparison to the reference sections a greatly reduced lateral force resistance (LFR) (see Figure 3.5). At 2 mm displacement the sections with USP in a straight line reach about 40 to 43% of the LFR of the reference section. A conclusive interpretation of these results will be possible after the UIC working group tests which will also discuss the SBB measurement method to check how useful it is for USP tracks. The LFR values of the USP sections in the curves are roughly similar. At 2 mm displacement they show 15.79 kN in section 13 (USP Tiflex soft), 15.68 kN in section 15 (USP Getzner soft), respectively 14.86 kN (USP CDM soft, flat). The difference between the sections is thus about 6%.

The USP in the straight sections induce, whatever the USP material type, higher LFR than the USP sections in the curve. The difference is at USP Tiflex 1.14 kN (8%), at USP CDM 2.90 kN (24%) and at USP Getzner 3.07 kN (24%) - all values relative to 2 mm of displacement. Section 14 is provided with an USP of the company CDM having a flat surface while section 18 is provided with the same USP of the company CDM but having a corrugated surface. The measurements do not show relevant increase in LFR for the corrugated surface, which was suspected.

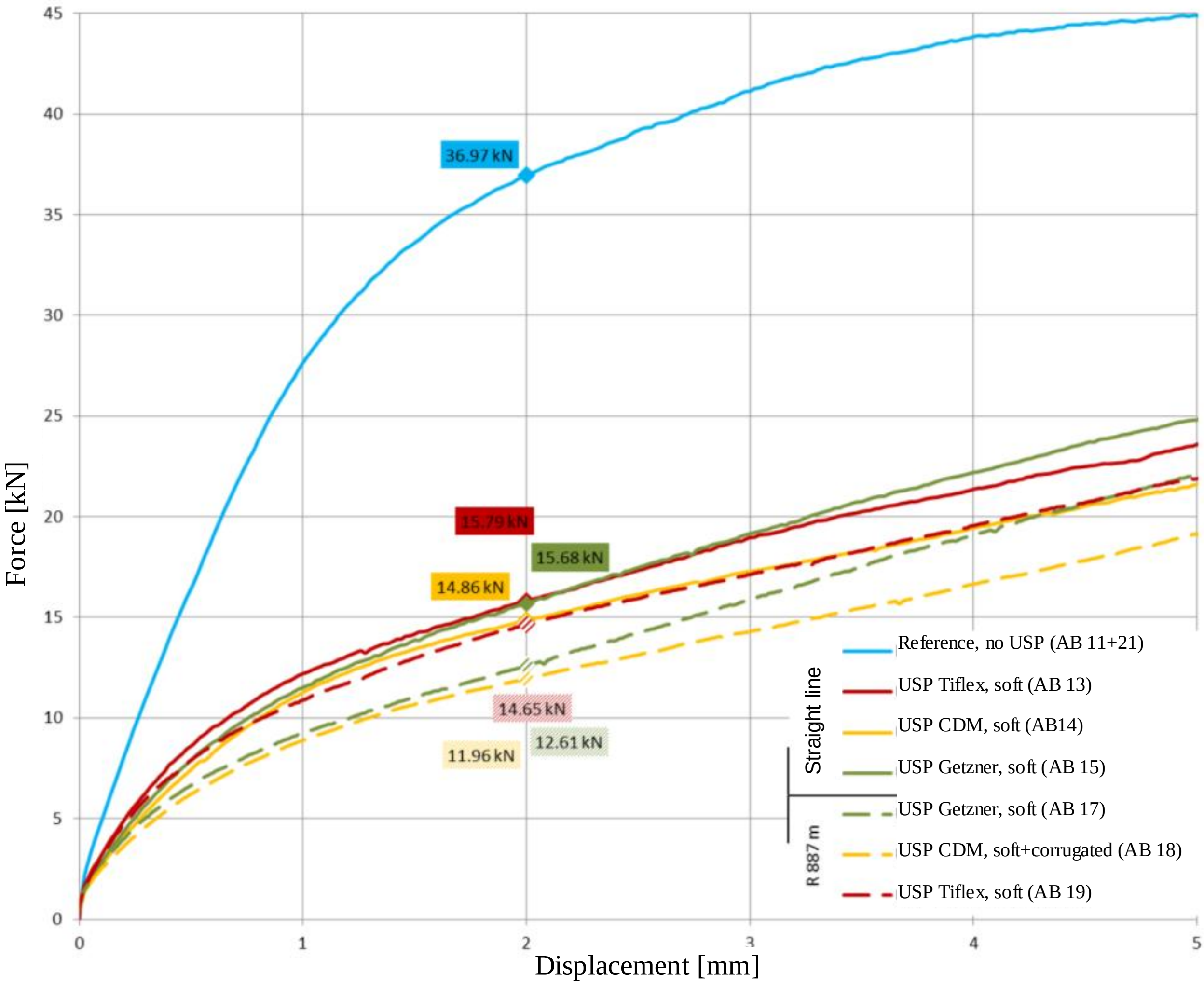


Figure 3.5: Mean values of LFR until 5 mm of lateral displacement

3.6 Sleeper acceleration measurements

In August 2012 the sections 11 to 16 were equipped with accelerometers to measure the vertical vibrations at 8 sleepers. During about 12 hours, all trains were recorded automatically. The Intercity tilting train (ICN) (see Figure 3.6) and the (coach type EWIV, locomotive Re 460) Intercity trains have been evaluated. The root mean square values as well as the frequency spectrum of the acceleration have been calculated.

The highest root mean square values of the vibrations (RMS values) result in section 13 (USP Tiflex, soft). The sections 11 (reference), 12 (USP Tiflex, stiff) and 14 (USP CDM, soft) are in between. In sections 15 and 16 (USP Getzner soft and stiff), there were the lowest amplitudes of the vibrations. The highest amplitudes in the frequency spectrum are between 600 and 1300 Hz. However, the frequency response is strongly dependent on the speed of the trains. For the IC trains resonance phenomena occur.

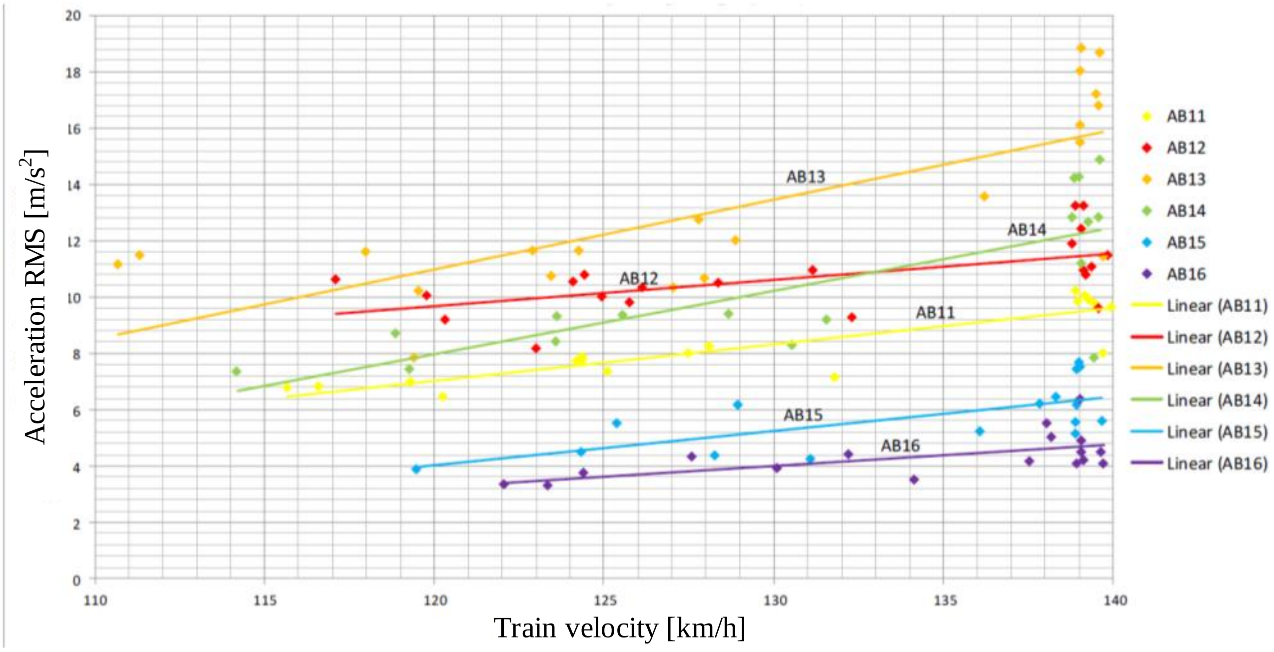


Figure 3.6: Trend lines of accelerations per section for Intercity trains (ICN). Mean values of all 8 measurement points per section (all straight line) per train.

Especially the soft railpads affect the frequency of the highest amplitude. For the reference section (AB11) it is at 1250 Hz, respectively 1600 Hz (see Figure 3.7). In USP sections with soft railpads (AB12-AB16), however it is at 630 Hz (lowering the railpad stiffness would lower this resonance frequency, which will affect sleeper vibrations at this frequency), the only exception is section 13, where both 630 Hz and 1600 Hz have the highest amplitudes.

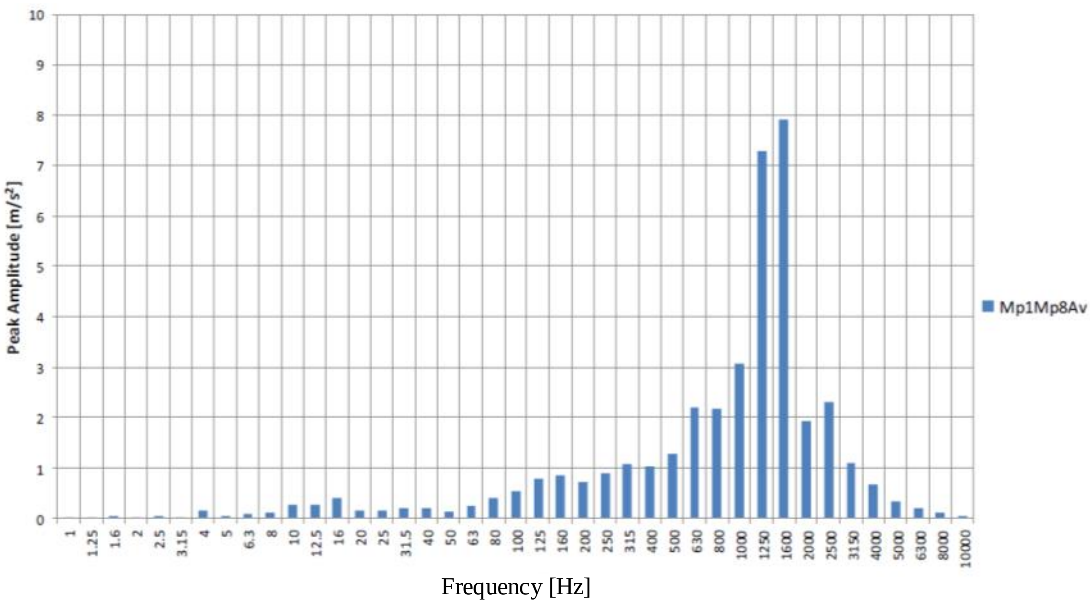


Figure 3.7: Frequency spectrum for section 11, measurement 177 of ICN with 139 km/h. Mean of peak amplitudes in m/s^2 of MP1-MP8.

3.7 NOISE MEASUREMENTS

A) Measurements next to track

The noise-measurements were performed in April 2013, for measurement points R1, R2, … G3 see Figure 2.1, whereas the installation of the softer railpad and the USP was in October 2011. The results for SEL[1] are summarized in Table 3.7. Only trains on the southern track were measured, so it is not possible to build up “transfer functions” to correct for possible “measurement errors” as it is performed in Chapter 4.

Noise levels determined for IC-compositions									
Number of measurements: 36	**R1 [dBA]**	**R2 [dBA]**	**R3 [dBA]**	**K1 [dBA]**	**K2 [dBA]**	**K3 [dBA]**	**G1 [dBA]**	**G2 [dBA]**	**G3 [dBA]**
USP Material, stiffness c_{stat} (kN/mm)	-	-	-	*Tiflex 0.114*	*CDM 0.115*	*Getzner 0.127*	*Tiflex 0.114*	*CDM 0.115*	*Getzner 0.127*
Railpad stiffness c_{stat} (kN/mm)	*700*	*700*	*700*	*100*	*100*	*100*	*100*	*100*	*100*
Energetic average	86.7	87.2	85.8	89.0	89.5	88.8	90.8	88.3	87.4
Maximum value	89.0	89.6	88.3	91.5	91.9	91.4	94.4	93.0	91.9
Minimum value	83.7	84.1	82.6	86.2	86.7	86.2	86.6	84.4	83.9
Noise levels determined for regional train-compositions									
Number of measurements: 30	**R1 [dBA]**	**R2 [dBA]**	**R3 [dBA]**	**K1 [dBA]**	**K2 [dBA]**	**K3 [dBA]**	**G1 [dBA]**	**G2 [dBA]**	**G3 [dBA]**
USP Material, stiffness c_{stat} (kN/mm)	-	-	-	*Tiflex 0.114*	*CDM 0.115*	*Getzner 0.127*	*Tiflex 0.114*	*CDM 0.115*	*Getzner 0.127*
Railpad stiffness c_{stat} (kN/mm)	*700*	*700*	*700*	*100*	*100*	*100*	*100*	*100*	*100*
Energetic average	84.6	84.9	84.0	89.6	89.7	89.6	90.2	89.4	89.5
Maximum value	86.8	86.9	86.5	93.9	94.4	94.2	94.2	93.7	94.3
Minimum value	81.4	82.3	80.0	82.2	82.5	81.7	86.0	82.1	78.8
Noise levels determined for freight train-compositions									
Number of measurements: 15	**R1 [dBA]**	**R2 [dBA]**	**R3 [dBA]**	**K1 [dBA]**	**K2 [dBA]**	**K3 [dBA]**	**G1 [dBA]**	**G2 [dBA]**	**G3 [dBA]**
USP Material, stiffness c_{stat} (kN/mm)	-	-	-	*Tiflex 0.114*	*CDM 0.115*	*Getzner 0.127*	*Tiflex 0.114*	*CDM 0.115*	*Getzner 0.127*
Railpad stiffness c_{stat} (kN/mm)	*700*	*700*	*700*	*100*	*100*	*100*	*100*	*100*	*100*
Energetic average	100.4	100.9	100.5	104.1	104.7	104.4	104.9	104.7	104.1
Maximum value	105.3	105.7	105.5	109.3	110.4	109.8	110.0	110.1	109.6
Minimum value	89.2	89.8	89.2	94.3	94.9	94.3	94.2	94.3	93.7

Table 3.3: Noise-measurements compiled for intercity-, regional train- and freight train-compositions. R=Reference, K=Curve, G=Straight line. SEL-values normalized to 80 km/h.

It has to be pointed out that measurement data obtained by running trains in a straight line and curve (track with USP and soft rail pads) are compared with data of running trains on a straight line (track without USP and hard rails pads). So there are many reasons possible for all differences measured

[1] SEL: Sound Exposure Level is a Leq noise level or event normalized to 1 second.

since the reference track and the test track differ in two components (railpad and UP) and the curve in three components (reference is straight line) and perhaps also in further facts like status of the track system and/or soil conditions.

The 3 reference measurement points R1, R2 and R3 have very small differences, the three measurement points indicate homogeneous conditions / measurement conditions. All 3 measuring points can be used as a reference.

For statistical reasons the 3 reference measurement points R1, R2 and R3 for the reference as well as K1, K2 and K3 for the curve or G1, G2 and G3 for the straight line were averaged into one value. Based on the results of the external noise measurements, which are detailed in the report [4], important results were summarized for the effect of soft railpads and USP application (the values of SEL are in this report normalized to v = 80 km/h):

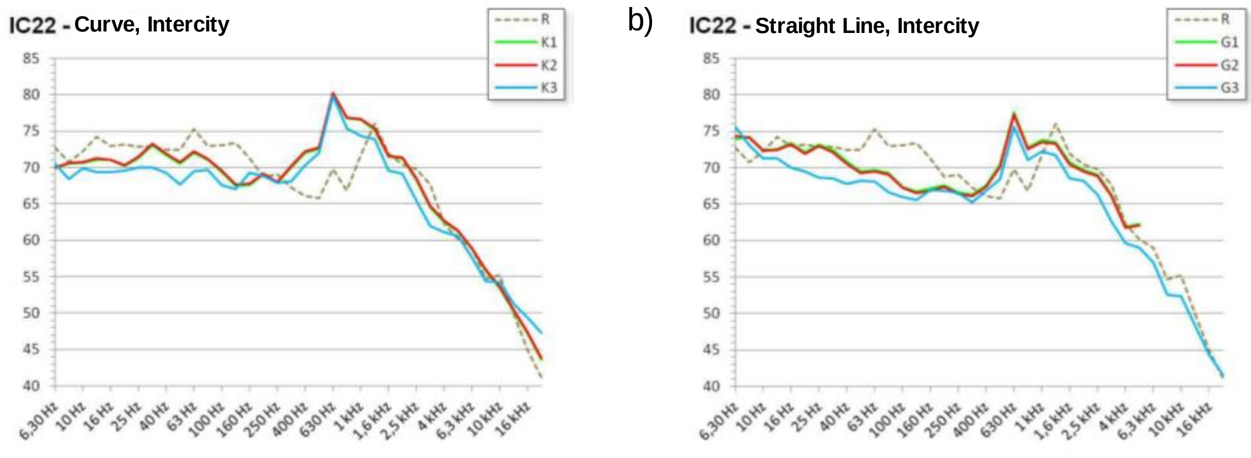
The measured values, which were collected in the curve, show that IC compositions have the smallest increase in the SEL values, compared to the reference section. A mean increase of approximately 2.5 dBA was found. For freight trains, the average increase in the curve is approximately 4.0 dBA. The largest increase of about 5.0 dBA was found for regional trains. Analogous considerations in the straight line show similar trends: For IC compositions, the lowest increase was approximately 2.0 dBA compared to the reference section. For freight trains an increase of approximately 4.0 dBA and for regional trains, an increase of approximately 5.0 dBA were determined. As it is indicated later in this Chapter the main influence of noise increase is most probably coming from the soft railpad in the test track (7 times softer than for the reference section).

Regarding the test section in the straight line is striking that G1 caused significantly higher values, especially for IC trains. This difference is probably due to measurement conditions. A systematic comparison between the results for the curve with those for the straight line indicates that G1 in the straight line for all train categories has significantly higher SEL values. The SEL values, which were determined on the sections G2/K2 are mostly relatively uniform, larger deviations were only observed for IC compositions. A similar trend can be noted for G3/K3: mostly similar values, with the exception of IC compositions, were reported in curve and straight line.

Valuable information for further characterization of the observed noise increases provide the frequency spectra analysis. A selection of frequency spectra of the exterior noise measurements for each train category for the curve or straight line is shown in the Figure 3.8 below.

Noise in Curve — Noise in Straight Line

a) b)



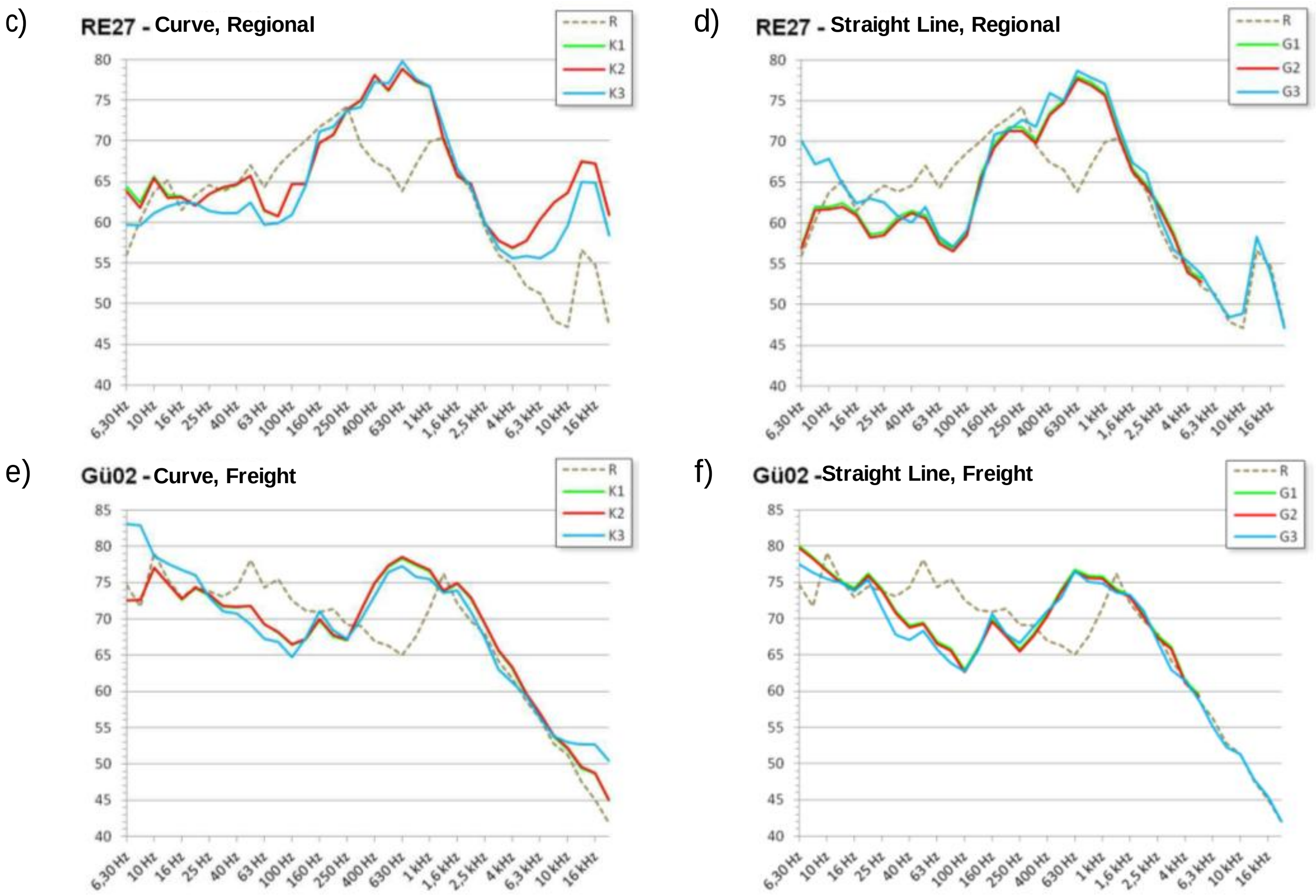


Figure 3.8: Some 1/3-octave frequency spectra of the noise measurements. For every train type the frequency spectra are shown for curve and straight line and in comparison for the reference section.

Regardless of the train category the frequency spectra for the different test sections of the curve or straight line are different in relation to the reference area. In contrast to the reference section both the curve and the straight line show clear peaks at 630 Hz (which is also the resonance frequency of the soft railpad). The increase in the SEL values can be attributed to the frequency range of 315-1250 Hz, where a significant increase in the spectral data was recorded. In the frequency range between 25 to 160 Hz, however, a striking decrease of the noise level compared to the reference section was observed. Parts of this decrease could be attributed to less noise radiated by the ballast due to the USP mitigation effect. For all train categories it can be stated that in terms of frequency spectra of the exterior noise measurements basically similar and comparable results for all USP materials with soft railpad were received.

B) Measurements in track

COMPARISON OF RAIL ROUGHNESS

The rail roughness and wheel roughness (summed to give the total roughness) produce the excitation forces which cause the running noise. Theoretical models show that the noise and the overall roughness of the corresponding frequency band are proportional to each other. During a noise measurement it is important that the rail roughness for the different sections is comparable, so that its influence is negligible. Otherwise, the noise differences cannot be attributed to the effect of the mitigation measure.

Figure 3.9 shows the rail roughness (averaged over left and right rail) measurements [5] (1.7.-4.7.2013) of the sections where also the noise measurements were performed (18.4.2013). Within the reference sections and the sections of the straight line (G) the rail roughness is sufficiently homogeneous so that differences in the noise emission due to the differences in rail roughness may be negligible. The comparison between the reference and G sections (Figure 3.9 right part: dashed and coloured curves) shows, however, from a wavelength of 2.5 cm (corresponding to a frequency of 1100 Hz at a speed of 100 Km/h, large wavelengths mean smaller excitation frequencies) differences, that might be relevant. In Figure 3.10 the rail roughness for the curve is shown, which has similar amplitudes for lower wavelength as for the straight line. To better understand and quantify the problem after RIVAS, a frequency-dependent analysis of noise measurements is needed associated with the rail roughness.

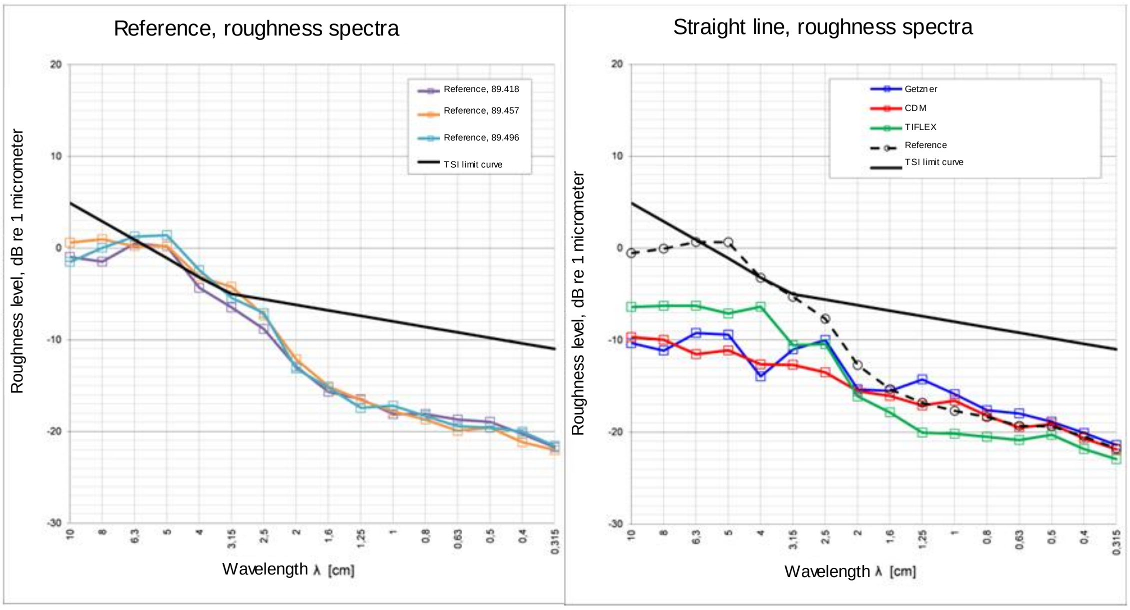


Figure 3.9: Rail roughness of the sections: Left: R1, R2 and R3. Right: G1, G2, G3 and the mean of reference sections (dashed).

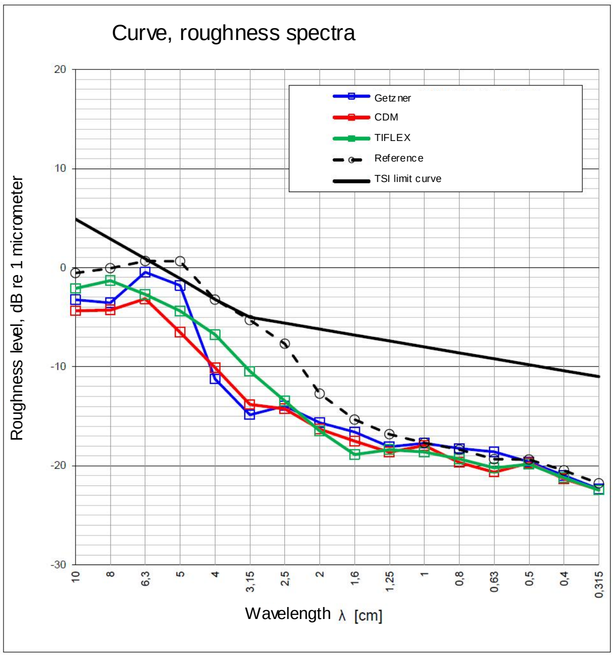


Figure 3.10: Rail roughness for curve: K1, K2, K3 and reference (straight line).

TRACK DECAY RATE (TDR) MEASUREMENTS

For each section where an acoustic measurement has been performed, the TDR has been measured (details in [6]) from 1.7.-4.7.2013. As a result, a total of 9 TDR spectra, one for R1, R2, R3, G1, G2, G3, K1, K2 and K3 are calculated.

It has been clearly observed that the TDR spectra just for the straight line respectively for the curve and for the reference sections differ very little, "little measurement scattering" (see [6], and see also the little "scattering" of curve and straight line in Figure 3.11, left). This allows to take the arithmetic mean of the TDR spectra for straight line, curve and reference. Thus it is possible to compare test sections in the straight line and reference. The comparison of the mean of these sections is shown in Figure 3.11.

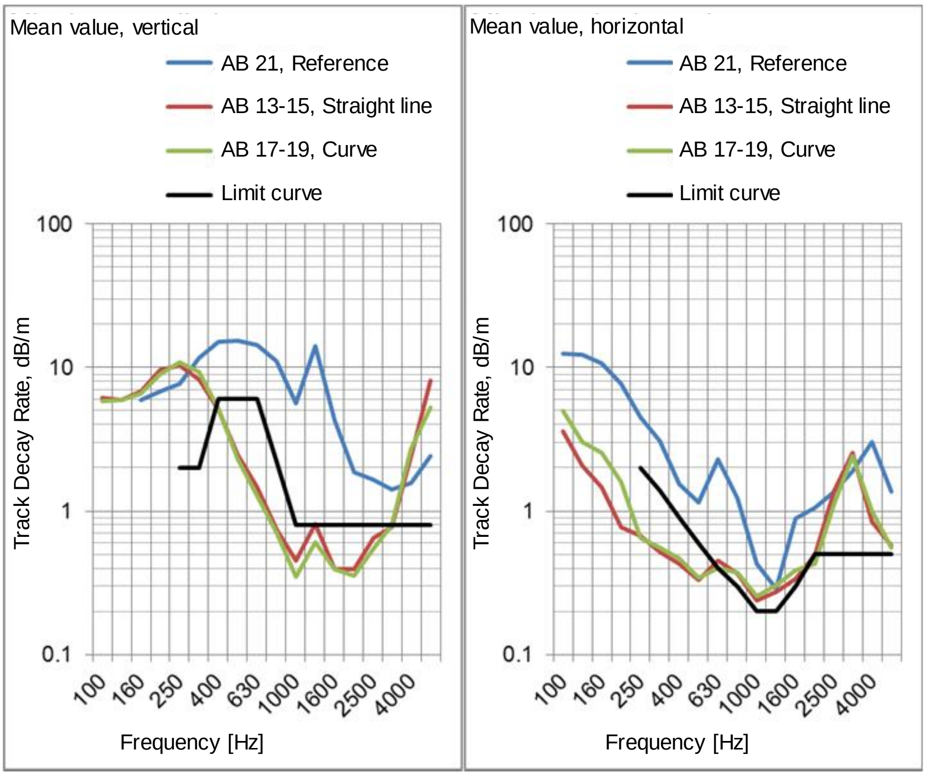


Figure 3.11: Comparison of mean TDR spectra (vertical and horizontal) of the reference, curve and straight sections.

The TDR of sections with and without USP differ significantly in the medium frequency range . In the vertical direction the TDR of the equipped USP + soft railpads sections in the frequency bands from 400 Hz to 3150 Hz sometimes is over 10 dB lower than in the reference section. In the horizontal direction are recorded on the USP + soft railpads sections significantly lower TDR in the frequency bands up to approximately 1000 Hz.

Sleeper and rail are coupled by the railpads. This coupling is frequency dependent, the stiffer the railpad the more the coupling comes at higher frequencies. With rigid railpads the rail is vibrating decoupled from the sleeper typically from 900 Hz vertical and above 300 Hz horizontal, with a softer railpad typically the decoupling starts at 500 Hz and 300 Hz.

Differences of the TDR (vertical and horizontal) are visible in the higher frequencies, as well as the noise increases, so it could be claimed that the difference is primarily due to the different dynamic stiffness of the railpad. The USP should not have a big impact on the TDR because normally the softening influence of USP is for lower frequencies. However, in the Figure 3.11 the influence starts over 315 Hz. So far no physical influence of USP is corresponding to this TDR effect but soft railpads have relevant influence on the TDR at these frequencies. However, as two parameters (railpad stiffness and USP application) are changed at the same time, no definitive conclusions can be drawn so far.

It is to be noted that for different TDR spectra, as shown in Figure 5, noise differences of several (2-4) dB (based on modelling and experimental values) should be expected.

C) International results on noise phenomena

UIC investigations
In the UIC report [1] it is mentioned that there is not yet possible to draw definitive conclusions about additional noise phenomena when soft USP are installed. Most of the measurements show only very little increase in noise level for USP test tracks in comparison to reference tracks (see Figure 3.9).

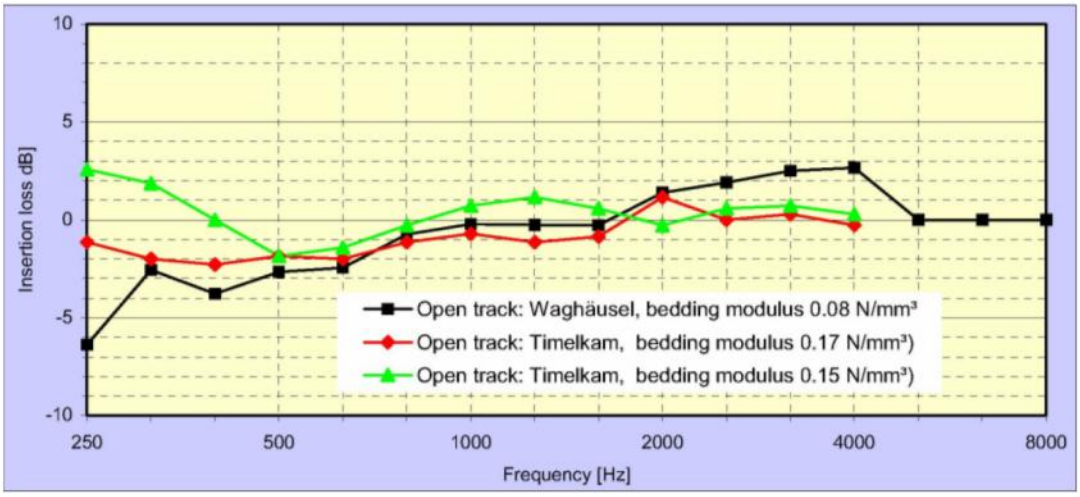


Figure 3.9: Noise decrease („insertion loss“, positive values are decrease for USP) in dependency of frequency for different static stiffness of USP [1].

The UIC test measurements in Belgium [11] show that the installation of USP produce more vibrations of 5 to 6 dB at the end of the sleepers. This did not imply any increase in noise levels. The 13 measurement sections with measurement point at 7.5 m show a spread of around 3 dBA but do not correlate with USP dynamic stiffness.

Note: In Germany DB has similar experience of no influence (Project LZarG).

3.8 Conclusion

The laboratory measurement showed about the same static stiffness of about 0.12 N/mm3 for all three USP under investigation according to the new CEN-Standard for characterization of USP stiffness. The dynamic stiffnesses are not much higher, but here the Tiflex material showed around 20% lower dynamic stiffness at 30 Hz in comparison to the Getzner and CDM material.

The track deflection measurement showed that the test site has relatively high disturbances in the track subgrade, so that even the influence of these soft USP may be sometimes smaller than considerable differences in the ground stiffness. The USP equipped sites showed additional deflections of about 0.6-1.2 mm.

The reference track shows a settlement almost three times more strongly than in sections with soft USP during one year.

The sections with soft USP have on average in comparison to the reference sections a greatly reduced lateral force resistance. At 2 mm displacement the sections with USP in a straight line reach about 40 to 43% of the lateral force resistance of the reference section. A conclusive interpretation of these results will be possible after the UIC working group for lateral force resistance will have tested and discussed the used SBB measurement method for lateral force resistance.

The highest values of the vibration accelerations (RMS values) of the sleepers in the straight line arise for USP Tiflex. The reference, USP Tiflex, stiff and USP CDM, soft for the straight line are in between. For USP Getzner soft and stiff, there were the lowest amplitudes of the vibrations. The highest amplitudes in the frequency spectrum are between 600 and 1300 Hz. The USP's and railpads affect probably the frequency of the highest amplitude. For the reference section it is at 1250 Hz, respectively 1600 Hz (for the stiff railpad, Cstat = 700 kN/mm). In USP sections with the soft railpad (Cstat = 100 kN/mm), it appears at 630 Hz.

The comparison of the noise measurements of the straight reference section with hard railpads and without USP revealed an increase of 2 dBA to 5 dBA depending on the train type running over the straight and curve sections with soft railpads and USP. Based on experience and physical models, it is assumed that this effect rather arises from railpads than from USP: considering the track decay rate (TDR) measurements and the analysis of the collected TDR spectra, differences of about 2-4 dB are expected. With a more accurate and frequency dependent evaluation of the noise measurements, it would be possible to verify the contribution of the soft railpads. This additional noise effect potentially could be reduced by the installation of harder rail pads than C_{stat} = 100 kN/mm.

The rail roughness measurements show clearly that the reference section exhibits the highest roughness. This indicates that the additional noise is due to effects such as track component stiffness (such as soft railpad which could lead to additional track dynamics in higher frequencies) or measurement conditions, but not due to rail roughness.

4. GROUND VIBRATION MEASUREMENTS FOR MITIGATION EFFECT

The mitigation effect for the USP have been analysed for max values as well as for the 1/3-octave frequencies.

4.1 MAX VALUES ANALYSIS

A first evaluation of the results indicates that normal comparison of test track to normal track is not correct because the ground conditions along the track are varying considerably. It seems to be better to determine the mitigation effect of the under sleeper pads by comparing the datasets recorded for events on the northern track (conventional track without under sleeper pads, distance to instrument 4 m) with events on the southern track (with under sleeper pads, distance to instrument 8 m). In this case, normally the ground conditions are similar at least for the measurement point, which is the same and therefore the coupling of the sensor is the same. Additionally, the subgrade under the track is most probably similar. However, the difference in distance to the instrument has to be accounted for with appropriate scaling factors (“transfer function”).

Transfer function: To allow applying this methodology, it is supposed that track and ground between the 2 tracks are homogenous. Assuming a uniform propagation of vibration impulses in the range of the tracks, a simple set of transfer functions can be calculated for different excitations (Freight, Regional, Intercity: the same train excites always all measurement points). This transfer function is transferring the values at 4 m (no USP) from the northern track to the distance of the southern track so that the mitigation effect can then be calculated by using the transferred reference (from 4m -> 8m). The addition of this scaling factor is meant in decibel to account for the difference in distance and can be described as a formula (from SBB experience):

$$\mathbf{v(r) = v_0 + const_{traincategory}.} \qquad (1)$$

with r… „desired“ distance to source of ground vibration

$v(r)$… velocity of ground vibration in distance r (in dB)

v_0… velocity of ground vibration in distance r_0 (in dB)

$const_{traincategory}$ difference between v(northern track, reference section) and v(southern track, reference section) for each train category Freight, Regional and Intercity train. (in dB)

This approach is useful because according to experience different train types can show a different vibration behaviour.

The obtained mitigation for different train categories measured in terms of v_{RMS} and using the scaling factors is presented in Figure 4.1. Based on the obtained values, mitigation factors can be calculated for every type of under sleeper pad and train category, respectively. A summary of the corresponding mitigation factors is presented in Table 4.1.

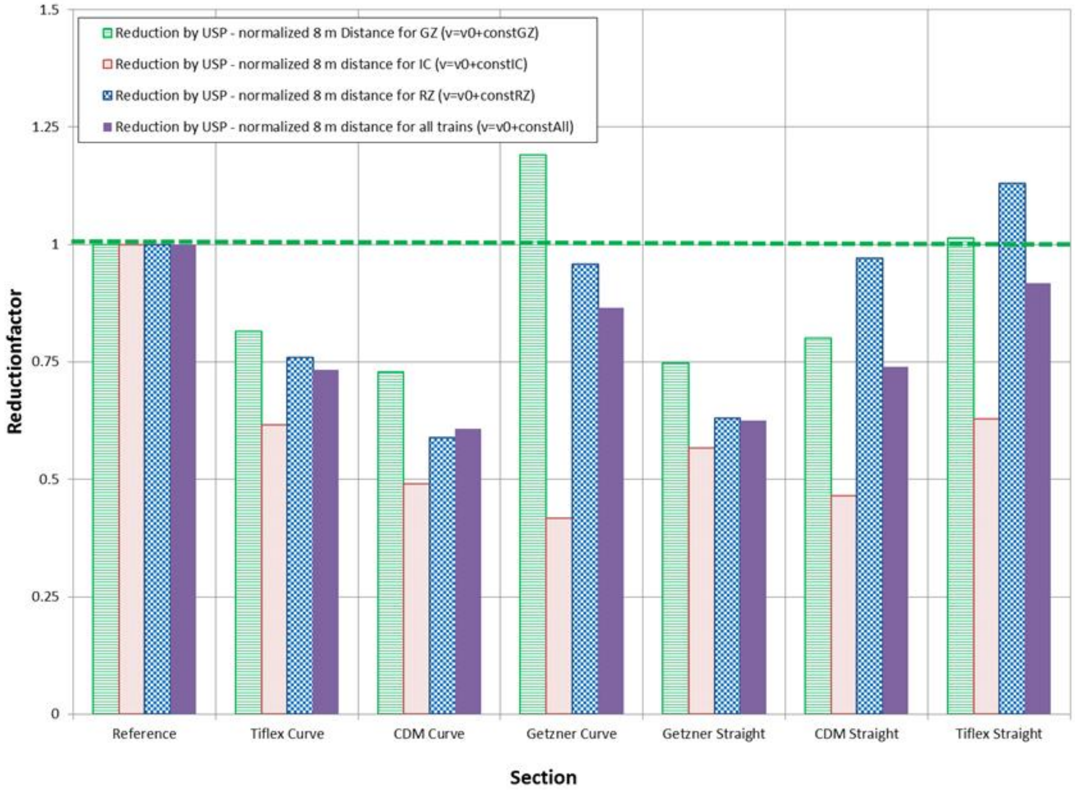


Figure 4.1: Mitigation of ground vibration determined from the v_{RMS} dataset. The effect of the USP is presented as mitigation factor, the raw data was scaled to the unifying distance of 8 m assuming $v = v0 + const_{traincategory}$. The horizontal line refers to the factor 1 (no effect).

Mitigation Factor							Effect
V_{RMS} [mm/s], scaled to 8 m ($v(r) = v_0$+const.)							distance 8m
Treatment / **train category**	**Tiflex curve**	**CDM curve**	**Getzner curve**	**Getzner straight**	**CDM straight**	**Tiflex straight**	
GZ	0.814	0.729	1.190	0.748	0.801	1.014	**0 - 0.3**
IC	0.616	0.491	0.417	0.567	0.465	0.628	**0.4 – 0.6**
RZ	0.759	0.589	0.957	0.630	0.970	1.129	**0 – 0.4**
all train categories (GZ, IC, RZ)	0.733	0.607	0.865	0.626	0.740	0.918	**0.10 – 0.40**

Table 4.1: Mitigation of ground vibration by under sleeper pads, presented as mitigation factors. The raw data was scaled to the unifying distance of 8 m assuming $v = v_0$ + const. The effect of the under sleeper pads is summarized in the last column for the three different train categories.

4.2 1/3-OCTAVEBAND ANALYSIS

A first view of all the measured datasets at 8 m (see also Figure 4.2) show for the frequency analysis, as for the v_{RMS} analysis, generally big differences. These differences can be observed between:

i) some of the sections,
ii) individual measurement points (MP) in a section,
iii) the measured values of a measurement point in the same train category.

The differences between some of the sections (i) as well as between measurement points in a section (2) are mostly due to inhomogeneity of the transmission conditions for vibration in the ground. But some of the measurement points could be identified, with big unexplainable differences, which are therefore not used for further analysis, see Table 4.2.

MP	USP	Track (km)	Remarks
1	None	89.484	Fixed behind pylon base
8	CDM	89.181	Fixed on pylon base
23	CDM	88.807	Fixed on pylon base
27	Tiflex	88.674	Fixed on pylon base
28	None	88.575	Big MP scattering in comparison to reference section in the west
29	None	88.550	Big MP scattering in comparison to reference section in the west
30	None	88.520	Big MP scattering in comparison to reference section in the west

Table 4.2: Problematic vibration measurement points (MP) at 8m distance not used for the analysis.

Figure 4.2: Vibration measurement points at 8 m distance (not at 8m: MP 10,11,13,14,16,17,19,20).

The differences between individual measurements for a certain measurement (iii) point can be high. This scattering is probably due to differences in out of round wheels of rolling stock and also the combination of rolling stock and ground resonances.

Further hints for characterization of transmission conditions could be gathered from Chapter 3.3/3.6/4.3.

Emission spectra

In Figure 4.3 the vibration measurements at 8 m distance of the western reference section are visible for the Intercity train. The amplitudes of MP 1 are quite different, and about a factor of 2 to 3 lower than the other sensors in the frequencies 40-63 Hz. The sensor position was behind a pylon base, which could give rise to a decrease in amplitudes. Therefore this disturbed sensor was not used for further calculation. MP2 and MP3 are also different from one to the other, particularly around 16, 25 and 32 Hz.

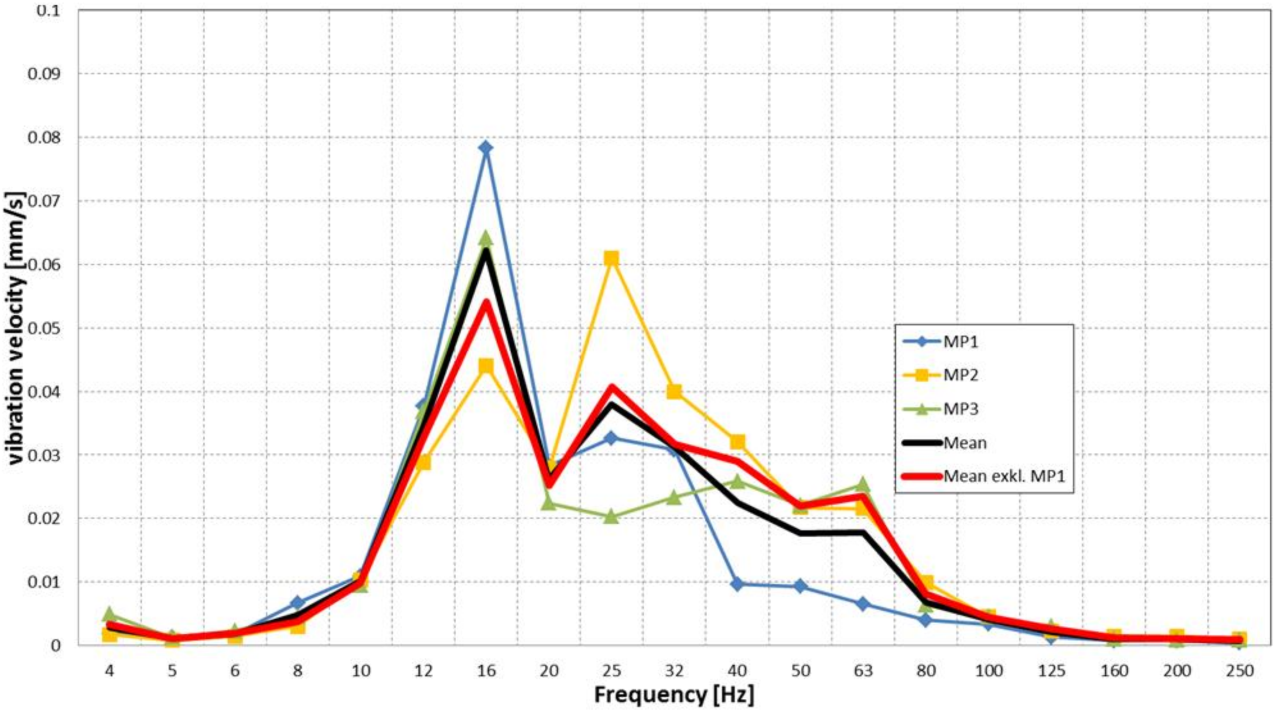


Figure 4.3: Vibration measurements of Intercity trains in 8 m distance for reference track, southern track 2.

The east reference section (MP 28/29/30) was not used, the scattering in amplitudes were too high.

An overview of the vibration emission spectra in 8 m distance of Intercity, regional and freight train for the reference section are illustrated in Figure 4.4. For the frequency 16 Hz a high peak is visible for the IC on the southern track, but not for the other train types. The amplitude is even higher than the IC pass-bys on the northern track which is closer to the sensors. Otherwise all the vibration measurements from the northern track are normally higher then on the southern track. It can be concluded that the measurements at the reference site can be used but for IC results the 16 Hz value has to be used with care.

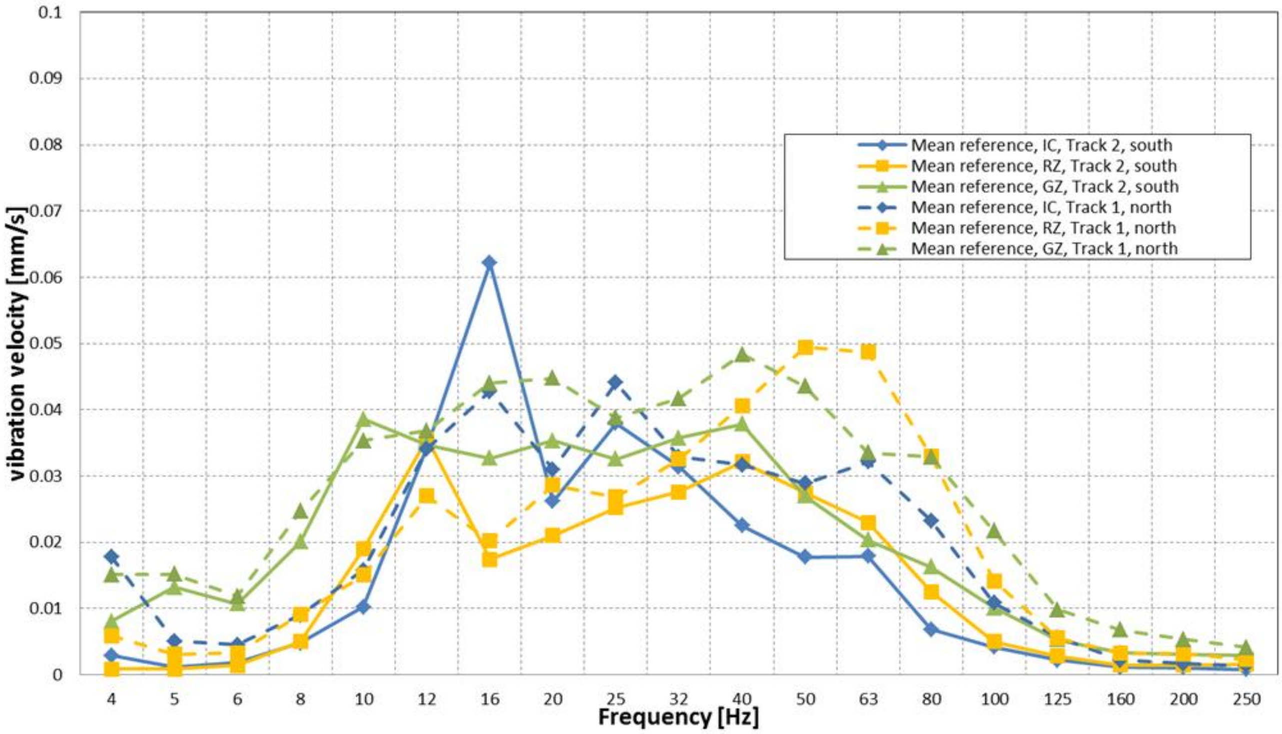


Figure 4.4: Vibration measurements of Intercity (IC), regional (RZ) and freight (GZ) trains in 8 m distance for reference track, southern track 2, and in 4 m distance for MP1,2,3 for northern track 1.

In Figure 4.5, for a few measurement points (all measurement positions can be found in Annex B, Figure B1), the mean emission spectra of Intercity trains on the southern track 2 in 8 m distance are given. There is quite a scattering visible. The arithmetic mean value is calculated here and in the following figures to show indicatively around which value the different sections are scattering. At 16 Hz up to a factor of 6 in amplitudes are recognized for different sensor positions but measuring the same Intercity trains. It seems that MP4 which is more in the vicinity of MP2 and MP3 has normally lower values for 8 Hz to 50 Hz.

These results are most probably not due to effects of the different materials but probably ground conditions below and next to the track could be the reason. To check this hypothesis a comparison of the Intercity train measurements of northern track 1 with 4 m distance are analysed in Figure 4.6 (for all test sections see in Annex B Figure B2). It is first clearly visible that quite a big scattering of the measurement points is also occurring on this northern track 1. Measurement points MP5 and MP6 show similar high amplitudes for both tracks which indicates that the sensor position or the transmission could be different from normal and also MP4 show low values quite similar as in Figure 4.5.

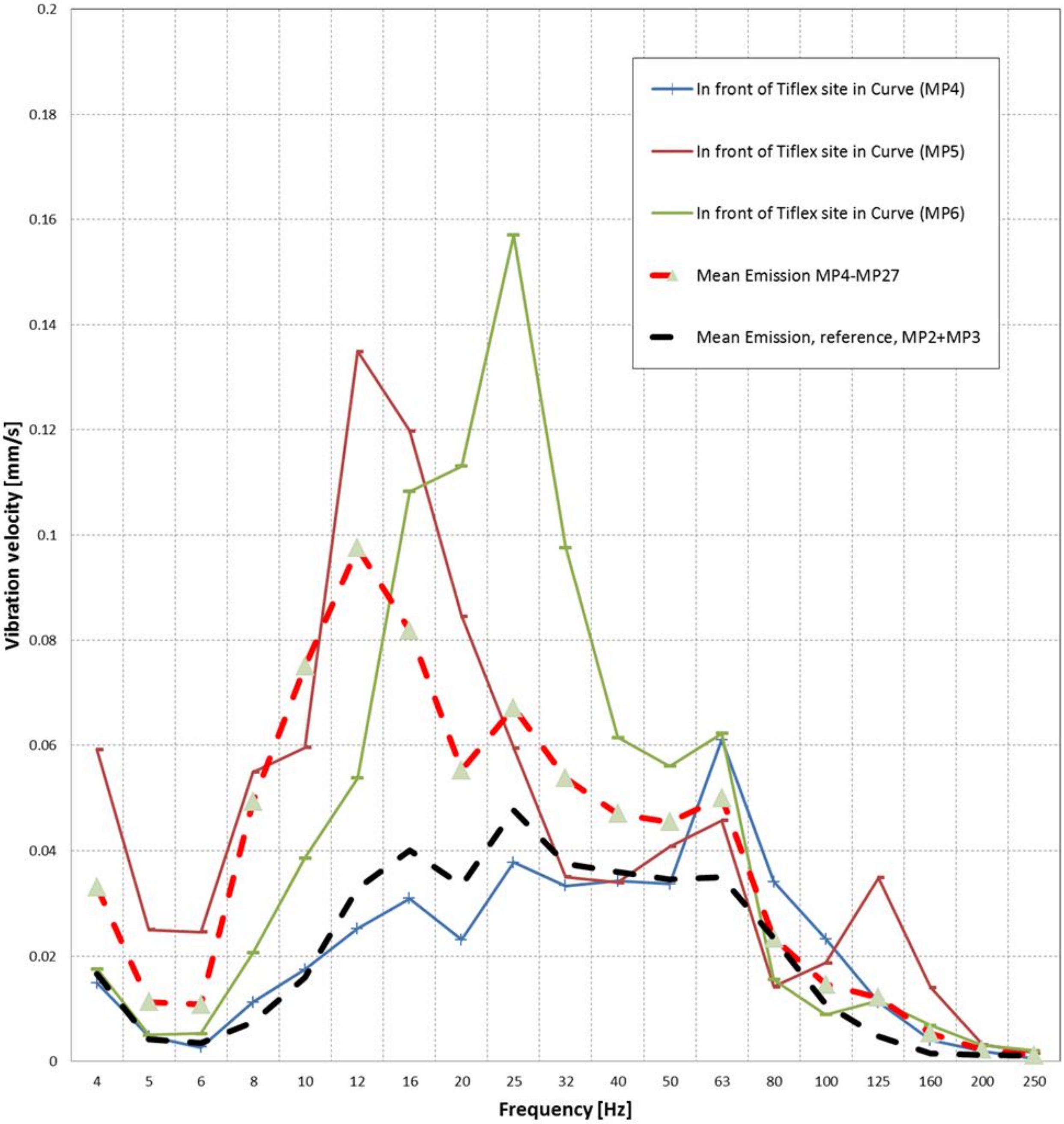


Figure 4.5: Emission spectra for IC on southern track 2, for MP4 to MP6 with USP, 8 m distance.

Further it is visible in Figure 4.6 that for the measurement positions at the reference track normally the values are lower than for the other positions. Comparing the mean curve in red (measurement points for USP test sections) to the mean curve in black (measurement points for reference) differences are visible especially from 5 Hz to 25 Hz but also quite visible from 32 Hz to 160 Hz. Normally these two curves should be more or less identical, because the same track with the same trains are measured at the same distance. Once again this makes it obvious that for the v_{RMS} calculations, but also for frequency analysis, corrections are necessary to get more realistic estimations of the mitigation effect. These corrections will be reported later in this report (page 31 and following pages).

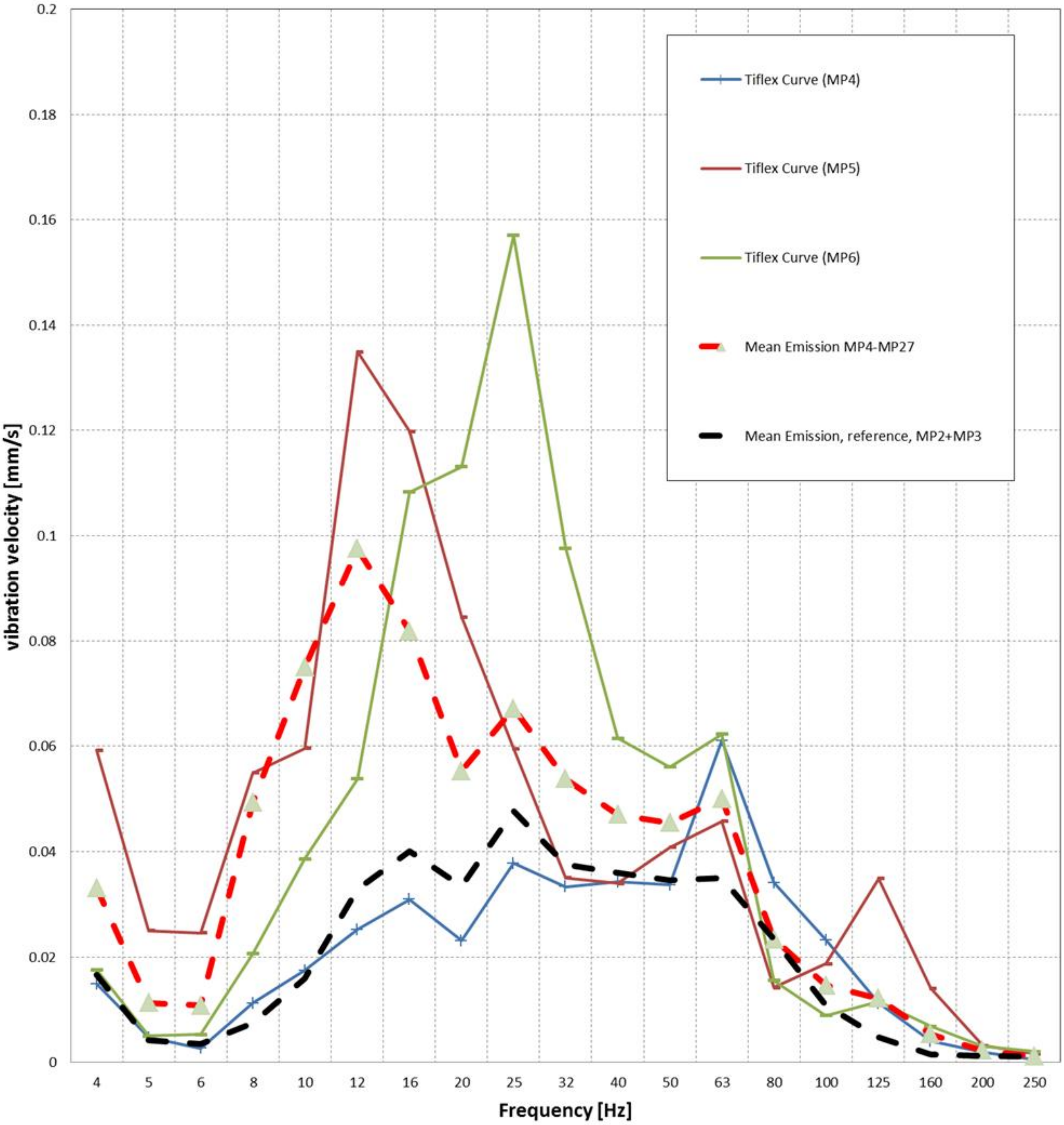


Figure 4.6: Emission spectra for IC on northern track 1 (for MP4 to MP6), without USP, incl. mean of MP2,3, all measurement points in 4 m distance.

Insertion loss calculation

Figure 4.7 shows the mitigation effect for the MP4-MP6, Tiflex test sections for the Intercity trains as an example (for further test sections see Annex B, Figure B3). It can be seen quite a big scattering and amplification of vibrations in lower frequencies (5-32 Hz).

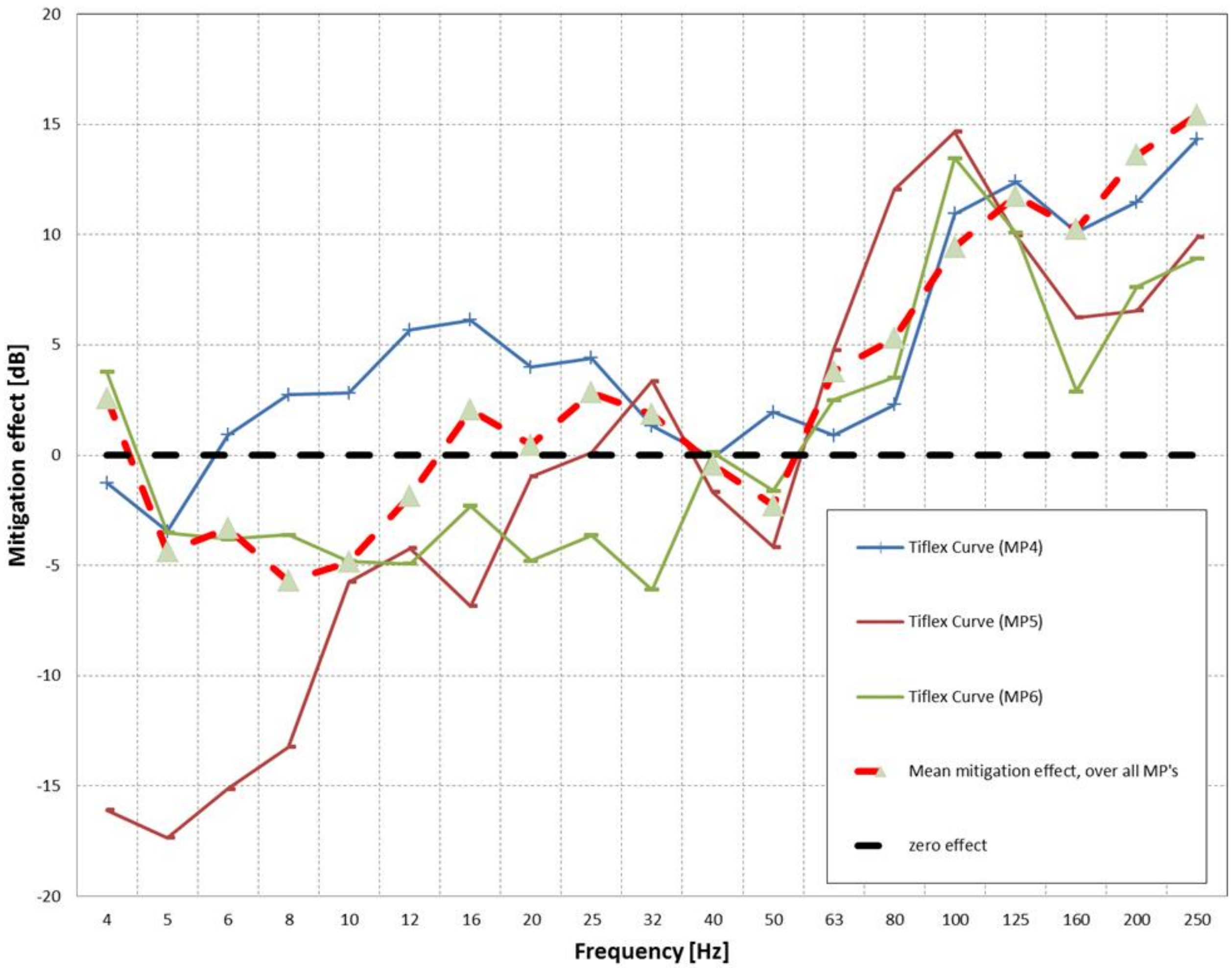


Figure 4.7: Insertion loss calculation for Intercity trains with the reference sensor positions MP2/MP3 for MP4-MP6.

A first look on the complete raw dataset indicates that it is dangerous to compare only the reference section of southern track 2 with the USP test sections on track 2. It is worth to consider and compare datasets of every measurement point for events on the northern track 1 (conventional track without under sleeper pads, distance to instrument 4 m) with events on the southern track 2 (with under sleeper pads, distance to instrument 8 m).

Transfer spectra: Therefore, analogous to Chapter 4.1, the current task is to calculate appropriate transfer spectra to compare the datasets obtained for events on the northern track (conventional track without under sleeper pads, distance to sensor positions 4 m) with events on the southern track (with under sleeper pads, distance to sensor positions 8 m). A simple way is to transfer the 4 m points to the 8 m points by multiplication of the factor which is given by division of the mean of IC trains of track 2 by the IC trains of track 1 in the reference section (see Figure 4.8). These new 8 m reference points (for every sensor of MP4 to MP27 there is a new reference now) can then be directly compared to the vibration results of track 2 (USP test sections). Applying such a process implies that it is supposed that there is a sufficiently homogeneous track substructure/superstructure on the 2 adjacent tracks, and thus the difference between the different measuring points come from the transmission and the coupling effects. That assumption for the process performed has been done since only small differences for USP tracks were visible for the interesting frequency range for the source (wheelset acceleration) as described in Chapter 4.3. Another method consisting in calculating transfer function track-ground, applying an impact hammer on the track platform, in front of the different measuring points was not applied in this field test.

The results of these calculations are shown in Figure 4.9 for MP4-MP6.

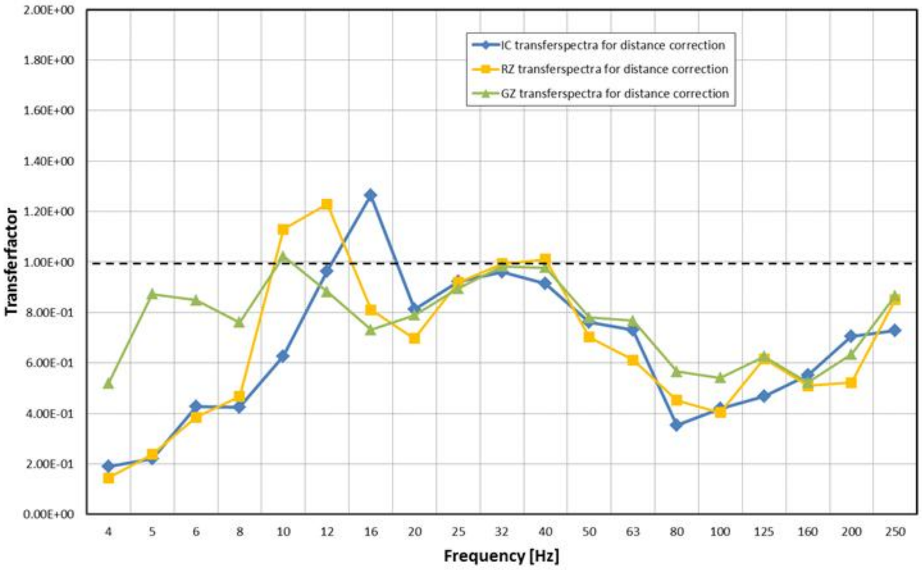


Figure 4.8: Transfer-factors for each train category to transfer the trains on track 1, in 4 m distance to the sensors, to the distance of track 2: which is 8 m.

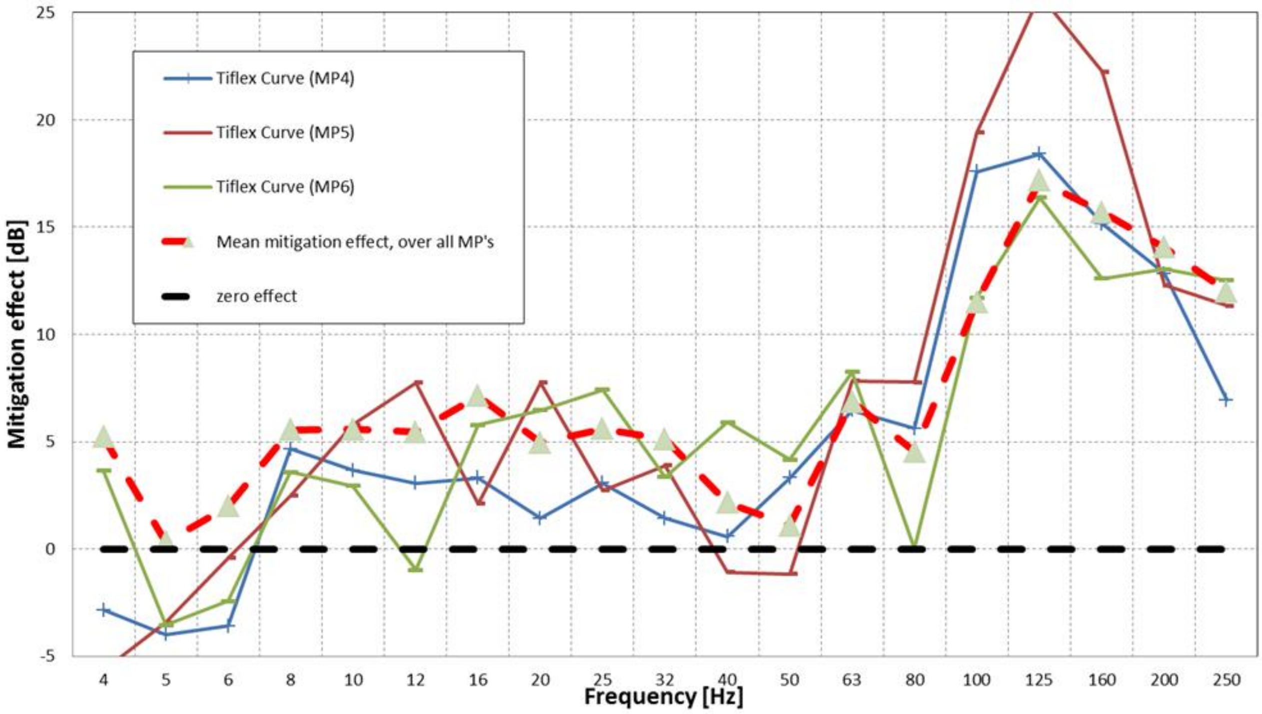


Figure 4.9: Mitigation effect of USP corrected by using the reference from track 1 transferred to the distance of 8 m by transfer-factors of Figure 4.8 for MP4 to MP6.

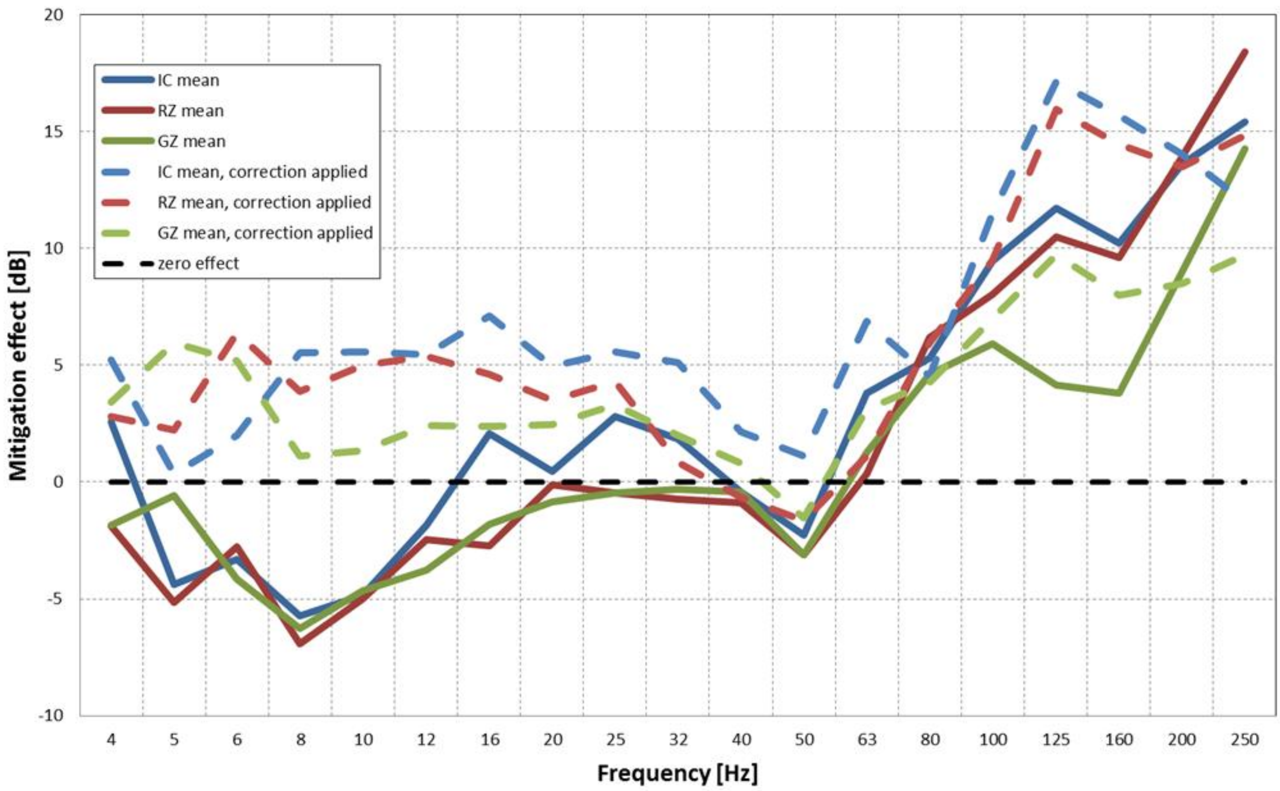


Figure 4.10: Mean mitigation effect for all USP test sites for different train categories of reference MP2/MP3 (solid line) and reference of track 1 but transferred to 8 m distance (dashed lines).

Figure 4.10 shows the mean mitigation effect for all USP test sites for different train categories with normal reference in the east of the test section (MP2/MP3) and as well as the reference of track 1 but transferred to the distance of the test track 2 (from 4 m to 8 m). It is obvious that the mitigation effect improves for lower frequencies a lot. It is doubtful that all these improvements are due to USP effects as normally no big effects are observed at low frequencies (It is possible that the transfer function overestimates this influence). Here effects can be seen of around 5 dB from 6 Hz to 25 Hz. Especially at 125 Hz and at 160 Hz also the mitigation effect improves by around 5 dB. Unfortunately at 63 Hz to 100 Hz no such improvement is observed.

Further mitigation effects can be found in the Annex B in Figure B3 and B4. A comparison of mitigation effects for Tiflex, CDM and Getzner can be found in in Annex B Figure B5.

4.3 COMPARISON WITH AXLE BOX MEASUREMENTS

In July 2013 axle box accelerations have been measured on-board at constant speed to assess the dynamic response of reference tracks and tracks equipped with USP [12]. The measuring wheel sets have been assembled with new wheel sets and the brake was disabled during the test runs. Hence the wheels of the test bogie were new without visible damages or OOR or problems of noise after fabrication. The wheel roughness has been measured directly after the test runs. All the wheel treads were smooth.

At the velocity spectra plots[2] in Figure 4.11, the USP equipped tracks imply significantly lower values of axle box velocities between 63 and 500 Hz. Straight track Tiflex stiff (AB12) shows lower values at 80 Hz in comparison to the reference sections. Track Tiflex soft (AB13), CDM soft (AB14), Getzner soft (AB15) and Getzner stiff (AB16) show the best behaviour in terms of low velocity excitation for 50-500 Hz. Track Tiflex soft (AB13, filled brown circles) seems to be in between the reference and the other straight tracks.

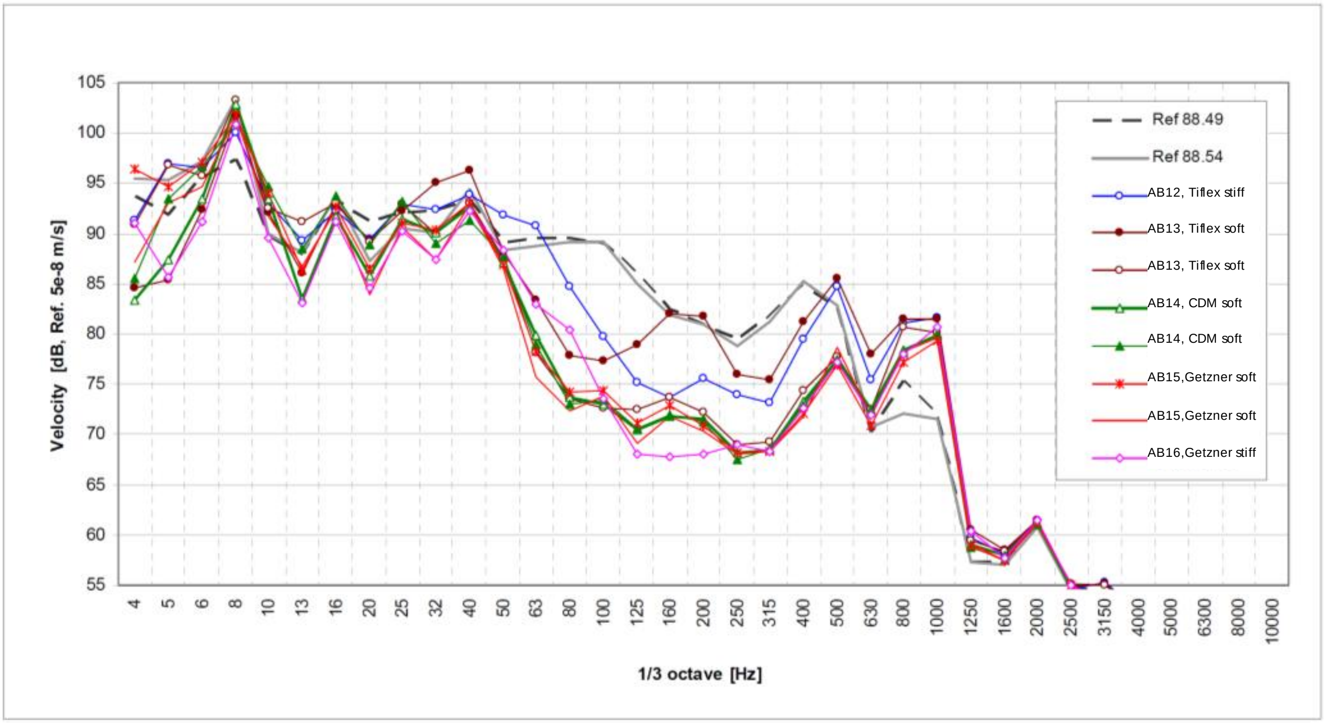


Figure 4.11: Axle box velocity spectra for USP straight line in comparison with reference.

The USP test sections in curves in Figure 4.12 show nearly the same frequency behaviour. The transition track Getzner stiff (AB16) gives the lowest track dynamic responses between 50 and 500 Hz. It is possible that the curve which starts after AB16 gets an influence on the axle box response. It is also interesting that Tiflex stiff shows mitigation effect at 80 Hz and higher.

[2] Axle box acceleration was integrated to velocity for about 40 m train pass-by and then fourier- transformed, normally two results for each USP section were obtained.

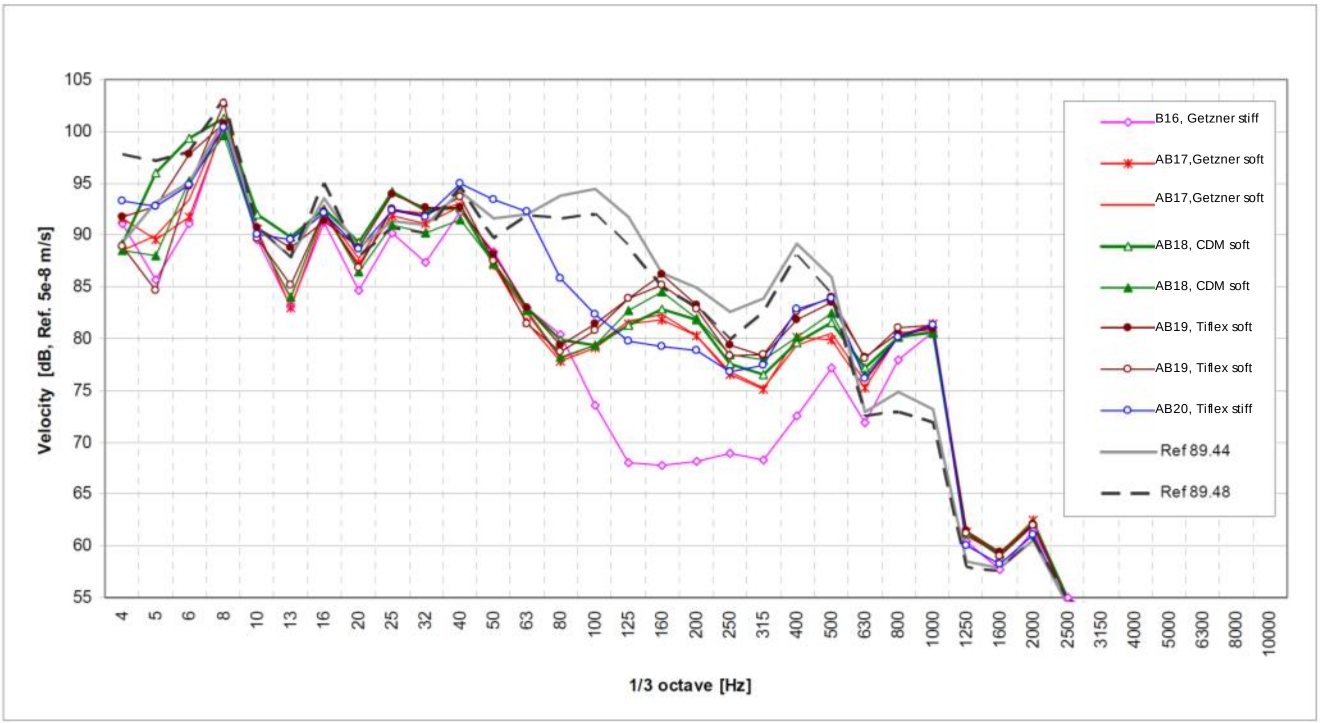


Figure 4.12: Axle box velocity spectra for USP curve in comparison with reference.

A very interesting fact of these measurements is the normally lower axle box velocities at 50 Hz in a range of 1-3 dB which is normally not observed in the vibration measurements in Pieterlen (Figure 4.10). But Figure 1.1 also suspects that for this soft USP stiffness an effect at 50 Hz could already appear.

4.4 Comparison of modelling with measurements

A comparison between calculations of USP mitigation effects in deliverable D3.2 [13] and the measurements in Lengnau-Pieterlen can be seen in Figure 4.13. The simulations are parametric studies and do not correspond directly to the measurement conditions and results reported in this deliverable. The mitigation effect is not directly comparable as it is not the same reference conditions (not the same railpads, not the same ground).

Without a direct comparison of the curves, it can be said that the amplification effect at the resonance frequency, predicted with numerical simulation, is much less visible in situ, and the maximum mitigation effect is around 15 dB as predicted.

Even if the simulations have not taken into account the properties of this measurement site it can be seen that the calculations performed by the German "Bundesanstalt für Materialforschung" BAM (railpad dyn. stiffness: 300 kN/mm) [14] for 8m seems to predict effects of a smaller mitigation effect at 80 Hz which is visible at least in the corrected measured mitigation effect (see red dashed line in Figure 4.13). The calculation for 4m is quite accurate at 80 and 100 Hz.

The results obtained by the Catholic University of Leuven (KUL) for 16 m (railpad dyn. stiffness: 150 kN/mm) are quite near to the measured results between 50 Hz and 100 Hz except for 80 Hz.

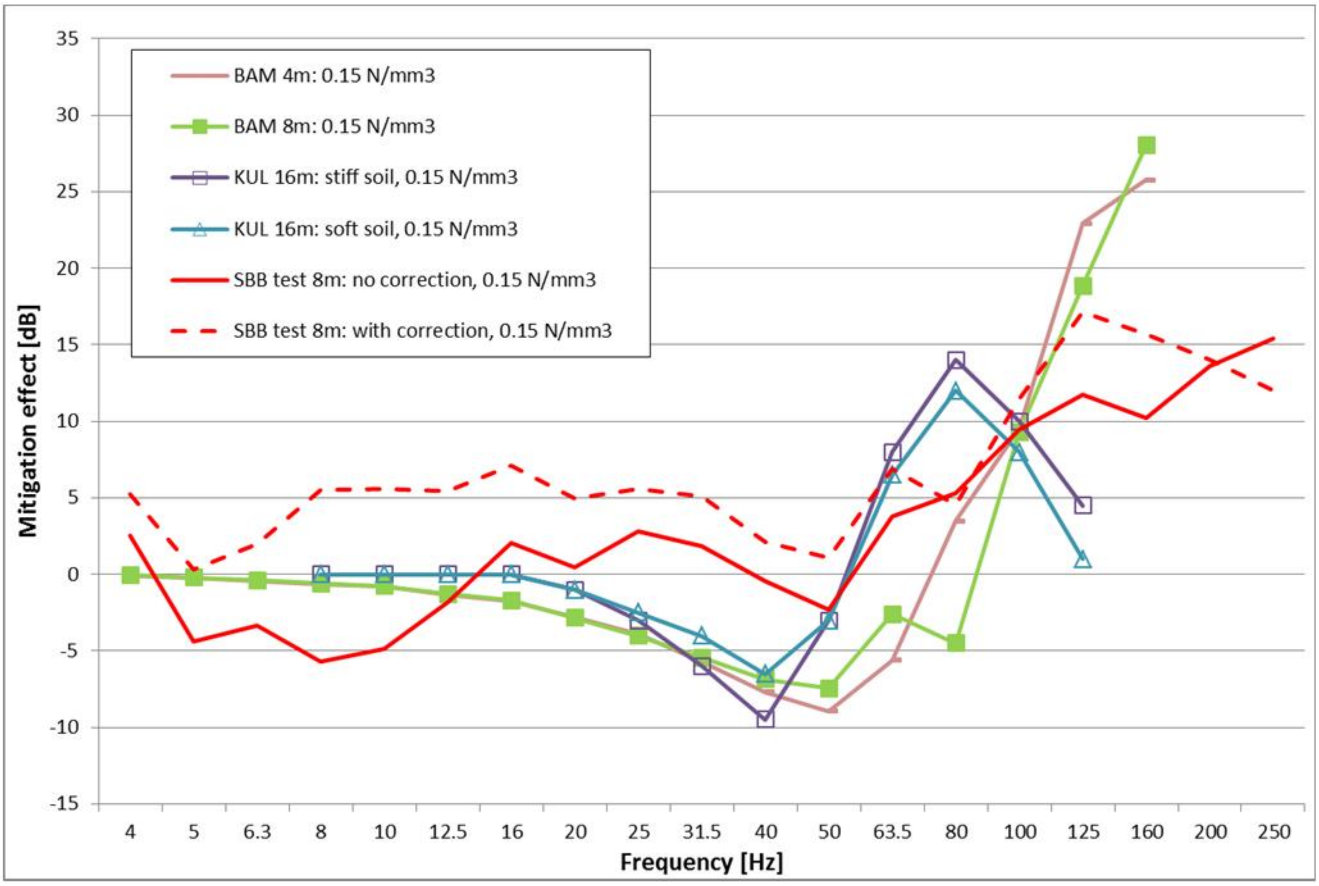


Figure 4.13: Comparison of modelling USP (C_{dyn}) by BAM [14] and KUL [13] with USP test measurements of Lengnau-Pieterlen by IC results (see also Figure 4.10).

4.5 Discussion on mitigation effects

The mitigation effects are derived by the measurements at 8 m. Unfortunately, even for the sensors just next to the track, quite a big influence is seen from ground probably due to parameter changes below and in the vicinity of the track. Therefore, a suitable correction algorithm has to be determined. This was done by using the measurements of the trains on the adjacent track but using the same sensors. In this way a correction can be gathered accounting for differences in coupling of the sensors as well as some ground conditions below and next to the track.

Also the track parameters have been checked by axlebox measurements to see if homogeneity of the track is acceptable.

The mitigation effect is quite in accordance with some USP insertion loss calculations but the measurements do not show such a large amplification factor at the resonance frequency as the calculations.

The obtained mitigation effect by using the correction is in accordance with the mitigation factors of the the max values analysis. There the observation reveals about 10% to 40% reduction of vibration for all train categories which is also observed in the frequency analysis for lower frequencies (5 dB reduction is equal to about 43%).

The inhomogeneity of the measurement conditions did not allow for a further and more precise analysis of the different USP products, since the results scatter too much but the material properties such as C_{dyn} or C_{stat} differ only slightly and would therefore need very precise results for a validation.

4.6 Conclusion

A reduction of vibration can be observed for v_{RMS} values if a correction for geology influence is applied and shows about 10%-40% mitigation effect if all train categories are taken into account.

The frequency analysis of the measurements show that a mitigation effect can be observed above 50 Hz which reaches about 15 dB at 250 Hz. The scattering of the different mitigation effects for the test sections in comparison to the reference section makes it meaningful to apply a correction algorithm to eliminate the biggest differences by using train passbys on the adjacent track which can serve as a second reference when transferred to 8 m distance by using a suitable transfer function. The results show in this case that also for lower frequencies (8 Hz - 31.5 Hz) a mitigation effect of about 5 dB is reached.

The comparison of the measurement results with/without corrections to the calculations made for deliverable D3.2 shows that the measured mean mitigation effect corresponds relatively well. But for most of the measurement results the high amplification of vibrations at the resonance frequency is much less visible than for the calculations.

The inhomogeneity of the measurement conditions did not allow for a further and more precise analysis of the different USP products, since the results scatter too much but the material properties such as C_{dyn} or C_{stat} differ only slightly and would therefore need very precise results for a validation. It should be validated by a more precise measurement method such as laboratory measurements or products with much larger differences should be tested in track.

Axlebox measurements give an interesting insight of excitation mechanisms. Such results could give statistical relevant information of mitigation effects at the interesting frequency range.

5. CONCLUSIONS

SBB tested 3 different USP types for a curve and for the straight line for track stability, additional noise and vibration mitigation effects.

The results of the track characteristics and stability measurement campaign as well as from the noise measurements are presented in Chapter 3. Track deflection measurements reveal a quite highly disturbed track subgrade along the test track. Therefore, the deflections of the USP test site are potentially underestimated to some extent due to considerable differences in ground stiffness. Overall, deflections of about 0.6 to 1.2 mm are observed. The settlement measurements revealed a much more pronounced (up to three times higher values) settlement in the reference section compared with the sections with USP. The lateral force resistance measurements showed that in comparison with the reference section, the lateral force resistance in sections with USP is significantly lower. At a displacement of 2 mm, about 40% to 43% of the lateral force resistance was found in straight track sections with USP compared with the straight reference section. A conclusive interpretation of the lateral force resistance results will be possible after the UIC working group for lateral force resistance will have tested and discussed the SBB measurement method for lateral force resistance. The vibration measurements of the sleepers in the straight line reveal that the highest vibration acceleration (RMS values) arise for the sleeper product Tiflex. The lowest vibration amplitudes is found for the product Getzner (soft and stiff).

The static stiffness was determined in laboratory experiments following the CEN-standard for characterisation of USP stiffness for all the tested USP samples. The measurements reveal a value of about 0.12 N/mm^3. The dynamic stiffness is only around 30% higher, but for the product Tiflex, the dynamic stiffness at 30 Hz is about 20% lower compared to the products Getzner and CDM.

The comparison of the noise measurements of the straight reference section with hard railpads and without USP revealed an increase of 2 dBA to 5 dBA depending on the train type running over the straight and curve sections with soft railpads and USP. Based on experience and physical models, it is assumed that this effect rather arises from railpads than from USP: considering the track decay rate (TDR) measurements and the analysis of the collected TDR spectra, differences of about 2-4 dB are expected. With a more accurate and frequency dependent evaluation of the noise measurements, it would be possible to verify the contribution of the soft railpads. This additional noise effect potentially could be reduced by the installation of harder rail pads than C_{stat} = 100 kN/mm.

The rail roughness measurements show that the reference section exhibits the highest roughness. This indicates that the additional noise is due to effects such as track component stiffness (such as soft railpad which could lead to additional track dynamics in higher frequencies) or measurement conditions, but not due to rail roughness.

The results from the vibration data analysis with respect to the quantification of the mitigation effect of USP on ground vibrations is presented in Chapter 4. Accounting for correction of the influence of the heterogeneous geology, a distinct reduction of vibration can be observed by means of the v_{RMS} values; considering all train categories (i.e. intercity, regional and freight trains), the achieved mitigation effect is in the range of about 10%-40%.

The frequency analysis of the measurements shows that a mitigation effect can be observed above 50 Hz, which reaches about 15 dB at 250 Hz. The scattering within the vibration data for the test sections in comparison to the reference section made it meaningful to apply a correction algorithm by using train pass-bys on the adjacent track to eliminate the biggest differences probably due to heterogeneous geology. These train pass-byes then serve as a second reference after being transferred to 8 m distance using a suitable transfer function. The corresponding results show that also for lower frequencies (8 Hz - 31.5 Hz) a mitigation effect of around 5 dB is achieved.

The comparison of simulations of deliverable D3.2 with these measurement results for the mitigation effects shows that the observed mean mitigation effect corresponds relatively well to the calculations. However, the high amplification of vibrations at the resonance frequency is much less evident from the measurement results than is expected from simulations.

The inhomogeneity of the measurement conditions did not allow for a further and more precise analysis of the different USP products, since the results scatter too much but the material properties such as C_{dyn} or C_{stat} differ only slightly and would therefore need very precise results for a validation.

The analysis of axle box measurement data indicate that further insight of the excitation mechanisms can be achieved. Such results may help to provide statistically relevant information of mitigation effects for the frequency range of interest.

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ANNEX A: LABORATORY TESTS FOR THREE USP MATERIALS

A1. Results of the static bedding modulus

Tiflex TR1-86GF

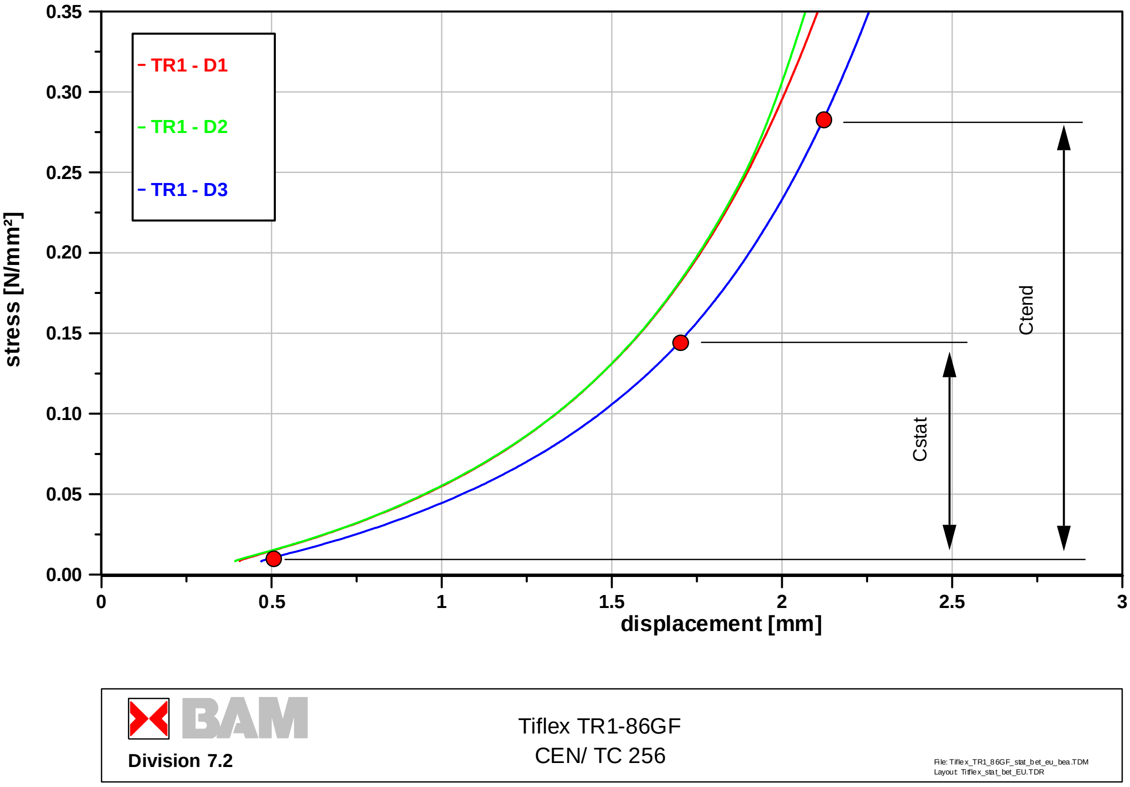

Figure 3.1: Static bedding modulus (stress over displacement at the 5th loading)

Tiflex TR1 86 GF - Static bedding modulus - CEN/ TC 256				
sample	**D01**	**D02**	**D03**	**Average**
C_{stat}	0,1164 N/mm³	0,1156 N/mm³	0,1098 N/mm³	**0,1139 N/mm³**
C_{tend}	0,1750 N/mm³	0,1753 N/mm³	0,1666 N/mm³	**0,1723 N/mm³**

Table 3.1: Tiflex TR1 86-GF - Static bedding modulus CEN/ TC 256

CDM USP H400

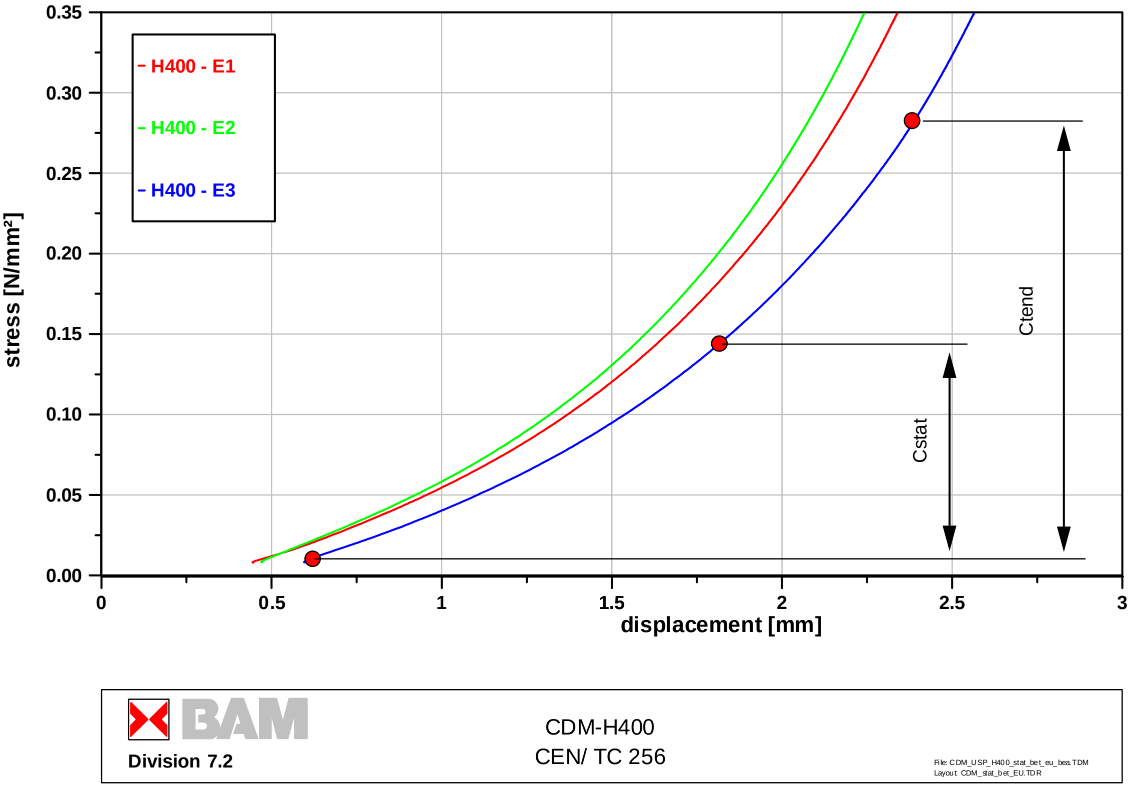

Figure 3.2: Static bedding modulus (stress over displacement at the 5th loading)

CDM USP H400 - Static bedding modulus - CEN/ TC 256				
sample	**E01**	**E02**	**E03**	**Average**
C_{stat}	0,1137 N/mm³	0,1220 N/mm³	0,1100 N/mm³	**0,1152 N/mm³**
C_{tend}	0,1597 N/mm³	0,1701 N/mm³	0,1526 N/mm³	**0,1608 N/mm³**

Table 3.2: CDM USP H400 - Static bedding modulus CEN/ TC 256

Getzner SLN 1510

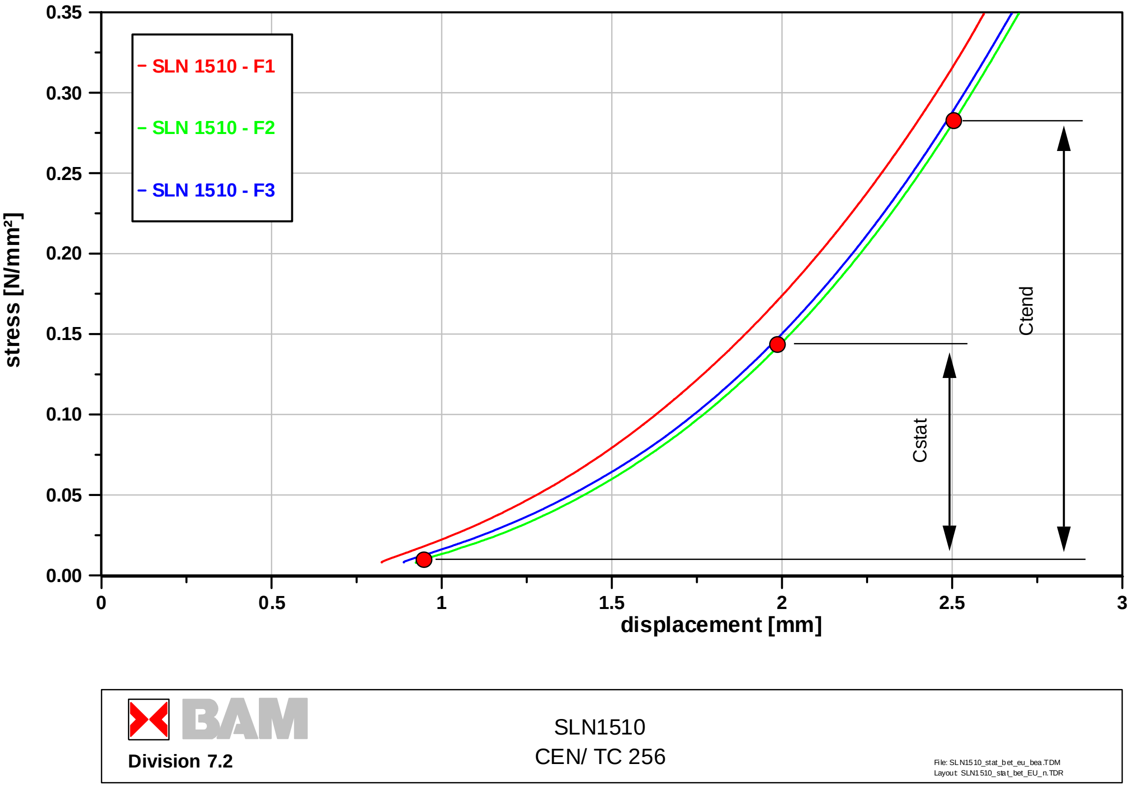

Figure 3.3: Static bedding modulus (stress over displacement at the 5th loading)

Getzner SLN1510 - Static bedding modulus - CEN/ TC 256				
sample	**F01**	**F02**	**F03**	**Average**
C_{stat}	0,1297 N/mm³	0,1261 N/mm³	0,1246 N/mm³	**0,1268 N/mm³**
C_{tend}	0,1743 N/mm³	0,1740 N/mm³	0,1722 N/mm³	**0,1735 N/mm³**

Table 3.3: SLN 1510 - Static bedding modulus CEN/ TC 256

A2. Results of the low dynamic bedding modulus

Dynamic bedding modulus TR1-86 GF CEN/ TC 256				
Frequenz	**D01**	**D02**	**D03**	**average TR1**
4 Hz	0,1283 N/mm³	0,1258 N/mm³	0,1193 N/mm³	**0,1245 N/mm³**
10 Hz	0,1295 N/mm³	0,1268 N/mm³	0,1198 N/mm³	**0,1254 N/mm³**
20 Hz	0,1315 N/mm³	0,1283 N/mm³	0,1217 N/mm³	**0,1272 N/mm³**
30 Hz	0,1337 N/mm³	0,1300 N/mm³	0,1237 N/mm³	**0,1291 N/mm³**

Table 3.4: Tiflex TR1-86GF - dynamic bedding modulus CEN/ TC 256

Dynamic bedding modulus CMD H400 CEN/ TC 256				
Frequenz	**E01**	**E02**	**E03**	**average CDM H400**
4 Hz	0,1434 N/mm³	0,1509 N/mm³	0,1349 N/mm³	**0,1431 N/mm³**
10 Hz	0,1510 N/mm³	0,1590 N/mm³	0,1412 N/mm³	**0,1504 N/mm³**
20 Hz	0,1576 N/mm³	0,1665 N/mm³	0,1475 N/mm³	**0,1572 N/mm³**
30 Hz	0,1611 N/mm³	0,1712 N/mm³	0,1521 N/mm³	**0,1615 N/mm³**

Table 3.5: CDM USP H400 - dynamic bedding modulus CEN/ TC 256

Dynamic bedding modulus SLN1510 CEN/ TC 256				
Frequenz	**F01**	**F02**	**F03**	**average SLN1510**
4 Hz	0,1476 N/mm³	0,1480 N/mm³	0,1445 N/mm³	**0,1467 N/mm³**
10 Hz	0,1515 N/mm³	0,1521 N/mm³	0,1482 N/mm³	**0,1506 N/mm³**
20 Hz	0,1552 N/mm³	0,1557 N/mm³	0,1518 N/mm³	**0,1543 N/mm³**
30 Hz	0,1577 N/mm³	0,1591 N/mm³	0,1547 N/mm³	**0,1572 N/mm³**

Table 3.6: SLN 1510 - dynamic bedding modulus CEN/ TC 256

ANNEX B: RESULTS OF VIBRATION FREQUENCY ANALYSIS AT 8 METER

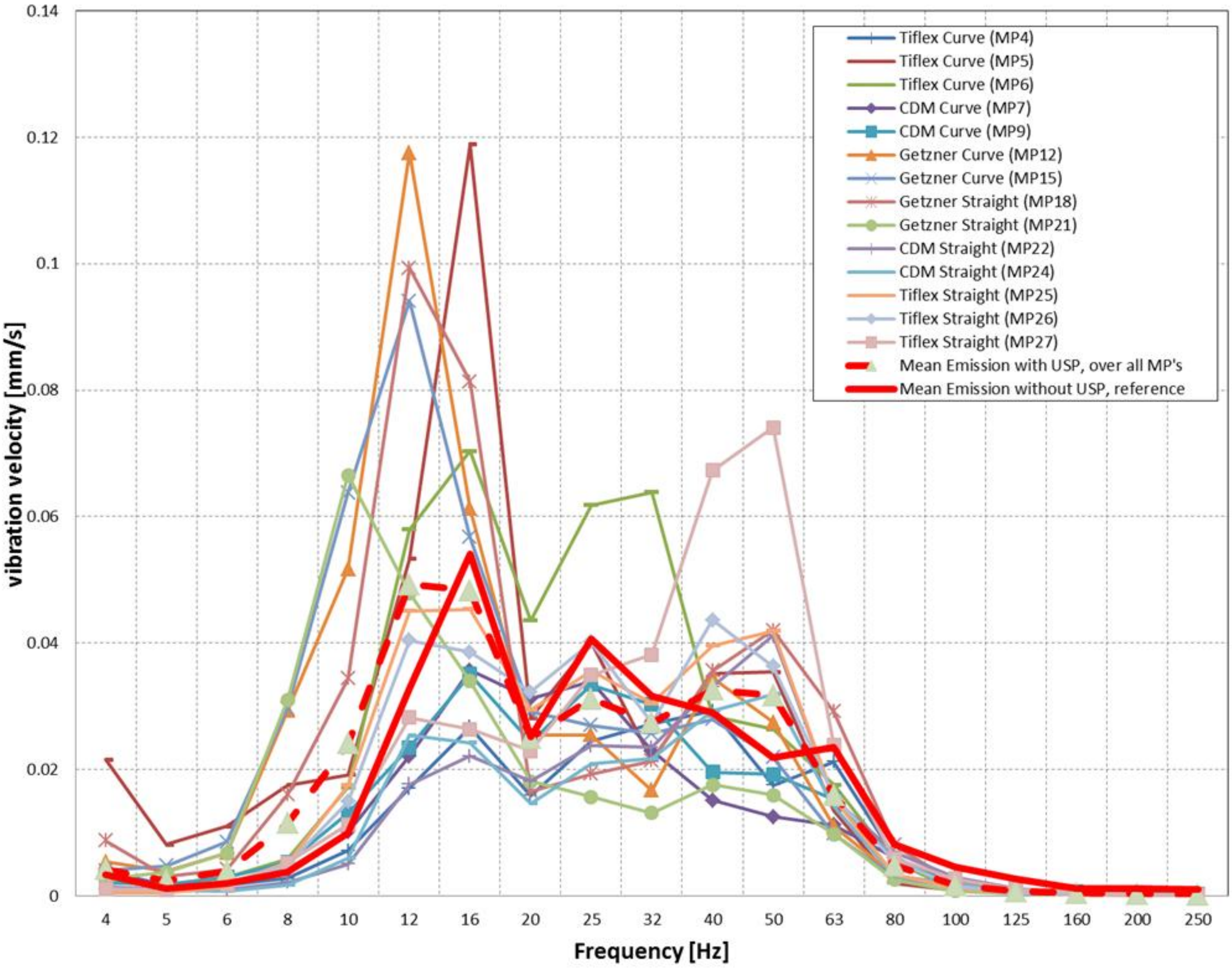

Figure B.1: Emission spectra for IC on southern track 2, all test sections with USP, 8 m distance.

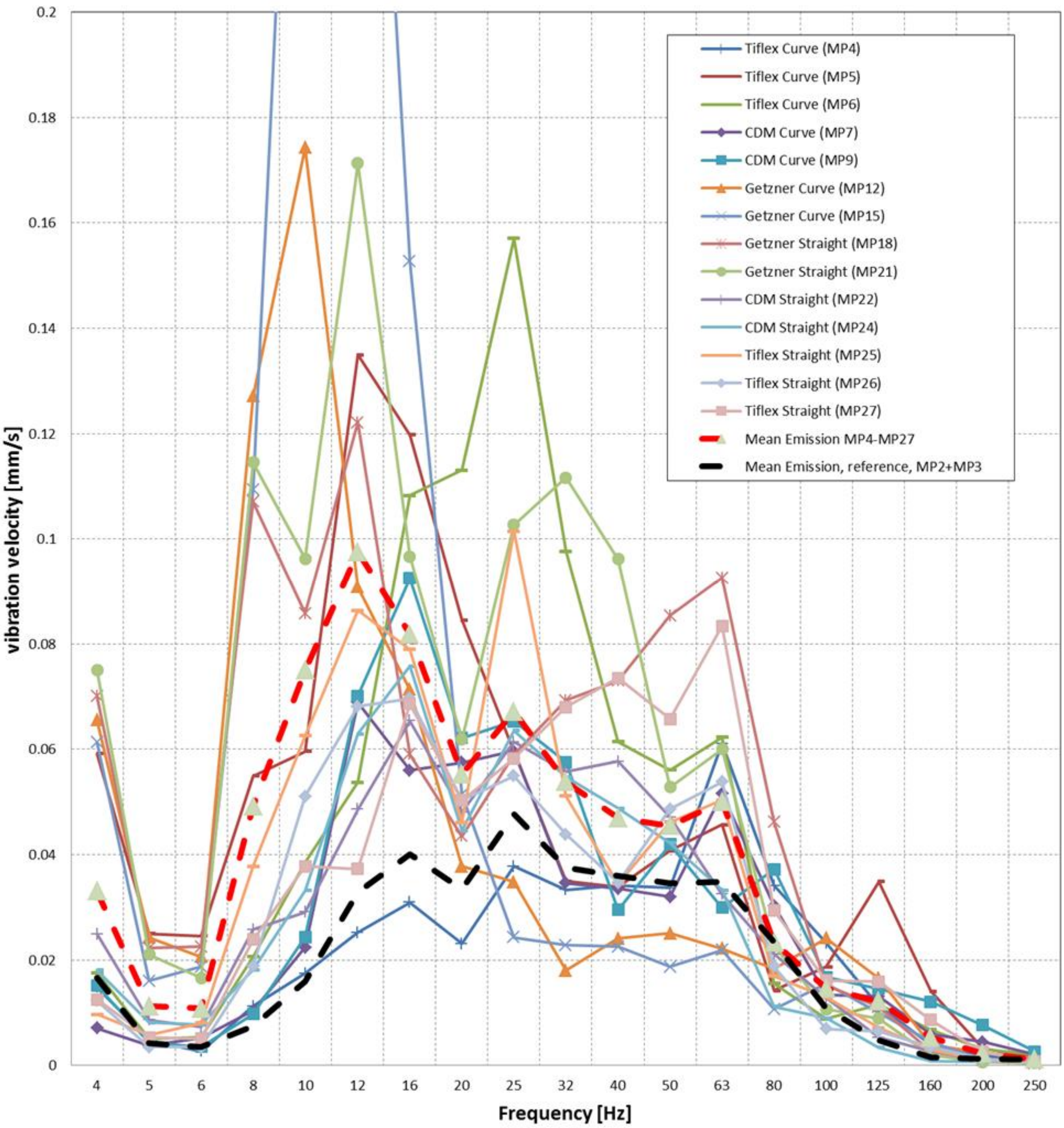

Figure B.2: Emission spectra for IC on northern track 1, without USP, incl. mean of MP2,3, all measurement points in 4 m distance.

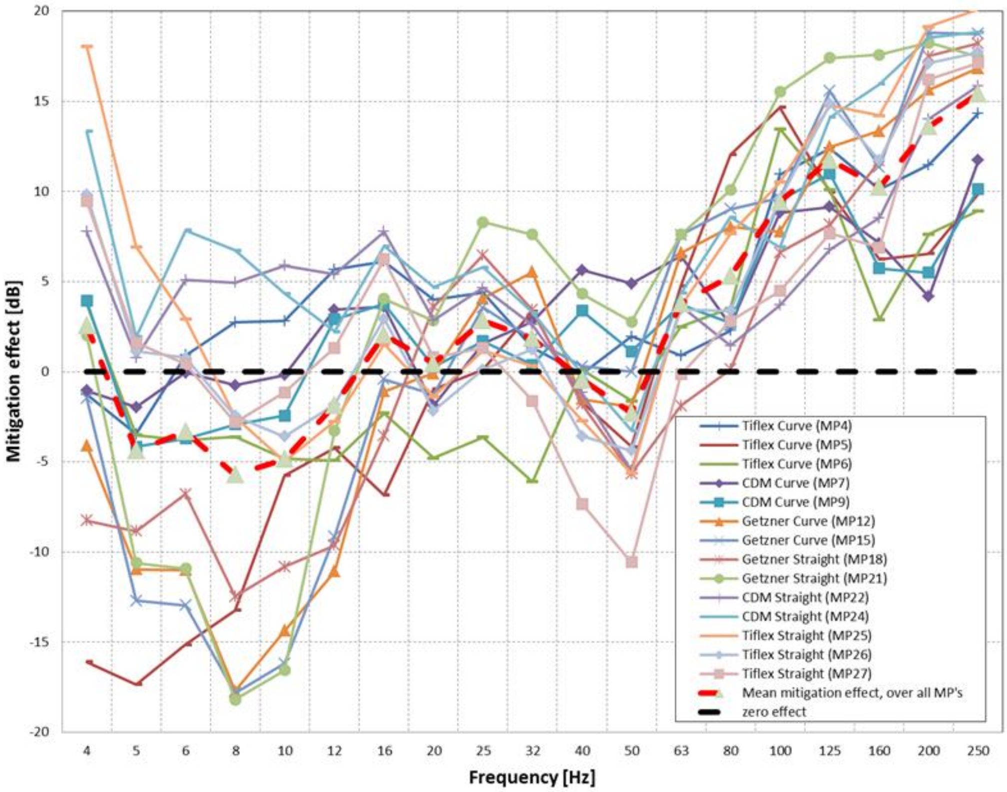

Figure B.3: Mitigation effect for Intercity trains with the reference sensor positions MP2/MP3.

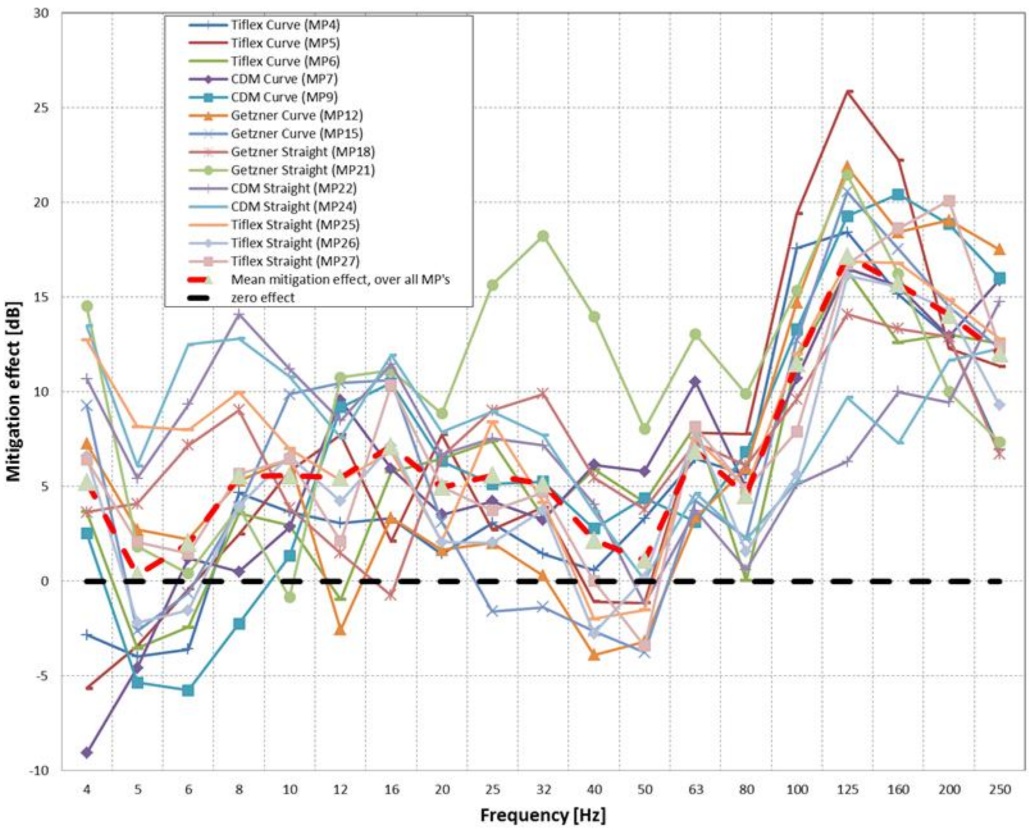

Figure B.4: Mitigation effect of USP corrected by using the reference from track 1 transferred to the distance of 8 m by transfer spectra of Figure 4.8 for Intercity trains.

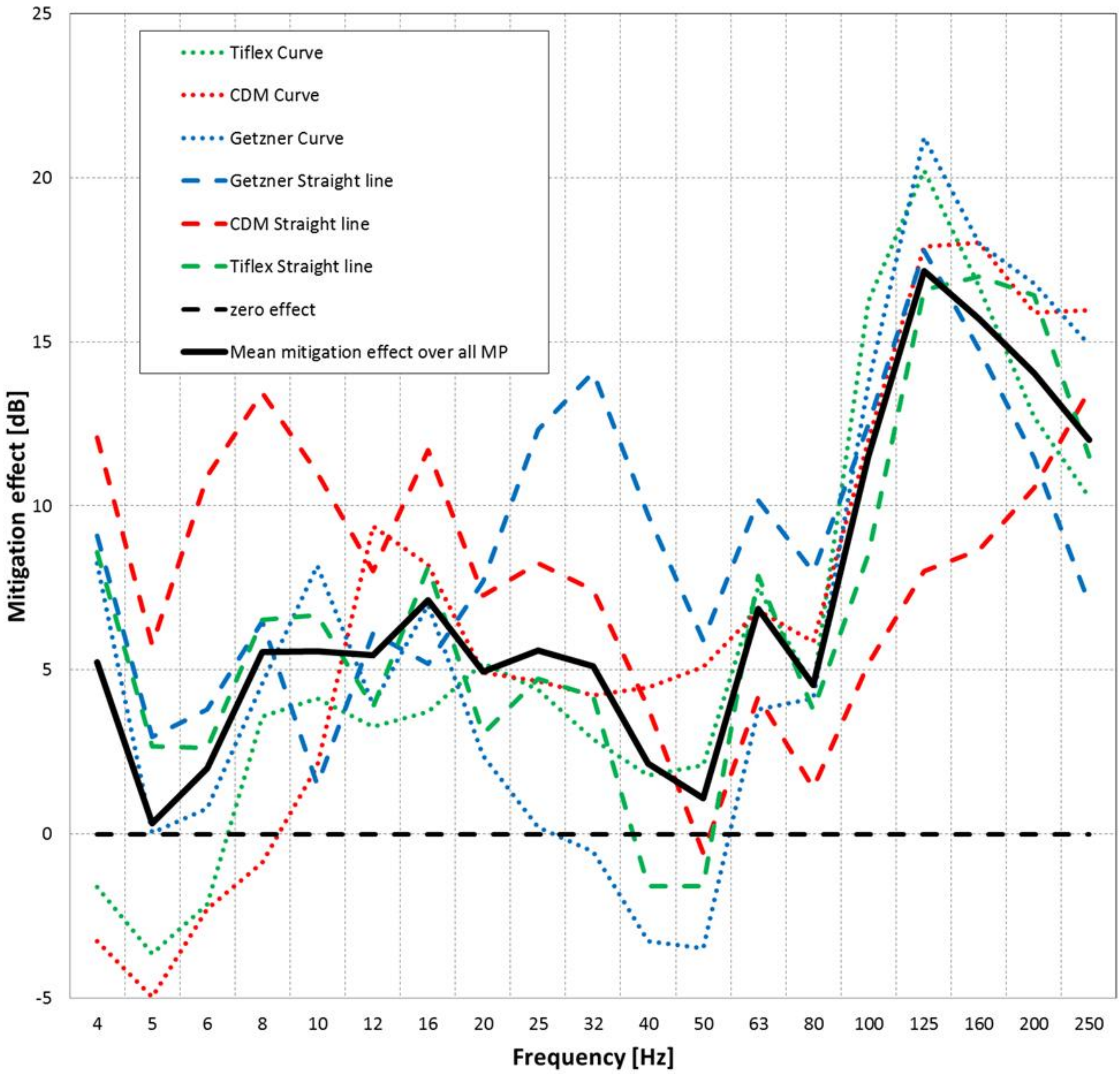

Figure B.5: Mitigation effect of USP (mean per USP type, curve or straight line) corrected by using the reference from track 1 transferred to the distance of 8 m by transfer spectra of Figure 4.8 for Intercity trains.