Assessment of a Railway Vibration Quality Indicator

Through an analysis of field vibration measurement data ProRail

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Executive Summary

The railway vibration quality (RVQ) indicator, created by Level Acoustics & Vibration, assesses track quality, and helps ProRail to evaluate the quality of track in relation to environmental vibrations. The RVQ indicator uses the recorded track geometry data of the Dutch national network monitoring system collected according to the EN 13 848 standard.

The current project aimed to investigate whether there is a correlation between vibration levels near the track, using existing vibration measurement data, and the RVQ indicator, using historical track geometry data. For this purpose, vibration measurement data collected before and after track modifications at the Dorst location were analyzed and assessed. The following phases were identified and carried out:

Phase 1: In this phase 1, the vibration measurement data were examined to ensure their suitability for in-depth analysis. Additionally, digital tools were set up to perform the analysis.

Phase 2: This phase involved comparing the measured vibration levels before and after maintenance. The objective was first to analyze differences in the output parameters of the RVQ indicator using the historical track geometry data before and after maintenance works. Secondly, the RVQ indicator data will be compared with possible trends in the measured vibration levels. In doing so, the historical track geometry data from Level Acoustics & Vibration concerning the values before and after maintenance and modification were employed.

Based on the findings of this study, the following conclusions can be drawn:

- There is a significant level of agreement between the RMS values obtained from the historical track geometry data and the existing vibration measurement data at various distances from the track. This trend is consistent across all frequency octaves, with similar observations for all distances.

- It was found that the correlation coefficient (R2) for all trains was above 0.33 for 16 Hz and 0.86 for 32 Hz octave bands. These findings suggest that the Max values from historical track geometry data collected at the source of vibration and the processed vibration measurement data at different distances from the track in this study are well correlated, especially for the 32 Hz octave band.

This study has identified both potentials and limitations. One limitation is that at the Dorst location, not only the level crossing was replaced, but also some insulated joints were renewed. There were also some changes in the surroundings such as the placement of new metal fences. These changes make it difficult to determine the contribution of each change to the reduction or increase of vibrations. Therefore, it is recommended to conduct similar research at locations where only track maintenance are performed.

From the current study it is unclear how the following factors influence the vibrations:

- The presence of a complex geometry for the second track.
- The influence of another type of level crossing.
- The influence of maintenance.

Further validation is therefore needed to confirm whether the results are generic and can be applied in different areas. Additionally, advanced numerical simulations such as 2D or 3D FEM can be used to better understand the impact of soil, including soft layers like peat or clay, and track conditions like geometry on the generated vibration. This research will help optimize the maintenance regime that is applied.

1 Introduction

1.1 Project objectives

The current project aims to investigate whether there is a correlation between the vibration levels recorded near the track and the RVQ indicator. This indicator is used as a tool that was created by Level Acoustics & Vibration, commissioned by ProRail [1]. The RVQ indicator assesses track quality and helps ProRail to evaluate the quality of track in relation to environmental vibrations. The output of the RVQ indicator is based on power spectral density calculations of 200 m track segments. In the Netherlands, track geometry of the network is measured every six months. The RVQ indicator uses the recorded track geometry data of the Dutch national network monitoring system collected according to the EN 13 848 standard [2].

The present study focused on the correlation between the RVQ indicator data and existing vibration measurements [3]. As part of this project, existing data will be collected from earlier field vibration measurements. The collected data include data from track side vibration measurements carried out at Dorst [3]. The vibration measurements were carried out before and after track maintenance and modification works. Vibration levels were measured at different distances from the track. The goal of the original field measurements was to assess the effect of maintenance and modification works on the measured vibration levels in the vicinity of the track. In this project, the same collected data will be analyzed to investigate the correlation between parameters of the RVQ indicator and measured vibration levels.

Examining these vibration measurement data can help to identify whether there is a correlation between the track quality at a given track position derived from the RVQ indicator and the measured vibration levels near the track. To achieve this, the following phases were identified:

- Phase 1: In this phase, the vibration measurement data are examined to ensure their suitability for in-depth analysis. Additionally, digital tools are set up to perform the analysis.

- Phase 2: This phase involves a comparison of the measured vibration levels both before and after maintenance interventions. The objective is to analyze differences in the output parameters of the RVQ indicator using the historical track geometry data before and after maintenance works and compare these with possible trends in the measured vibration levels.

The present report provides a detailed summary of the analysis findings, along with recommendations on how to improve the RVQ indicator using the vibration measurement data.

The current report only covers the analysis concerning the Dorst location (see Figure 1).

1.2 Report status

- This document has version 1.1 and status S3 according to ISO 19650. In this version all comments made on version 1.0 have been addressed.

- This document is classified as Confidential according to ISO27001.

2 The project location: Dorst

2.1 General description of measurement site

The Dorst location is located between Breda and Tilburg in the Netherlands, see Figure 1. The railway track between Breda and Tilburg crosses the village Dorst in the northern part, with a double track level crossing.

Figure 1 Location of Dorst and the level crossing of interest (source: Google maps).

2.2 Modifications works of the level crossing

Witteveen+Bos and D2S International conducted a study [3], commissioned by ProRail, to quantify the effect of replacing concrete slabs at level crossing with rubber panels on railway vibrations. The practical test location is at a level crossing at Spoorstraat/Wethouder van Dijklaan in Dorst. The vibration measurement results are available in the D2S documents ([4] and [5]), which are included as appendices in [3]. During the modification work, the level crossing was replaced and the insulated joint welds on both sides were also renewed. The track modifications before and after maintenance are shown in Figure 2 for comparison.

Figure 2 Track modifications before and after level crossing replacement (source: Google Earth).

2.3 Ground conditions

The ground conditions can influence the measured vibrations in the vicinity of the railway track. To provide a complete picture of the measurement site the following conclusions can be drawn for the ground conditions, based on the available data from DINOloket [6]:

- The available information is limited.
- No boreholes or CPTs were found within the location of the railway track.
- However, three boreholes and one CPT were located within approximately 60 meters from the railway track.
- The boreholes show relatively sandy layers for the uppermost 10 meters.
- The only CPT available shows that a top sandy layer overlays approximately 3 meters of soft clayey layers, followed by sand layers.

3 Starting points

In this section, all the assumptions used in the methodology and analysis are listed and described.

3.1 Vibration measurement data

The location of Dorst measurements during the measurement campaign conducted by Witteveen + Bos [3] is shown in Figure 3. The location consists of a level crossing with two railway tracks. Track 1 (south) is located closer to the vibration sensors than track 2 (north). Trains travelling to east use track 1, while those heading west use track 2.

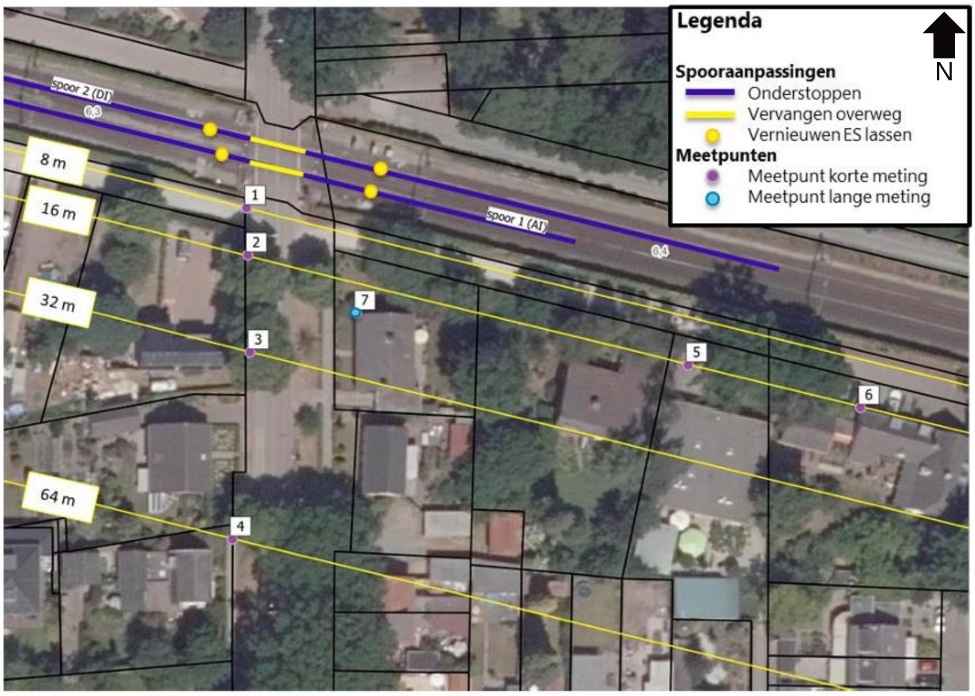

Figure 3 Location of measurement points and the modified level crossing and drawing agreement for positioning sensors relative to the track [3].

The available measurement campaigns are divided into two types:

1. Long-term vibration measurements, conducted through measurement point 7, started before the maintenance works and continued until 12 months after completion of the maintenance works.
2. Short-term vibration measurements, conducted through measurement points 1 to 6, include one day measurements. The short-term vibration measurement campaigns were performed as follows:

- Before track modifications set 1: 26/01/2021
- Before track modifications set 2: 25/05/2021
- After track modifications: 28/06/2021
- 6 months after track modifications: 30/11/2021
- 12 months after track modifications: 31/05/2022

Arcadis received the raw vibration measurement data, based on [3], which were checked and verified for the suitability of the project. After reviewing all the data, Arcadis along with ProRail concluded that only short-term measurements were available for the present analyses, since the long-term vibration measurement did not contain the train speed during the train pass-bys.

In Figure 3, points 1 to 4 are almost perpendicular to the track at varying distances of 8, 16, 32 and 64 m respectively. The points 5 and 6 are further away from the track modification area and are parallel to the track at 16 m (same as point 2). These two points are therefore not used for the comparison with the RVQ indicator data. Therefore, for the current analyses, only the data from (short-term) measurement points 1 to 4 were considered. These measurement points provide relevant data for the specific track section and area of interest in the current project, as they are located close to the track and can capture the vibrations caused by train pass-bys.

The vibration measurement data were made available to Arcadis in MATLAB ('.mat') format. These contained the starting time (T0), elapsed time (Time), and the measured vibration velocity levels in the X, Y, and Z directions. In Figure 4, the X, Y, and Z directions are shown relative to the track.

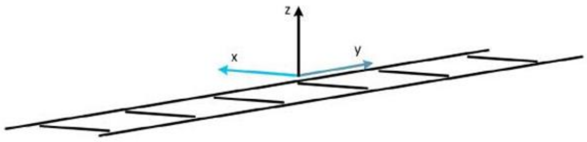

Figure 4 Drawing agreement for positioning sensors relative to the track [3].

The elapsed time (Time) is measured in seconds and the measurement results indicate vibration velocity in millimeters per second (mm/s), based on personal communication with Witteveen+Bos [7].

An example of these data, processed by Arcadis, is displayed in Figure 5. The graph shows the $V_{eff,\ max}$ in three directions for different measurement points and train speeds.

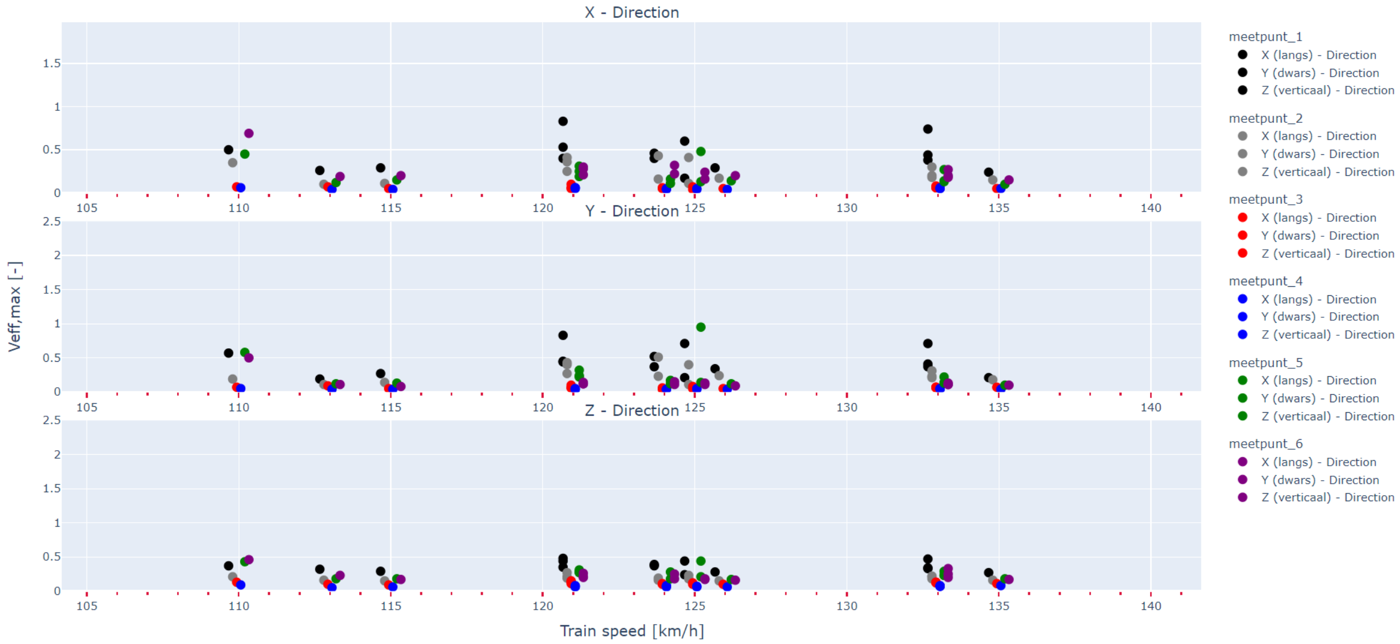

Figure 5 Example of vibration velocity versus time data, processed by Arcadis.

3.2 Train types

The vibration velocity from the train pass-bys was recorded during the measurement campaigns. This study considered three types of trains: Sprinter, TRAXX, and VIRM (in Dutch: Verlengd InterRegio Materieel). The following is a brief description of each train type.

3.2.1 Train type: Sprinter

The Sprinter, also referred to as SLT (NS commuter train), is mainly used for shorter distance journeys within the Netherlands. They are single-decker trains, powered by electricity and do not have a separate locomotive. With a maximum speed of around 140 km/h, they are typically found in urban areas and make frequent stops at various stations. Figure 6 shows an example of a Sprinter.

The length of Sprinter trains is approximately 75 to 80 m. The length can vary based on the train composition.

Figure 6 Example of NS Sprinter Light train (SLT) – Source: Amsterdamtips.com

3.2.2 Train type: TRAXX

The TRAXX, also referred to as “intercity direct train” or TRAXX F140 locomotive (Alstom former Bombardier), is used for both intercity and international services. The train composition consists of 6 ICR passenger cars between 2 TRAXX F140 locomotives. However, these trains are designed to be versatile and can be used in various configurations, such as incorporating multiple locomotives or having a single locomotive, in order to meet the specific needs of the railway operator. These trains are electrically powered and can also run on diesel in certain cases. They have a maximum speed of around 160 km/h and are frequently used for cross-border services, connecting the Netherlands with its neighboring countries. Figure 7 shows an example of TRAXX.

The length of TRAXX trains is approximately 100 to 150 m. The length can vary based on the train composition.

Figure 7 Example of NS TRAXX train

3.2.3 Train type: VIRM

The VIRM, also referred to as NS double stock passenger train, is used for intercity services throughout the Netherlands. These double-decker trains are electrically powered and do not require a separate locomotive. VIRM trains operate with a maximum speed of around 160 km/h. An example of VIRM train is shown in Figure 8.

The length of VIRM trains is approximately 100 to 120 m. The length can vary based on the train composition.

Figure 8 Example of NS double-decker Intercity train (VIRM) - Source: Amsterdamtips.com

3.3 Train speed

The measurement data indicates that trains have different speeds depending on their type. For the purpose of analyzing the vibration measurement data, all the train pass-bys were used independent of their speed. However, when comparing with the historical track geometry data (the RVQ indicator data), only train speeds ranging from 120 km/h to 140 km/h were considered. This range fall within the speed range of the maintenance train that was used to obtain the historical track geometry data.

3.4 Data processing

Initially, the vibration measurement data was stored in MATLAB files (.mat). However, this data is now being read through Python scripts that were specifically developed for this purpose by Arcadis. The Python tool has several advanced functions, including the ability to perform Fast Fourier transfer analysis, calculate correlations based on various methods and generate graphical results, which provides more in-depth insights.

3.5 RVQ indicator data

The measured vibration data has to be compared to the RVQ indicator data. In this section a description of the RVQ indicator data is given.

Rail and track unevenness is monitored in several countries, including the Netherlands, with the help of a Track Recording Car (TRC). This facilitates maintenance management by determining the need for maintenance, such as tamping of the track ballast [2]. The TRC measures the wavelength unevenness of railway track every six months according to the EN standard 13848. The wavelengths are divided into three categories: D1, where 3 m $< \lambda <$ 25 m, D2, where 25 m $< \lambda <$ 70 m, and D0, where 1 m $< \lambda <$ 5 m is also measured since 2021 [2].

The measured vibration frequency range is between 2 and 80 Hz. However, the most important vibrations in dwellings nearby railway tracks, are usually between 2 and 50 Hz. Therefore, the output of the corresponding wavelength domain of the RVQ indicator considers only wavelength between 1 and 12,5 m. This wavelength domain includes the main frequencies one can find in train pass-bys of freight trains (with a speed of 80 km/h) or passenger trains (with a speed of 130 km/h).

The output of the RVQ indicator contains two main parameters: The RMS value and the Max fast value of a sliding 200 m track segment. The RMS value is based on the geometrical track unevenness amplitudes in a 200 m track segment. The Max fast value is based on the maximum value of the geometrical track unevenness amplitudes in a 200 m segment. The output data of the RVQ indicator is presented in normalized levels compared to the average values of a 200 m segment in the Dutch railway network. The RVQ indicator values are derived from data in the wavelength domain in which the output is transformed to the frequency domain in 4 octave bands (4, 8, 16 and 32 Hz) using the equation f = v/λ. Table 1 shows the relationship between octave bands and wavelength. The presented frequencies in the output are based on a train speed of 130 km/h.

Table 1 Relationship between octave bands and wavelength based on a train speed of 130 km/h

Octave band (Hz)	Wavelength range (-)	Wavelength (m)
4	D1	9.0
8	D0/D1	4.5
16	D0	2.3
32	D0	1.1

For the analysis, the relative values in the RVQ indicator output are converted in absolute values. In order to compare the results of the present analysis with the historical track geometry data, it is necessary to understand the average vibration level provided in the historical track geometry data. The values, presented in Table 2, were obtained from personal communication [8]. To determine the maximum amplitude, the reference value per specific octave band must be multiplied by the maximum ratio in the results of the historical track geometry data.

Table 2 Reference average vibration values in the Netherlands for both height and shift (track geometry) per frequency octave [8]

Metric (-)	Wavelength range (-)	O4 (Hz)	O8 (Hz)	O16 (Hz)	O32 (Hz)
NL-hoogte-RMS	D0*	-	0.390	0.490	0.460
NL-hoogte-Max	D0	-	0.330	0.410	0.390
NL-hoogte-RMS	D1/D2**	0.693	0.595	-	-
NL-hoogte-Max	D1/D2	0.629	0.548	-	-
NL-schift-RMS	D1/D2	0.327	0.296	1.000	1.000
NL-schift-Max	D1/D2	0.304	0.267	1.000	1.000

* D0 is recommended for octave bands 16 Hz and 32 Hz.
** D1/D2 is recommended for octave bands 4 Hz and 8 Hz.

3.5.1 Historical track geometry data metrics

The data includes two important metrics: Root Mean Square (RMS) and Max values. RMS values provide an overall representation of vibration magnitudes considering the changes both in vertical and horizontal directions, derived from the track unevenness measurements, while Max values identify local discontinuities or spikes in vibration levels. Max values are also helpful in identifying the influence of specific track elements, such as insulated joint welds and level crossings.

3.5.1.1 Root Mean Square (RMS)

The process of calculating RMS Values involves several stages [1] en [2]. Firstly, as mentioned above, vibration measurement data is collected using a test train. This equipment measures both vertical and horizontal displacements that are generated by train pass-bys. Next, the collected displacement data is processed to remove any noise and ensure accurate track geometry measurement. The data is divided into sections of approximately 200 meters each.

The next step is to apply a Fast Fourier Transform (FFT) to each 200-meter section of data. This process converts the data from the time domain to the frequency domain and provides information about the amplitudes of different frequency components present in the displacement data.

After the FFT, the square of the amplitude of each frequency component is calculated to obtain the power spectral density (PSD) for that component. The PSD values are integrated over specified frequency bands, known as octave bands, to calculate the energy content within those bands.

The final stage is the Root Mean Square (RMS) Calculation. The integrated energy values for each octave band are averaged over the entire track area. The square root of the average energy value for each octave band is then calculated to obtain the RMS values.

3.5.1.2 Maximum values

To calculate the maximum values, the following steps are taken [1] en [2]:

- Vibration measurement data is collected and preprocessed in a manner similar to RMS calculation.
- FFT is applied to each 200-meter section to convert it to the frequency domain.
- The amplitudes of different frequency components in each octave band are analyzed to identify the maximum amplitude within that band.
- The highest amplitude value within each octave band is recorded as the Max value.

3.5.2 Historical track geometry data presentation

3.5.2.1 Location of Dorst

The data was collected and processed for the specified location by Level Acoustics and Vibration as shown in Figure 9:

Figure 9 Geocode 123, between km. 6.295 en km. 6.370, concerning the level crossing replacement.

3.5.2.2 Presentation of the results

The figures presented below display the RMS and Max values from RVQ indicator data for different frequency octaves, namely 4, 8, 16 and 32 Hz. The vertical axis of the data is a ratio calculated with respect to the average values of vibration data in the Netherlands (see 3.5). The figures do not contain values for higher frequency bands such as 64 Hz, for wavelength ranges of D0, D1 or D2. These bands are not present in the data since their acquisition requires the use of other filter techniques.

The historical track geometry data presented in Figure 13 as an example, include track geometry measurement data from spring 2020 which is related to the period before the track modification. Detailed historical track geometry data used for the period before the track and after the modification are shown in Appendix C.

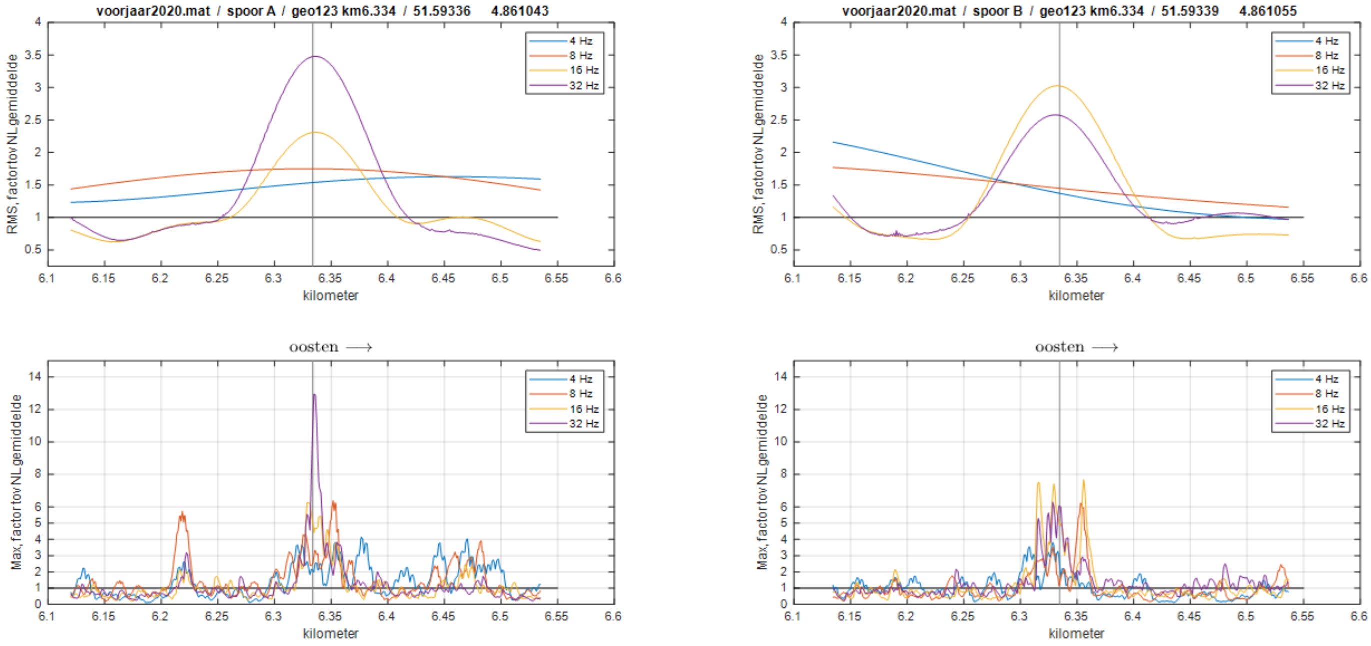

Figure 10 RMS and Max values for both tracks from spring 2020 track geometry measurement data

3.6 Methodology

The flowchart below provides a step-by-step methodology which is used in the Python tool (see 3.4), for analyzing vibration measurement data, regardless of the location. The process involves several stages, including data collection (3.1), preprocessing, applying filters, signal trimming, band filters, train pass-bys selection, and FFT analysis. Each stage has a unique purpose and helps refine the vibration measurement data for further analysis.

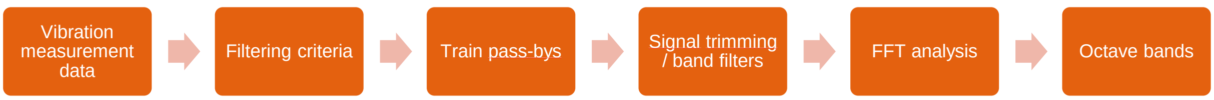

Figure 11 Step-by-step methodology for analyzing vibration measurement data.

3.6.1 Filtering criteria

At this stage, filtering criteria is applied to the vibration measurement data to narrow down the selected portions of data for further analysis. The filter considers several factors, such as train type, train speed, vibration measurements taken before and after track modifications, and the difference between tracks 1 and 2. Each of these factors plays a crucial role in ensuring that the vibration measurement data selected meets the desired conditions for analysis. For instance, the train speed and type may be used to differentiate data from different train models, while vibration measurements taken before and after track modifications can help identify changes in performance.

The filtering process is essential in focusing on relevant data that meets the desired conditions for analysis while eliminating irrelevant vibration measurement data points. This helps to make the analysis process more efficient by allowing more accurate identification of trends or anomalies in the data.

3.6.2 Train pass-bys

By applying the filtering criteria discussed, the required train pass-bys data is one by one obtained from the separate MATLAB data files. These datafiles contain the time versus vibration velocity data which is used in the analysis being conducted.

3.6.3 Signal trimming / band filters

In this step, a method called "percentage-based signal trimming" is used to trim the signal based on a certain percentage of the maximum amplitude. The trimming process is performed in a few steps:

- First, the maximum amplitude of the filtered signal is determined.
- Then, a percentage threshold is defined based on the maximum amplitude. For example, a certain percentage of the maximum amplitude between 1% and 10%. A value of 5% has been used, this value resulted in a proper trim. The percentage threshold is multiplied by the maximum amplitude to determine the actual threshold value.
- Next, the start and end points of the train pass-by are identified based on the threshold value. Typically, these points are where the signal exceeds the threshold value.
- Finally, the signal is trimmed by excluding the samples before the start point and after the end point. This technique helps to remove unwanted noise or background sounds and retain only the relevant pass-by of the train.

By applying this percentage-based signal trimming technique, the analysis focuses on the specific portion of the signal that corresponds to the train pass-by, thereby enhancing the accuracy and relevance of the subsequent analysis steps.

Additionally, a "bandpass filtering" technique is applied to isolate the desired frequency range of interest (0 to 100 Hz). By setting the lower cutoff frequency to 0.1 Hz and the upper cutoff frequency to 100 Hz, the filter allows only the relevant train-induced vibrations in the desired frequency range (0 to 100 Hz) while suppressing unwanted frequencies outside that range.

By combining the signal trimming technique with appropriate band filtering, the subsequent analysis steps can be performed on the refined and relevant signal data within the desired frequency range.

Figure 12 compares the measured vibration signal to the trimmed and filtered signal.

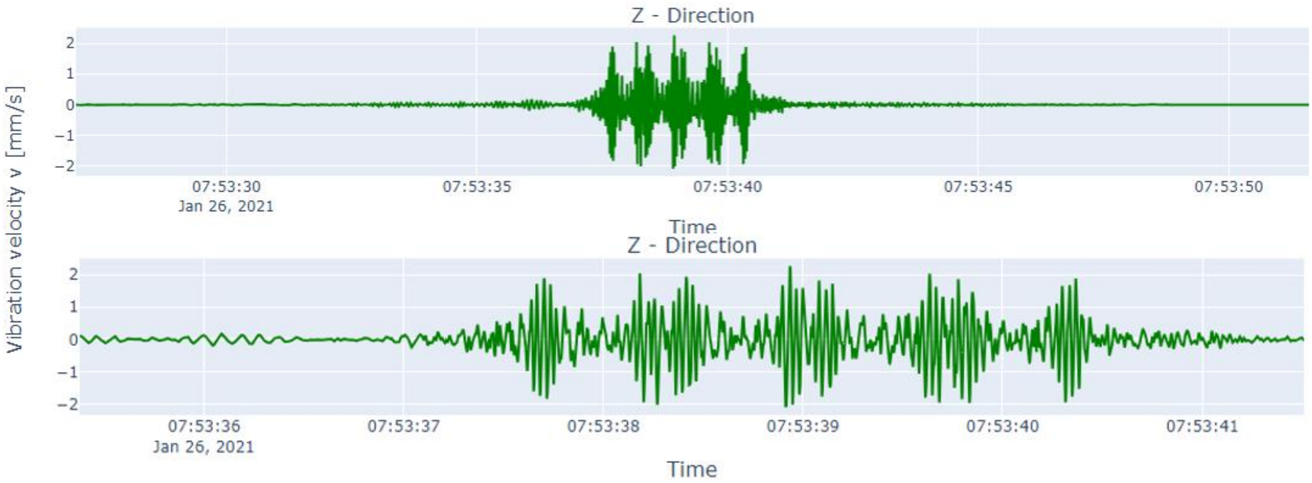

Figure 12 Comparison between the measured and filtered vibration signals, shown in the upper and lower figures, respectively.

3.6.4 FFT analysis

In this step, the trimmed and filtered signal data (see 3.6.3) undergoes Fast Fourier Transform (FFT) analysis. The FFT algorithm is a mathematical technique that transforms a signal from the time domain to the frequency domain. It decomposes the signal into its constituent frequencies and provides information about the amplitude and phase of each frequency component.

The FFT analysis is performed using the trimmed and band-filtered signal data to convert it into the frequency domain.

The frequency spectrum obtained from the FFT analysis provides valuable insights into the frequency characteristics of the vibration signal. It allows the identification of dominant frequencies or frequency ranges associated with the train-induced vibrations. Peaks in the spectrum represent the presence of specific frequencies or frequency components in the signal.

An example of the obtained FFT analysis results is shown in Figure 13.

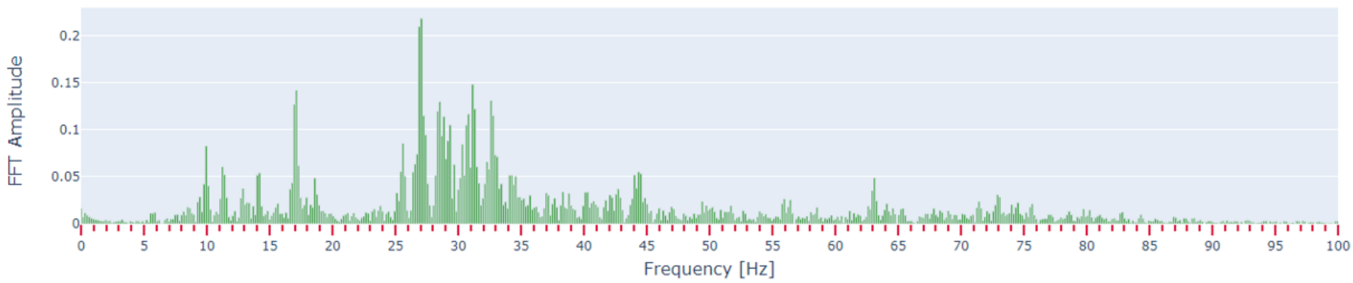

Figure 13 An example of FFT analysis results – FFT amplitude on the y-axis

3.6.5 Octave bands

After performing the FFT analysis, the frequency values are transformed into octave bands. Octave bands are a set of specific frequency ranges used in vibration analysis. Each octave band represents either a doubling or a halving of the frequency range.

The conversion into octave bands involves the following steps:

- Determining the center frequencies: The center frequencies for each octave band are calculated based on the desired frequency range and octave band width. For example, if the desired frequency range is 0 to 100 Hz and the octave band width is 1 octave, the center frequencies would be 0.5, 1, 2, 4, 8, 16, 32, 64, and 100 Hz.

- Integrating FFT results: The FFT results obtained in step 3.6.4 provide information about the amplitudes of different frequency components in the vibration signal. To convert these results into octave bands, the amplitudes within each octave band are integrated. This integration involves summing the amplitudes of all frequency components falling within a specific octave band.

- Calculating overall amplitude: After integrating the amplitudes within each octave band, an overall amplitude is calculated for each band. This overall amplitude represents the total energy or magnitude of vibration within that particular frequency range.

The results of the conversion into octave bands can be visualized by plotting the overall amplitudes against the corresponding center frequencies.

The conversion into octave bands simplifies the frequency data obtained from the FFT analysis, facilitating easier interpretation and analysis within specific frequency ranges. By analyzing the results, dominant frequency ranges can be identified, enabling a focused investigation and understanding of vibration energy distribution. This approach serves as a valuable tool for characterizing and analyzing the frequency content of measured vibrations, assisting in the assessment of vibration-related issues. Moreover, this will allow for a comparison with the historical track geometry data which are also given in octave bands.

An example of converted FFT results into octave bands is displayed in Figure 14.

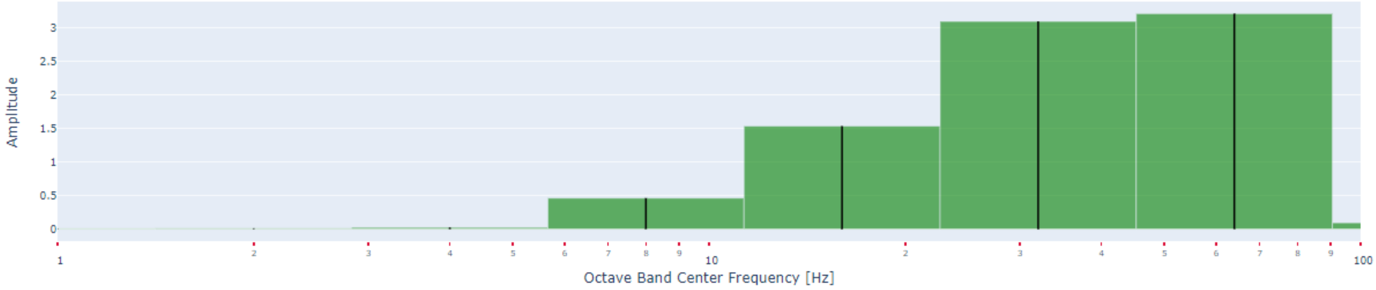

Figure 14 Octave bands (converted from FFT analysis results)

4 Analysis of vibration measurement data

This chapter presents the analysis results of the vibration measurement data categorized by train type as well as general observations that apply to all trains. The results include, among others, the analyzed data concerning the vibration measurements before and after track modifications for each train type. The maximum vibration level, determined from the vibration measurements based on SBR-B [9] framework, (Veff, max) vs. time for different measurement points and distances, before and after track modifications, will be compared and examined. Furthermore, general observations that are not limited to a specific train type will be presented. These observations will help identify overall trends and patterns in the vibration measurements, providing a broader perspective on the impact of track modifications on vibration levels and possible correlations among influential factors.

The focus of the study is mainly on the vertical direction (Z-direction), even though the results for horizontal directions are also displayed. The vibrations in vertical direction are critical when analyzing railway vibration data for environmental effects because they have a more significant impact on human perception and can cause substantial effects on buildings and structures. Regulatory standards often assess the environmental impact of railway operations based on the vertical vibrations. Therefore, only the results from the Z-direction will be presented and examined.

Appendix B contains the detailed results of Veff, max vs. time. The following section presents only the noteworthy observations and remarks per train type.

Regarding the vibration measurement data analyses before and after track modifications, only the results of track 1 for the vibration measurement data set 1 before track modification and vibration data directly after track modifications are included below. Appendix B includes a comprehensive overview of the results. The section below highlights the essential observations and remarks related to both tracks.

4.1 General observations

In this section, general observations that apply to all trains are summarized.

4.1.1 Effectiveness of track modifications

The track modifications have shown significant effectiveness in reducing vibrations in the 16 Hz and 32 Hz octave bands, with an average reduction of 54%.

However, the track modifications may have been less effective in reducing vibration levels at lower frequencies, such as at the 4 Hz and 8 Hz octave bands, as evidenced by the slight increase/decrease (almost no effect) in vibrations observed for the trains. The average reduction in these bands is 4%.

Overall, the data indicates that track modifications have varying effectiveness for different train types and frequencies.

4.1.2 Effect of distance to track

A general trend observed across all train types is that vibration levels decrease with increasing distance from the track. This behavior is as expected due to special and physical damping.

However, it is important to note that in some specific situations a significant increase in vibration levels occur at certain distances, such as at 64/68.5 m where a significant average increase of 27% in the 64 Hz octave band is present for all train types.

4.1.3 Effect of train type on vibration levels

Different train types, namely the Sprinter, TRAXX, and VIRM, exhibit distinct effects on vibration levels.

The Sprinter and TRAXX show slight increase/decrease (average decrease of 6%) in vibration levels at 4 Hz while the VIRM shows a significant average increase of 29% at this octave band frequency.

4.1.4 Frequency-dependent effects

The observations indicate frequency-dependent effects on vibration levels. Different frequencies show varying changes in vibration levels for all train types.

Some frequencies, such as 4 Hz for the Sprinter and VIRM, exhibit increases in vibration levels, while others, like 16 Hz for the Sprinter and TRAXX, show decreases.

4.2 Train type: Sprinter

In this section, the results of the vibration measurement data analysis for Sprinter trains are summarized. The results of the vibration measurement data set 1 for Sprinter trains before and directly after track modification are displayed in Figure 15, specifically for track 1. Appendix B contains more detailed results. Observations made from this figure are as follows:

- The amplitude values and their variations for 4 Hz and 8 Hz octave bands are insignificant and negligible and can be considered unaltered due to track modification. The results show an average decrease of 13%
- For the octave bands of 16 Hz and 32 Hz, there is a noticeable average decrease of 49% in amplitudes for the vibration measurements taken after the track modification compared to the results obtained before the modification.
- The most significant reduction of 73% is observable for the 32 Hz octave band results due to track modification.
- In the case of the 64 Hz octave band, there is an indication of a slight decrease in vibration amplitude due to track modification. The results show an average decrease of 15%.

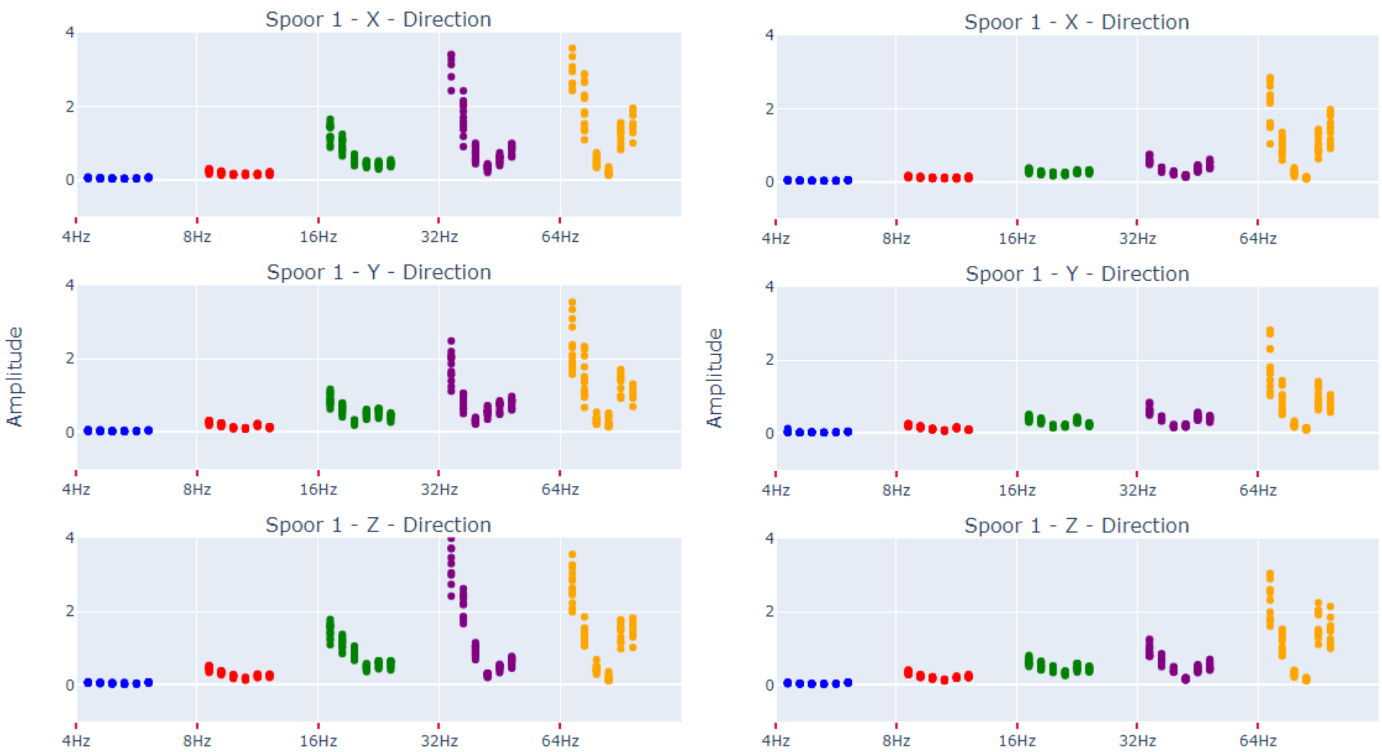

Figure 15 Vibration measurement data set 1 before track modification and data set directly after track modification - Sprinter trains - Track 1, shown in the left and right figures, respectively.

Based on the above graph and the other graphs in the appendix B, the following conclusions have been drawn:

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- The amplitude in the frequency range of 4, 8 and 16 Hz is lower compared to the range of 32 Hz and 64 Hz for both tracks. However, the results of track 1 show higher amplitudes than track 2 before track modification.
- Track modifications show a similar impact trend in all directions.
- Veff, max in vertical direction exhibited noticeable changes directly after the track modification, but also stabilized over time (see Appendix B).
- The results for the 64 Hz octave band have significantly lower amplitude at large distances compared to close distances from the track.

4.3 Train type: TRAXX

In this section, the results of vibration measurement data analysis for TRAXX trains are summarized.

The results of the vibration measurement data set 1 for TRAXX trains before and directly after track modification are displayed in Figure 16, specifically for track 1. Appendix B contains more detailed results. Observations made from this figure are as follows:

- The amplitude values and their variations for 4 Hz and 8 Hz octave bands are insignificant and only a slight reduction can be observed due to track modification. The results show an average decrease of 8%.
- For the octave bands of 16 Hz and 32 Hz, there is a noticeable average decrease 59% in amplitudes for the vibration measurements taken after the track modification compared to the results obtained before the modification.
- The most significant reduction of 83% is observable for the 32 Hz octave band results due to track modification.
- In the case of the 64 Hz octave band, there is a slight decrease in vibration amplitude due to track modification. The results show an average decrease of 14%.

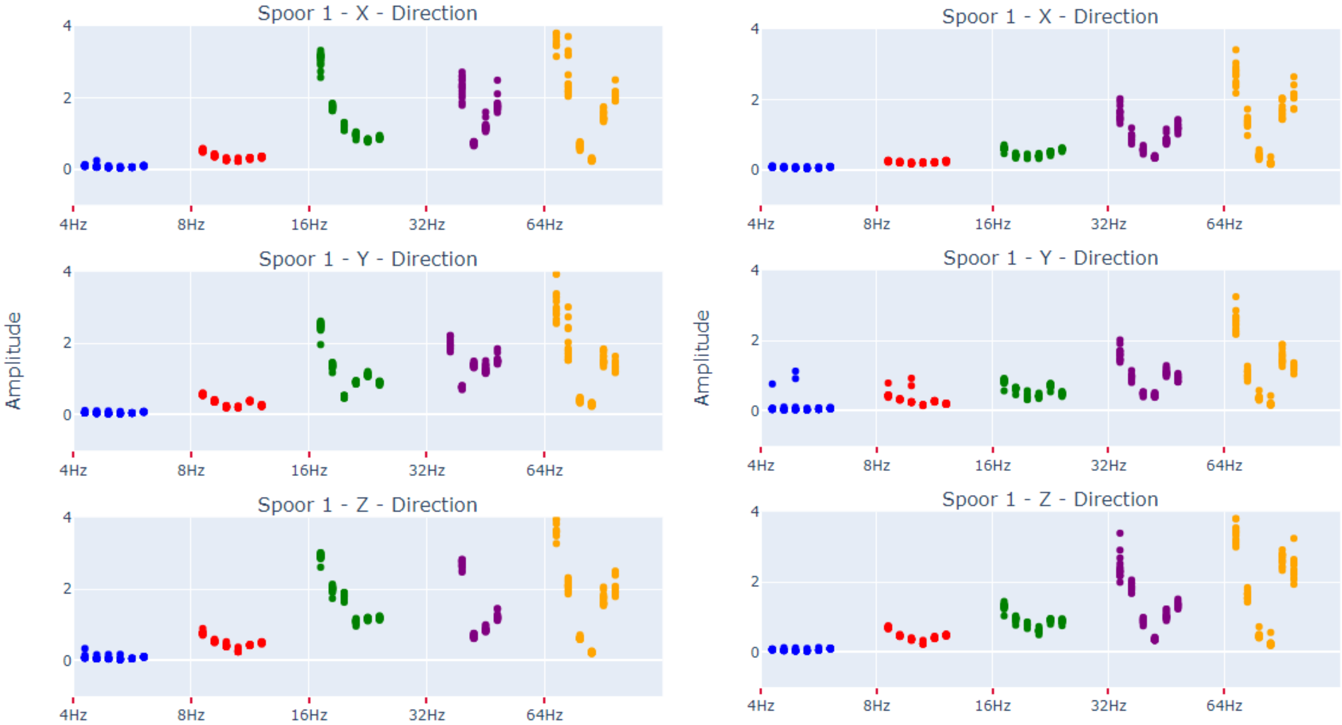

Figure 16 Vibration measurement data set 1 before track modification and data set directly after track modification - TRAXX trains - Track 1, shown in the left and right figures, respectively.

Based on the above graph and the other graphs in the appendix B, the following conclusions have been drawn:

- The maximum vibration level in the vertical direction remains constant regardless of the distance from the track.
- Before modifications, the amplitude values per octave were relatively low for lower frequencies (4 Hz and 8 Hz) and relatively high for higher frequencies (16 Hz, 32 Hz and 64 Hz).
- After modifications, there were significant reductions in amplitude values observed for the 16 Hz and 32 Hz octaves. A slight increase was observed for the lower frequency range (4 Hz and 8 Hz).

The detailed results concerning different data sets before and after track modifications are shown in Appendix B.

4.4 Train type: VIRM

In this section, the results of vibration measurement data analysis for VIRM trains are summarized.

The results of the vibration measurement data set 1 for VIRM trains before and directly after track modification are displayed in Figure 17, specifically for track 1. Appendix B contains more detailed results. Observations made from this figure are as follows:

- The amplitude values and their variations for 4 Hz and 8 Hz octave bands are insignificant and negligible and can be considered unaltered due to track modification. The results show an average increase of 7%.
- For the octave bands of 16 Hz and 32 Hz, there is a noticeable average decrease of 53% in amplitudes for the vibration measurements taken after the track modification compared to the results obtained before the modification.
- The most significant reduction of 80% is observable for the 32 Hz octave band results due to track modification.
- In the case of the 64 Hz octave band, there is a slight decrease in vibration amplitude due to track modification. The results show an average decrease of 10%.

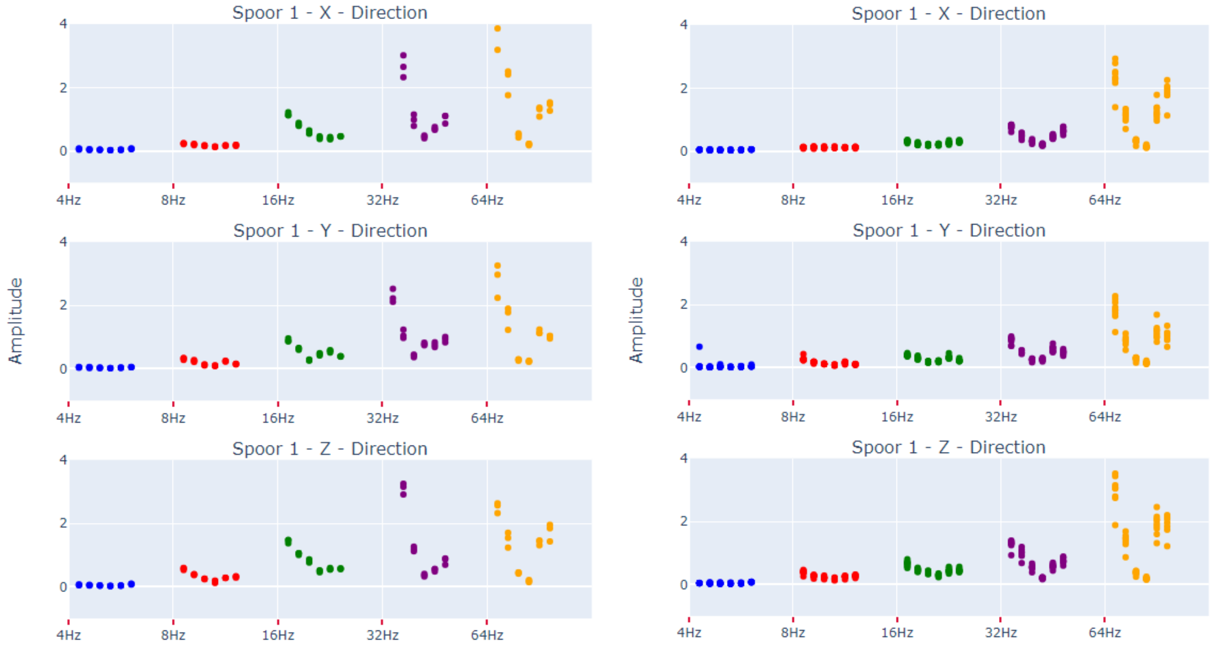

Figure 17 Vibration measurement data set 1 before track modification and data set directly after track modification - VIRM trains - Track 1, shown in the left and right figures, respectively.

Based on the above graph and the other graphs in the appendix B, the following conclusions have been drawn:

- These results indicate that proximity to the track is associated with higher vibration levels.
- Before modifications, the amplitude values per octave were relatively high, particularly in the lower frequency range.
- After modifications, there were significant reductions in the amplitude values across all octaves, especially in the lower frequency range.

The detailed results concerning different data sets before and after track modifications are shown in Appendix B.

5 Analysis of RVQ indicator data

In paragraph 3.5 it is explained that the historical track geometry data is obtained in a different manner than the vibration measurements next to the tracks. Therefore, the comparison was done via a calculation of the percentual change.

The amplitude changes before and after maintenance are compared for each octave band, namely 4, 8, 16 and 32 Hz. Unfortunately, for the 64 Hz band no comparison could be made as this band is not included in the historical data of the track geometry. If the 64 Hz data was available this could help understanding the relationship between the vibration measurement and the RVQ indicator data better.

In the comparison, the average of the vibration measurements captured immediately after the track modifications, six months after, and twelve months after, were taken together. This means three values were averaged per octave band. It is worth noting that significant changes in the vibration measurement data in terms of time after the track modifications are not anticipated. However, small neglectable differences were observed that can be caused by seasonal effect.

5.1 Comparison with vibration measurement data

In Figure 69, and other figures included in Appendix C, there is a vertical gray line in both RMS and Max results that indicates the exact location of the level crossing replacement. However, upon observing the results, it is apparent that the peak values do not fall exactly within the designated area. Therefore, to ensure adequate coverage of the studied area, a length of 20 meters (slightly larger than a wagon’s length, and more within the range of the level crossing) is considered. For the RMS, the average of the values is used. On the other hand, for the MAX, the maximum value within the 20-meter range is used.

To assess the impact of track modifications, the results of spring and fall 2020 (before the track modifications) were averaged together. Similarly, the results of spring and fall 2021, as well as spring 2022 (after the track modifications), were averaged together to evaluate the effect of the modifications on vibration levels.

Figure 18, Figure 19, and Figure 20 presented below provide a visual representation of the results obtained from comparing the processed vibration measurement data in this study with the historical track geometry data. The figures are no interpolation and illustrate the similarities and differences between the two datasets, allowing for a more comprehensive analysis and understanding of the effect of track modifications for three types of train, Sprinter, TRAXX and VIRM.

The vertical axis on each figure shows the difference in vibration reduction before and after track modifications for different distances to the track. The horizontal axis includes the octave bands. Due to the unavailability of historical track geometry data for 64 Hz, the comparison is limited to octave bands 4, 8,16 and 32 Hz. Based on Figure 18, Figure 19, and Figure 20 it is observed that there is a high level of agreement between the RMS values from the historical track geometry data and the existing vibration measurement data, at different distances from the track. This trend is consistent across all frequency octaves, with similar observations for all distances.

The Max values exhibit more significant changes across all octave bands when compared to the RMS values and analyzed vibration measurement data. For instance, at an octave band of 4 Hz, there is a slight reduction at further distances from the track, while a slight amplification is observed at closer proximity to the track for 4 Hz.

Furthermore, the RMS values provide more agreement with the closer proximity of the track at 16 Hz and 32 Hz, and it shows agreement with closer distances to the track for 4 Hz. At an octave of 8 Hz, it shows similar results for all distances from the track. As for track 2, the trend is relatively similar, but the data is more scattered. This is most probably caused by local soil and track conditions.

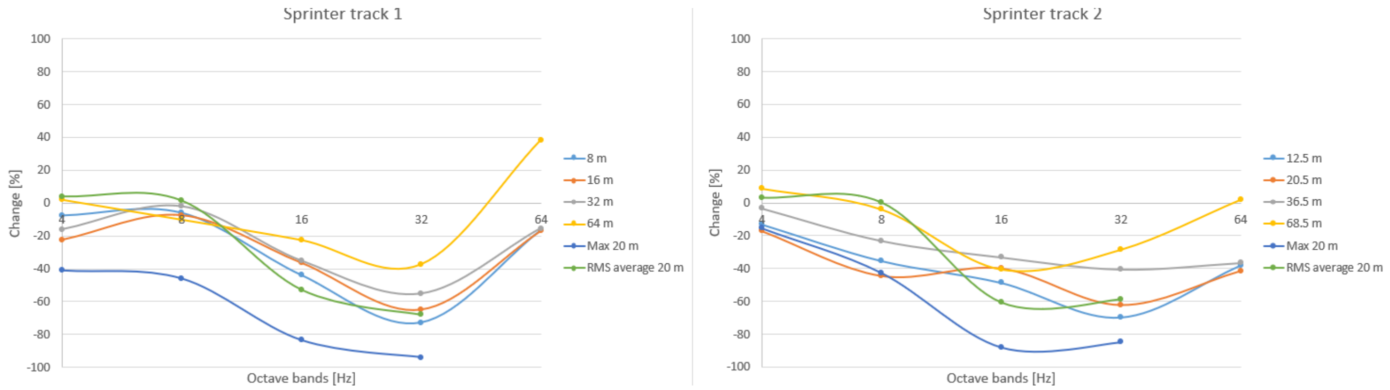

Figure 18 Comparison of the historical track geometry data with the processed vibration measurement data in this study for Sprinter trains - left and right figures concerning tracks 1 and 2 respectively.

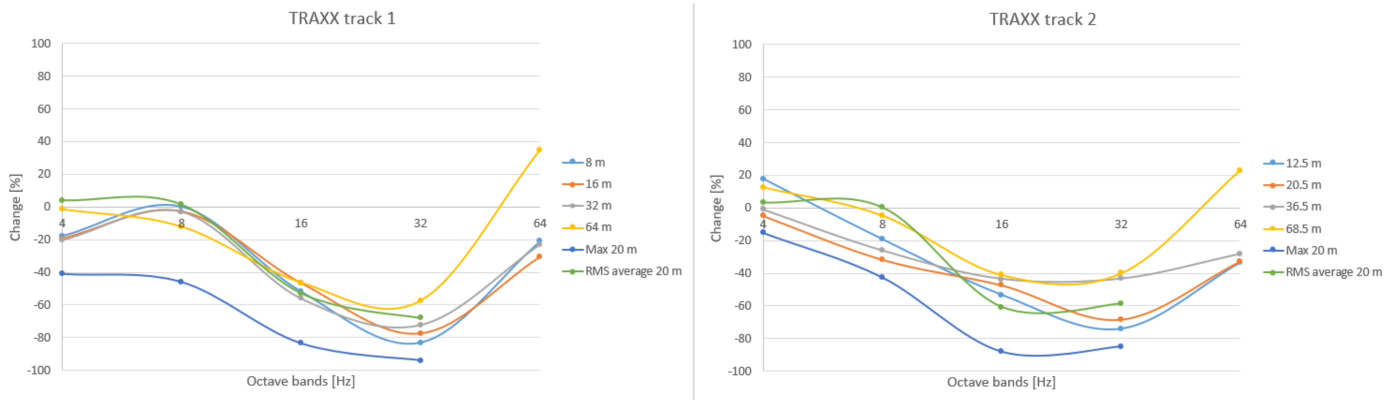

Figure 19 Comparison of the historical track geometry data with the processed vibration measurement data in this study for TRAXX trains - left and right figures concerning tracks 1 and 2 respectively.

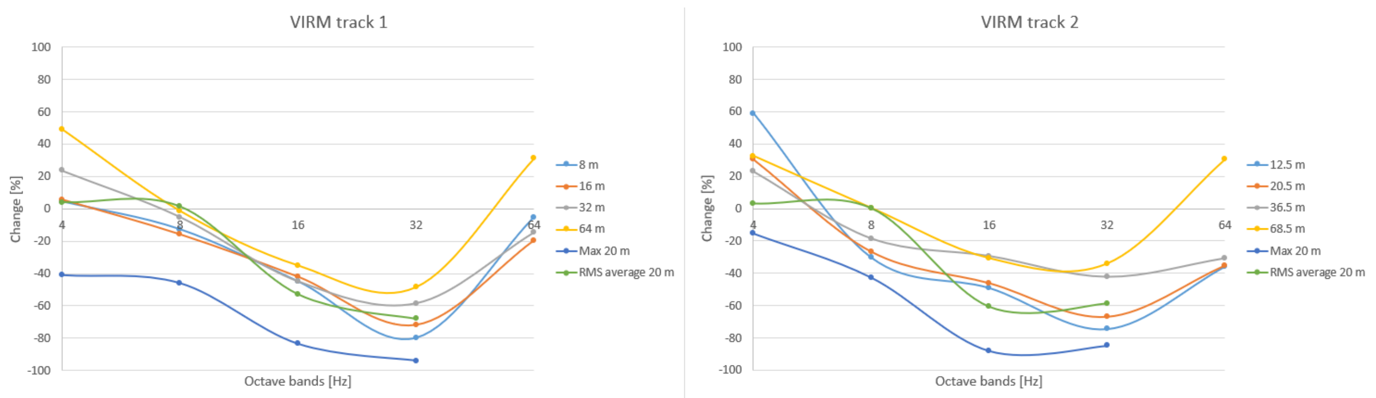

Figure 20 Comparison of the historical track geometry data with the processed vibration measurement data in this study for VIRM trains - left and right figures concerning tracks 1 and 2 respectively.

5.2 Correlations

In the previous chapter, the historical track geometry data was analyzed to evaluate the effect of the track modifications on the vibration levels. The results from spring and fall 2020 were averaged together, as were the results from spring and fall 2021 and spring 2022 with the track modifications.

To determine the correlation between the analyzed vibration measurement data and the historical track geometry data, the percentual change before and after modifications were used, as shown in Figure 18, Figure 19, and Figure 20. The max values per different frequency octave bands, including 4 Hz, 8 Hz, 16 Hz, and 32 Hz, were selected from the historical track geometry data. Then, the analyzed vibration measurement data was averaged per frequency octave band.

To account for the correlation between the historical track geometry data and the analyzed vibration measurement data, the above result was plotted against the distance from the track as shown in Figure 21, Figure 22 and Figure 23. Since the historical track geometry data was taken using the train test, the distance from the track is zero for these data. This allowed for finding the correlation between the historical track geometry data at a distance of zero from the track and the analyzed vibration measurement data at different distances from the track.

It was found that the correlation coefficient (R2) for all trains was above 0.33 for 16 Hz and 0.86 for 32 Hz octave bands. These results indicate that there is a correlation between the historical track geometry data taken at the source of vibration with the processed vibration measurement data at different distances from the track in this study, especially for the 32 Hz octave band.

In the figures below the R2 is shown for the 16 Hz and 32 Hz octave bands only.

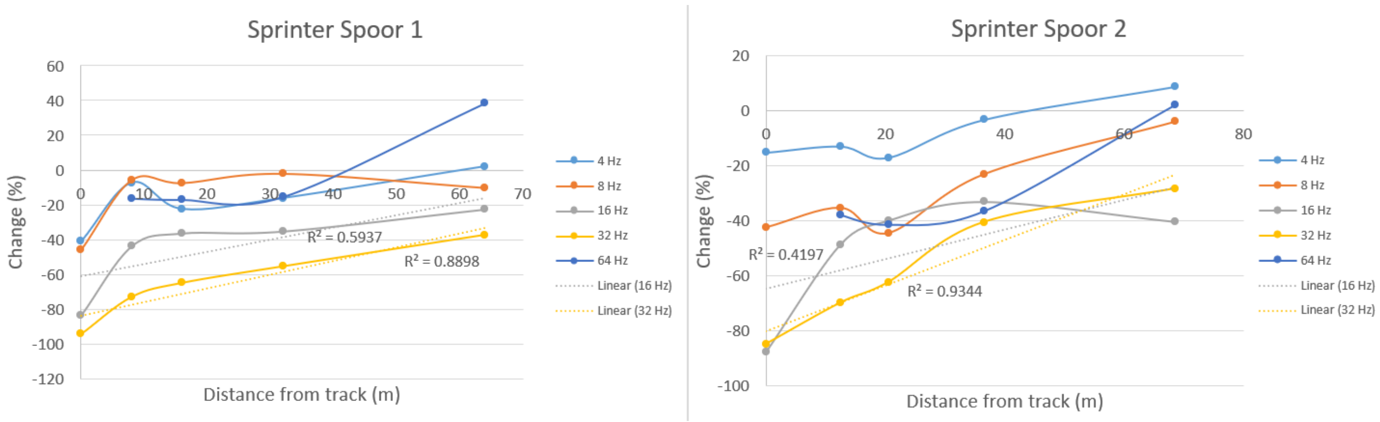

Figure 21 Correlation between the historical track geometry data with the processed vibration measurement data in this study for Sprinter trains - left and right figures concerning tracks 1 and 2 respectively.

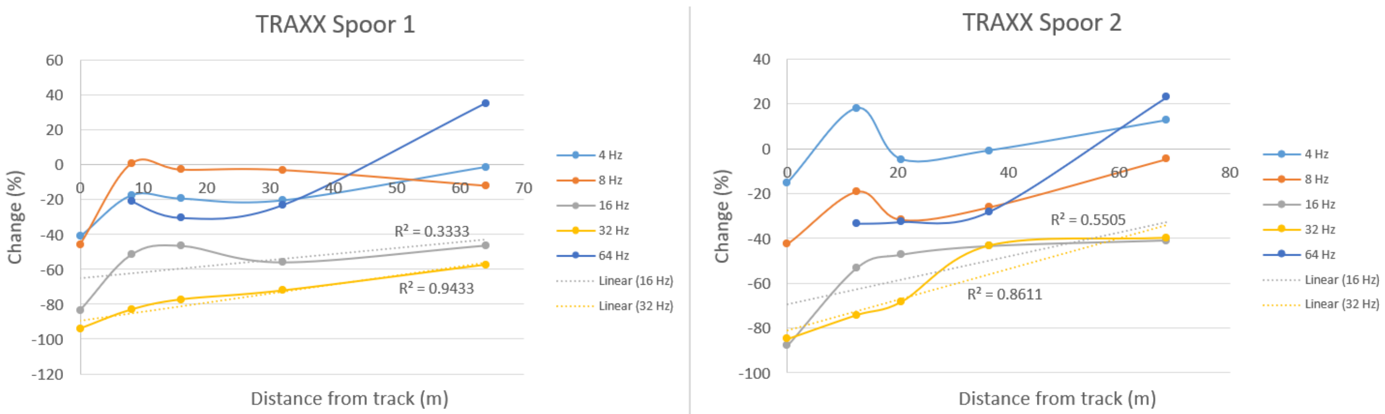

Figure 22 Correlation between the historical track geometry data with the processed vibration measurement data in this study for TRAXX trains - left and right figures concerning tracks 1 and 2 respectively.

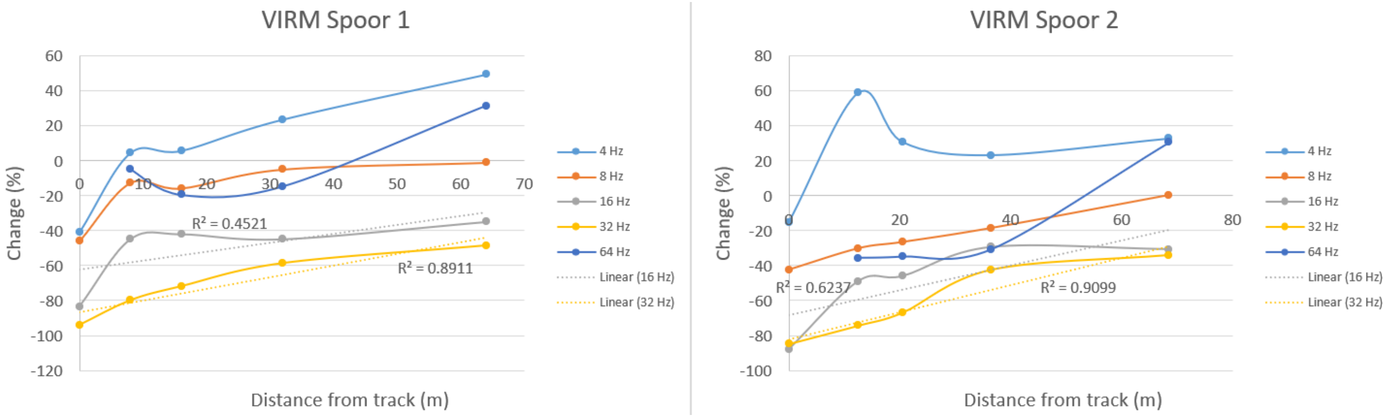

Figure 23 Correlation between the historical track geometry data with the processed vibration measurement data in this study for VIRM trains - left and right figures concerning tracks 1 and 2 respectively.

6 Conclusions and recommendations

The present study focused on the correlation between existing vibration measurements [3] and the RVQ indicator data near the track. For this purpose, vibration measurement data collected before and after track modifications at the Dorst location were analyzed and assessed. Based on this study, the following conclusions can be drawn:

- There is a significant level of agreement between the RMS values obtained from the historical track geometry data and the existing vibration measurement data at various distances from the track. This trend is consistent across all frequency octaves, with similar observations for all distances.

- It was found that the correlation coefficient (R2) for all trains was above 0.33 for 16 Hz and 0.86 for 32 Hz octave bands. This indicates a rather good correlation between the Max values from historical track geometry data collected at the source of the vibration and the processed vibration measurement data at different distances from the track in this study. This is especially the case for the 32 Hz octave band.

The following recommendations can be made for further analyses:

- This assessment was carried out using short-term vibration measurement data only due to unavailability of long-term vibration measurement data. Long-term vibration measurement data can be used to validate and understand the deviations or abnormalities in the short-term vibration measurement data. By filtering out possible deviations and abnormalities a better correlation could be found.

- It is recommended to perform a similar analysis for other locations. This will ensure that the RVQ indicator using historical track geometry data provide accurate prediction of vibration levels both before and after track modifications. This will allow to better understand the parameters influencing the vibrations and their respective uncertainties. These parameters, among others, include dominant frequency, distance from track, type and speed of trains, presence of insulated joints, seasonal effect, and maintenance quality.

This study has identified both potentials and limitations. One limitation is that at the Dorst location, not only the level crossing was replaced, but also some insulated joints were renewed. There were also some other changes in the surroundings such as the placement of new metal fences. These changes make it difficult to determine the contribution of each change to the reduction or increase of vibrations. Therefore, it is recommended to conduct similar research at locations where only track maintenance are performed.

From the current study it is unclear how the three factors mentioned below influence the vibrations:

- The presence of a complex geometry for the second track.
- The influence of another type of level crossing.
- The influence of maintenance.

Further validation is therefore needed to confirm whether the results are generic and can be applied in different areas. Additionally, advanced numerical simulations such as 2D or 3D FEM can be used to better understand the impact of soil, including soft layers like peat or clay, and track conditions like geometry on the generated vibration. This research will help optimize the maintenance regime that is applied.

7 References

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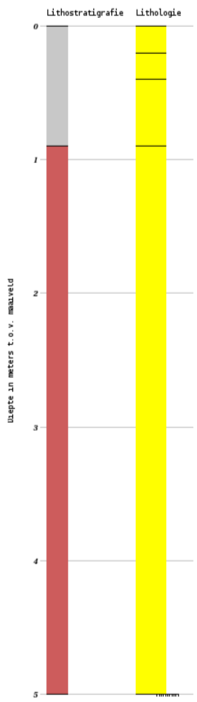
9. SBRCURnet: Building Research Foundation (SBR) - Vibration Directive (B) - Annoyance to people in buildings, measurement and assessment (in Dutch: Hinder voor personen in gebouwen meet- en beoordelingsrichtlijnen). Deel B (2003).

Appendix A: Available site investigation data

Dorst location

Boormonsterprofiel



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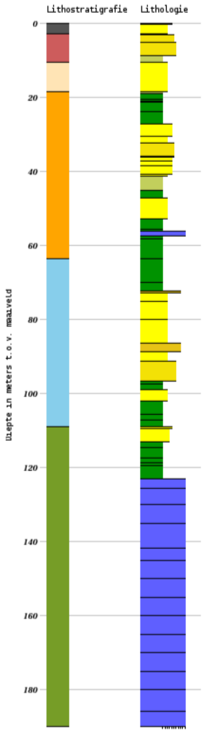
Maaiveld:	7.59 m t.o.v. NAP
Beschikbare informatie:	Digitale opnamegegevens
Beschrijfmethode:	Onbekend
Kwaliteit interpretatie:	Niet gevalideerd in ondergrondmodel

Lithostratigrafie
- AAOP
- ST

Lithologie
- Zand fijne categorie

Boormonsterprofiel



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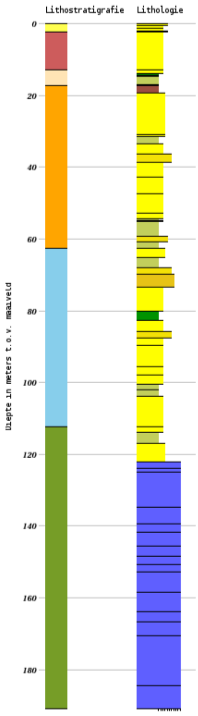
Beschikbare informatie:	Digitale opnamegegevens
Beschrijfmethode:	Onbekend
Kwaliteit interpretatie:	Niet gevalideerd in ondergrondmodel

Lithostratigrafie
- NN
- ST
- SY
- WA
- MS
- OO

Lithologie
- Leem
- Klei
- Zand fijne categorie
- Zand midden categorie
- Zand grove categorie
- Schelpen

Boormonsterprofiel



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Maaiveld:	7.20 m t.o.v. NAP
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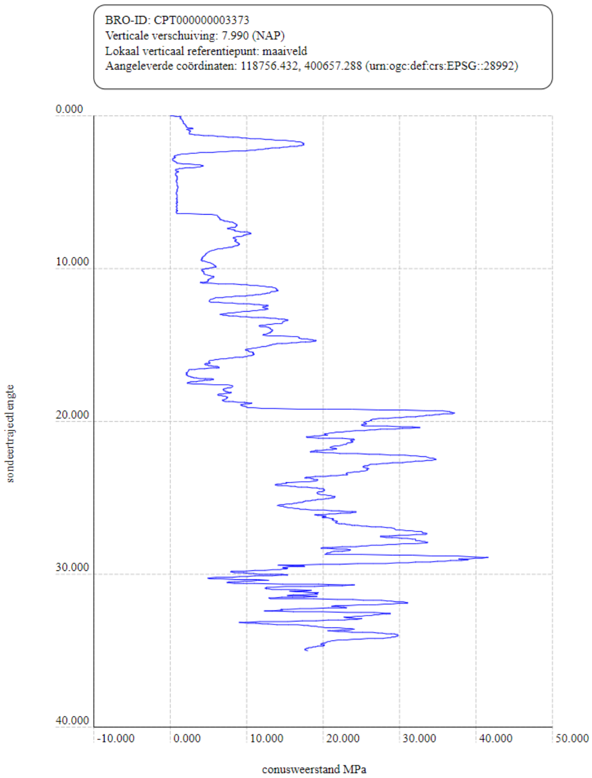
Beschrijfmethode:	Onbekend
Kwaliteit interpretatie:	Niet gevalideerd in ondergrondmodel

Lithostratigrafie
- BXWI
- ST
- SY
- WA
- MS
- OO

Lithologie
- Leem
- Klei
- Zand fijne categorie
- Zand midden categorie
- Zand grove categorie
- Schelpen
- Veen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Lokaal verticaal referentiepunt: maaiveld
Aangeleverde coördinaten: 118756.432, 400657.288 (urn:ogc:def:crs:EPSG::28992)
0.000
10.000
20.000
30.000
40.000
sondeertrajectlengte
-10.000
0.000
10.000
20.000
30.000
40.000
50.000
conusweerstand MPa

Appendix B: Dorst – Detailed results

Train type: Sprinter

The detailed results of different vibration measurement data sets before and after track modifications for Sprinter trains are shown below.

Measurement data before track modifications

Measurement data set 1

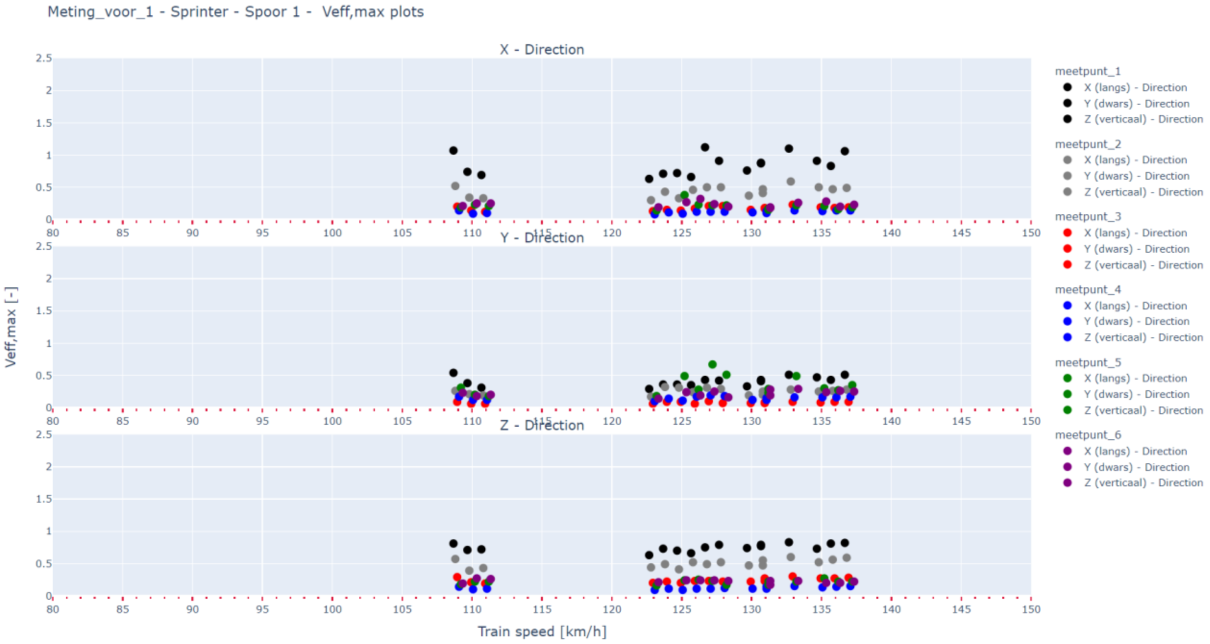

Figure 24 Vibration measurement data set 1 (Veff, max vs. train speed) before track modification - Sprinter trains - Track 1

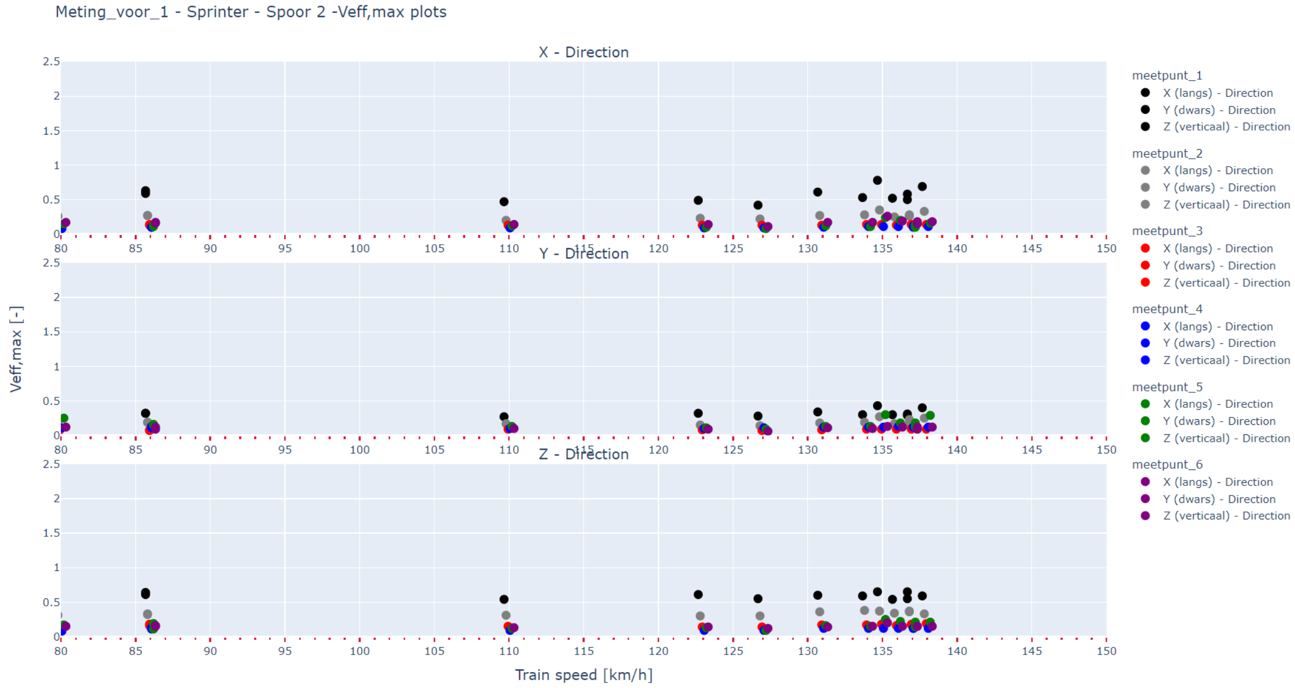

Figure 25 Vibration measurement data set 1 (Veff, max vs. train speed) before track modification - Sprinter trains - Track 2

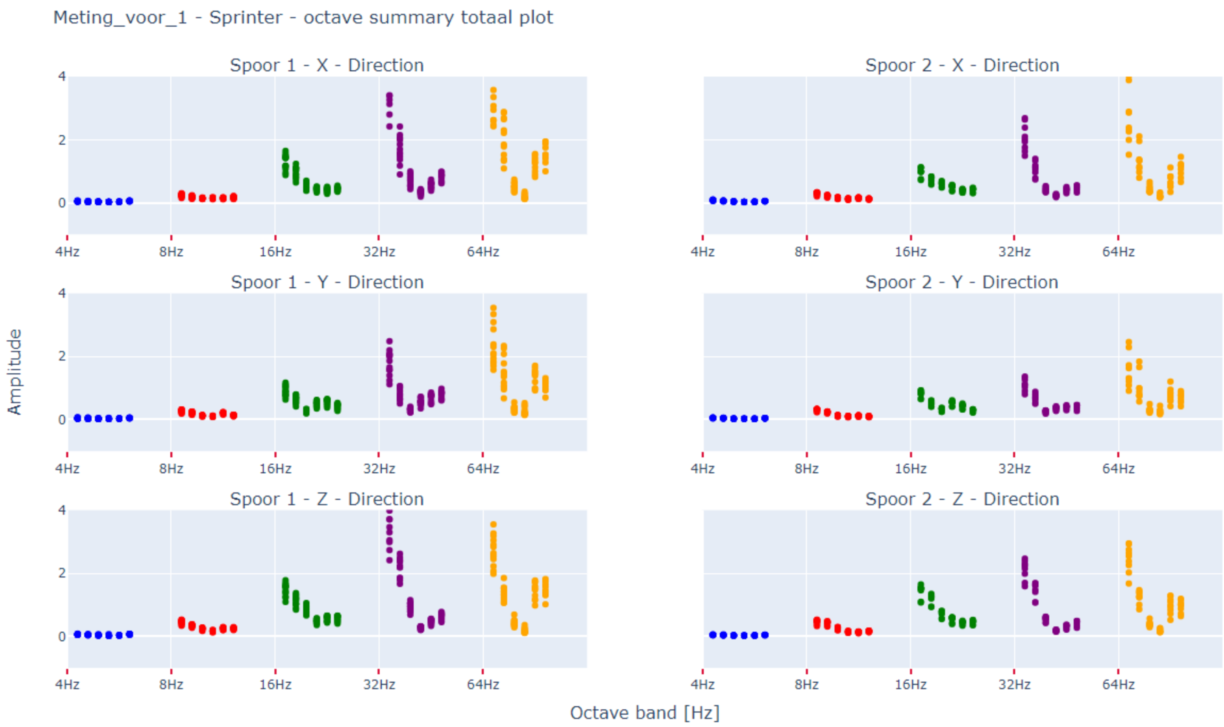

Figure 26 Vibration measurement data set 1 (Amplitude vs. octave bands) before track modification - Sprinter trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measurement data set 2

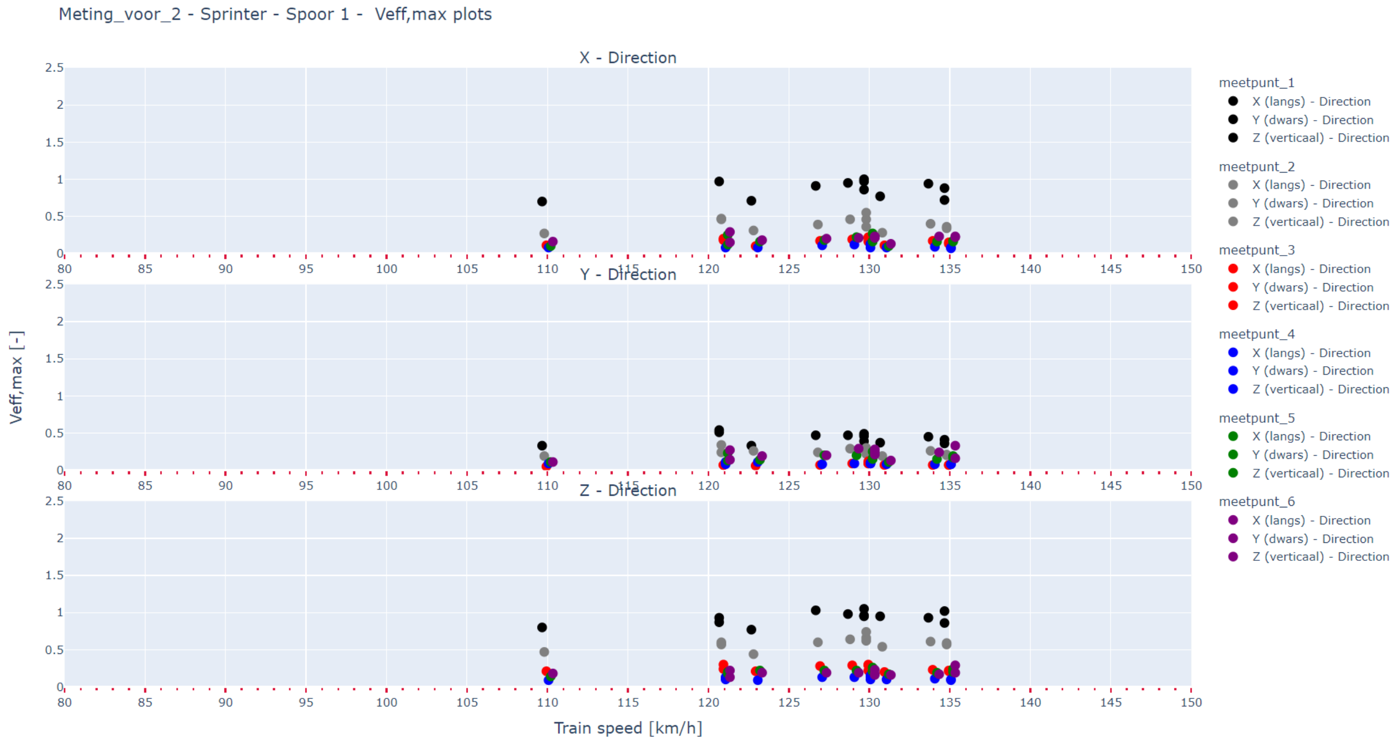

Figure 27 Vibration measurement data set 2 (Veff, max vs. train speed) before track modification - Sprinter trains - Track 1

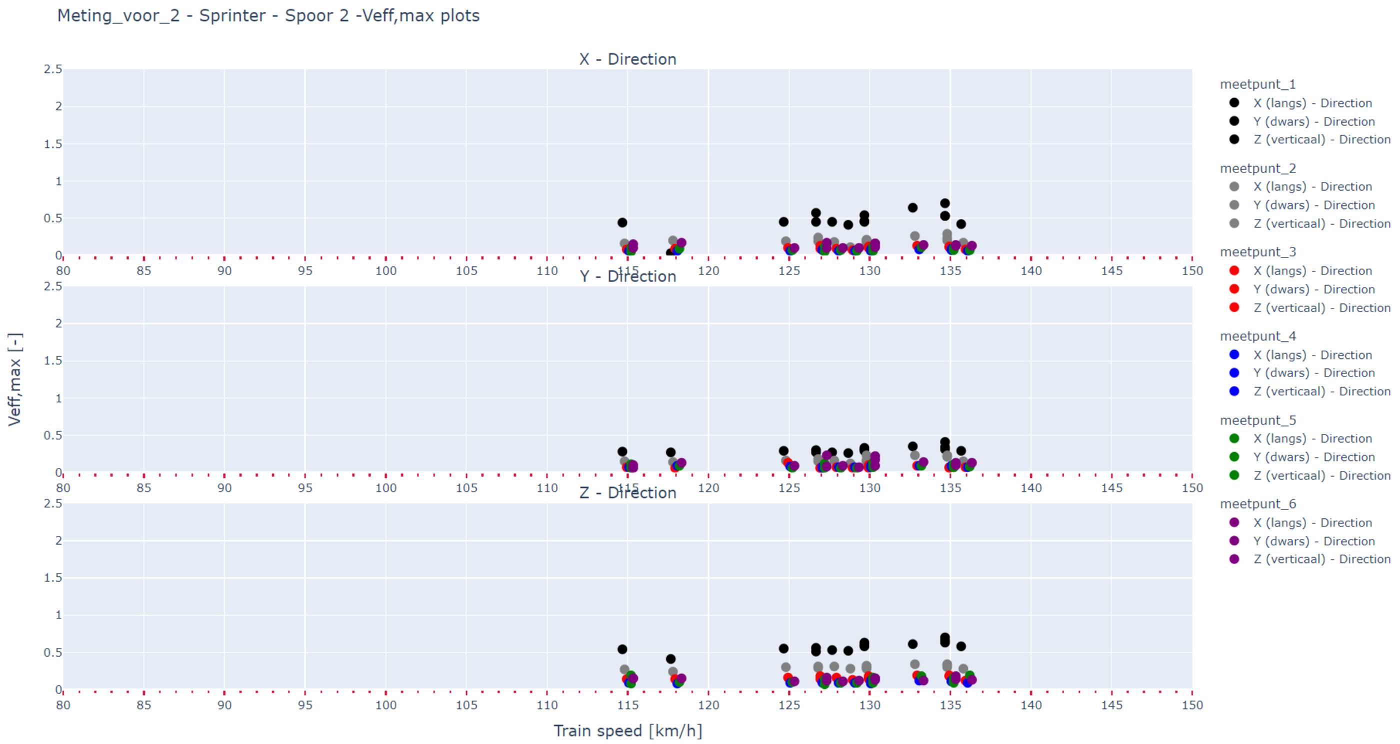

Figure 28 Vibration measurement data set 2 (Veff, max vs. train speed) before track modification - Sprinter trains - Track 2

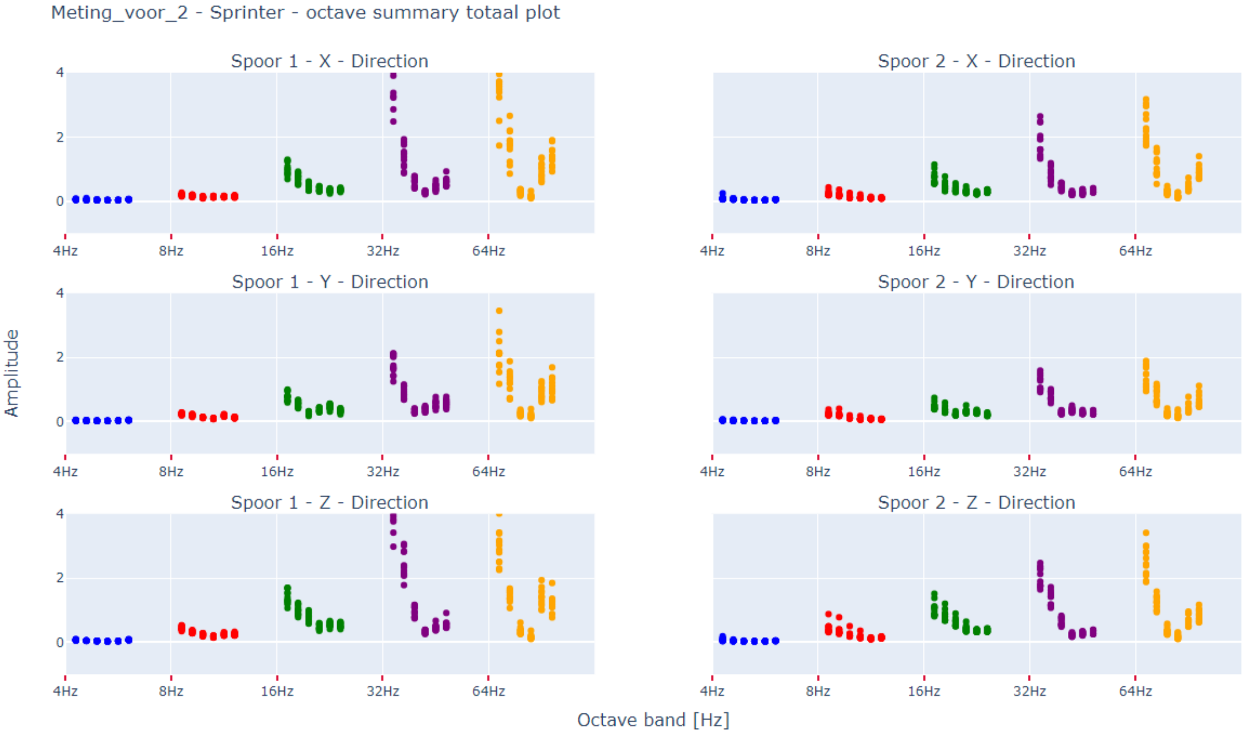

Figure 29 Vibration measurement data set 2 (Amplitude vs. octave bands) before track modification - Sprinter trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measurement data after track modifications

Measured directly after track modifications

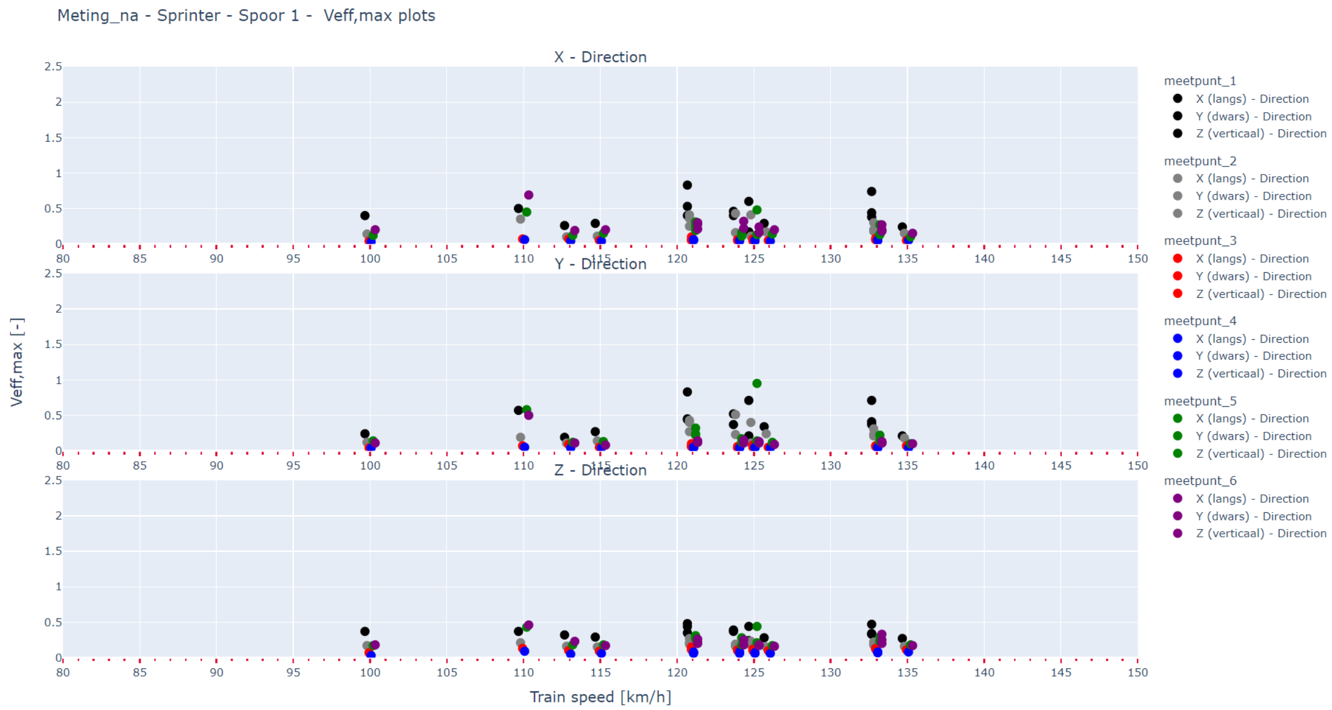

Figure 30 Vibration measurement data set (Veff, max vs. train speed) directly after track modification - Sprinter trains - Track 1

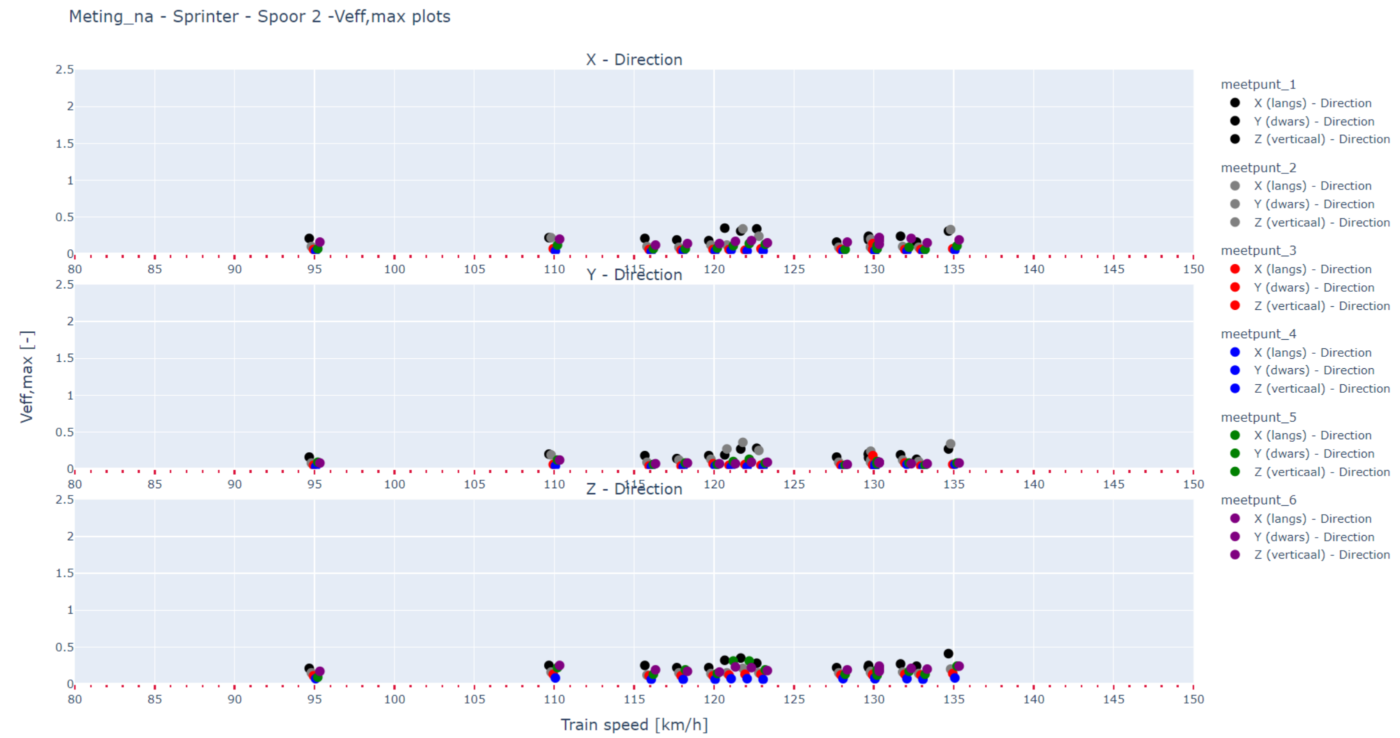

Figure 31 Vibration measurement data set (Veff, max vs. train speed) directly after track modification - Sprinter trains - Track 2

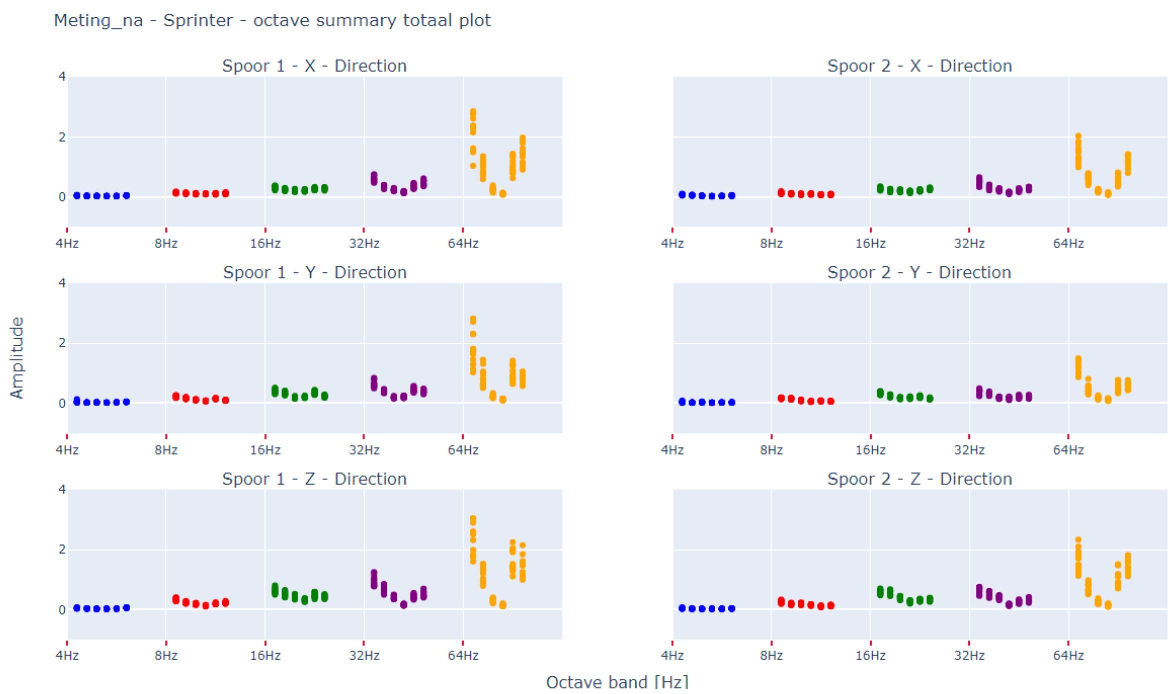

Figure 32 Vibration measurement data set (Amplitude vs. octave bands) directly after track modification - Sprinter trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measured 6 months after track modifications

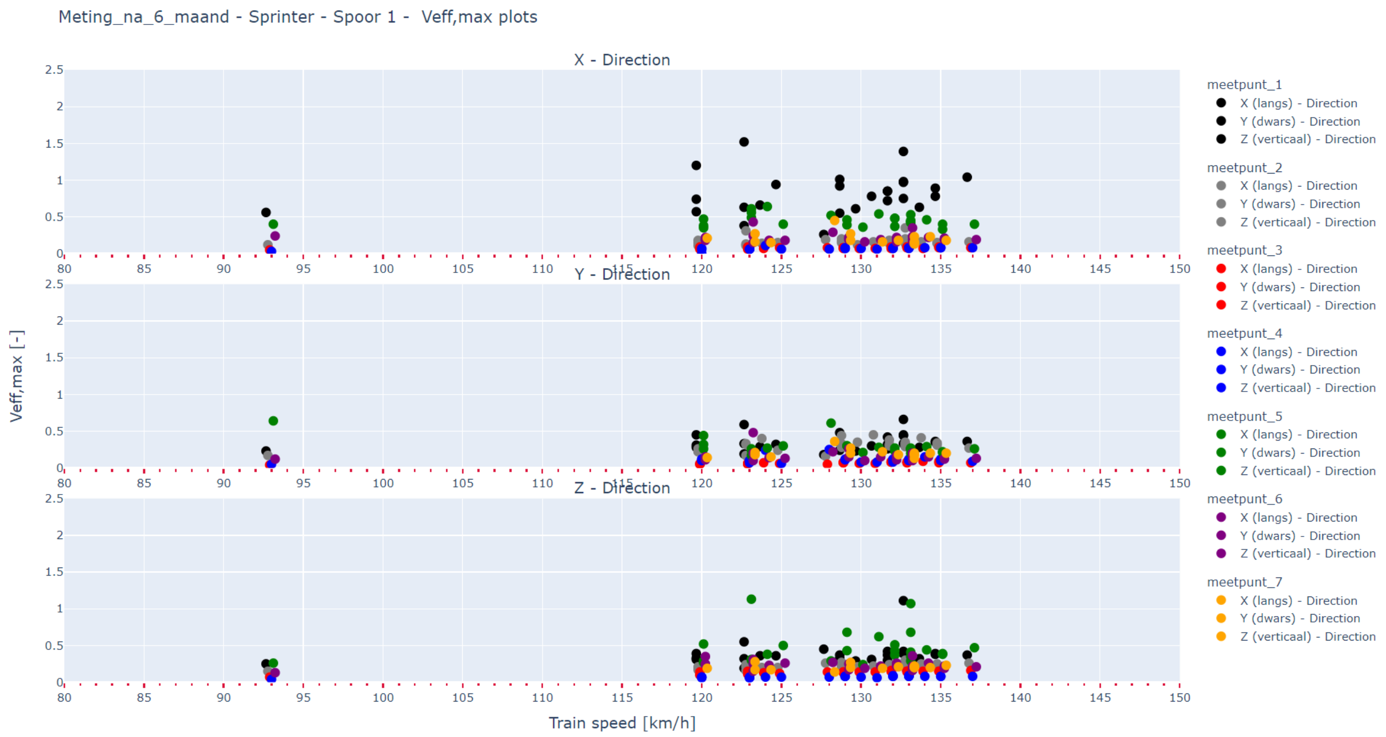

Figure 33 Vibration measurement data set (Veff, max vs. train speed) 6 months after track modification - Sprinter trains - Track 1

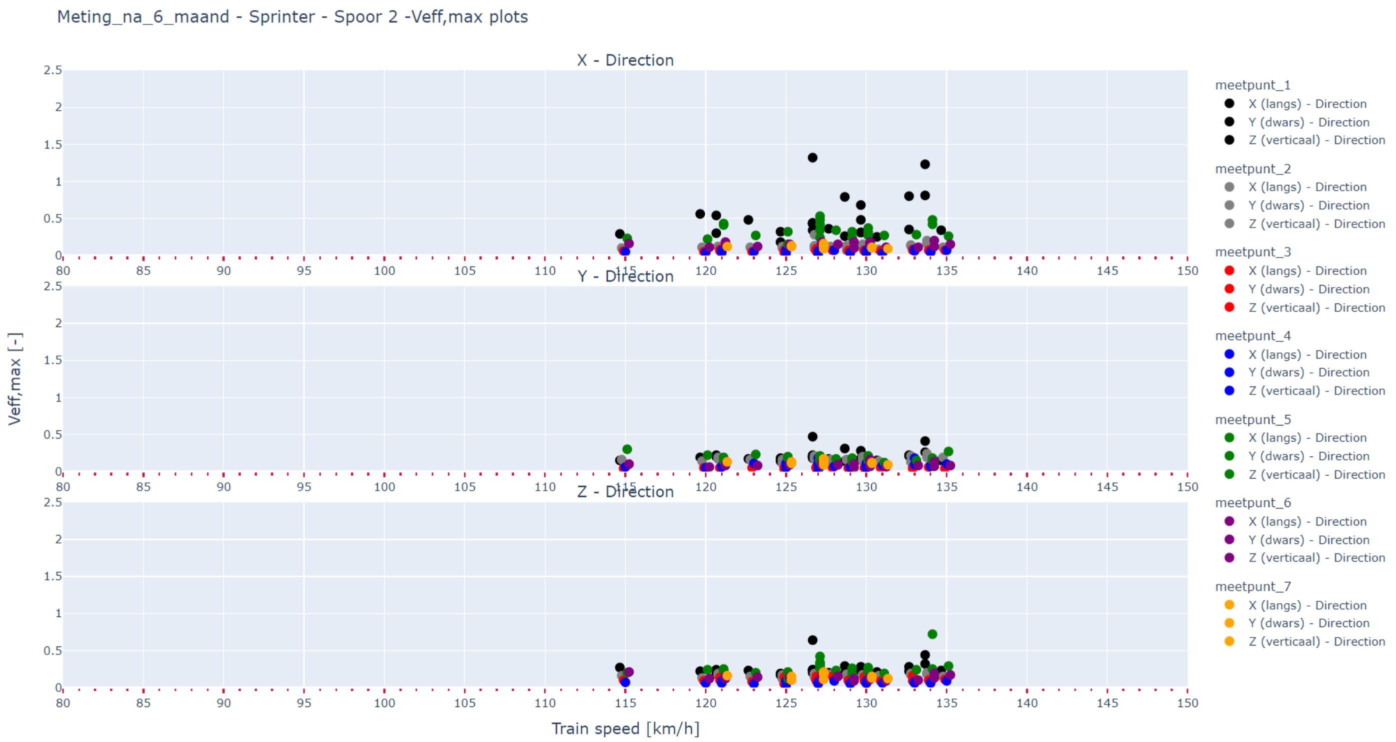

Figure 34 Vibration measurement data set (Veff, max vs. train speed) 6 months after track modification - Sprinter trains - Track 2

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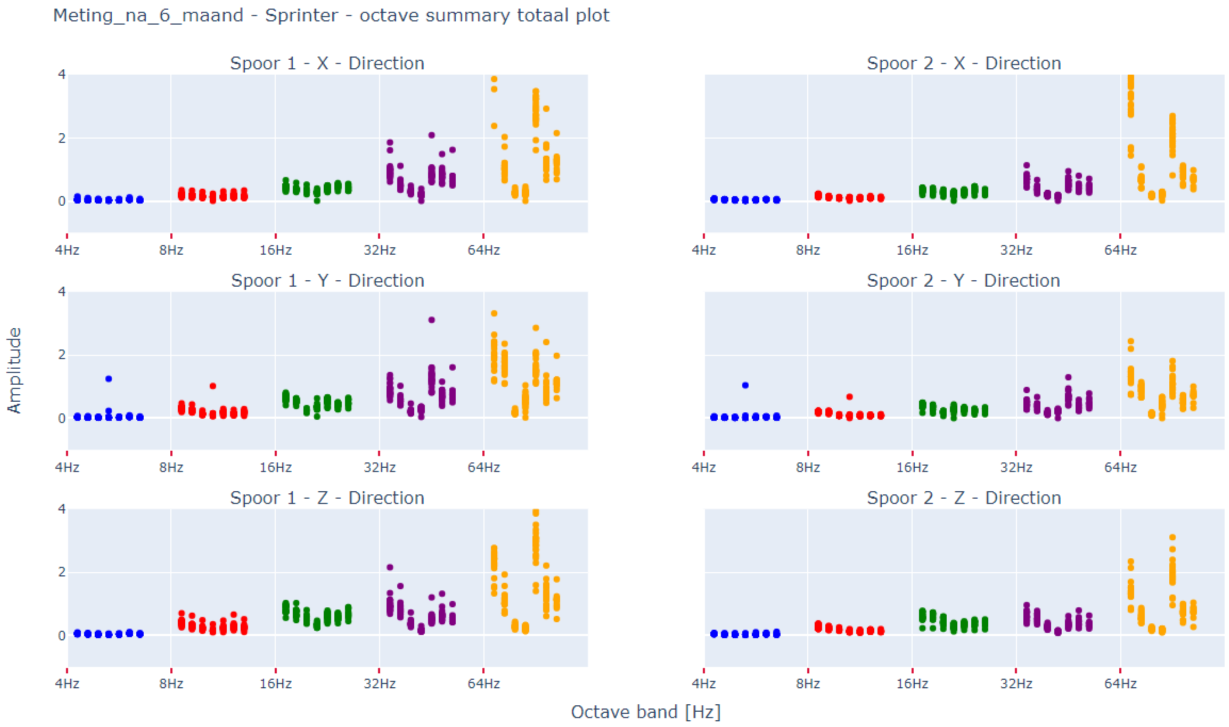

Figure 35 Vibration measurement data set (Amplitude vs. octave bands) 6 months after track modification - Sprinter trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measured 12 months after track modifications

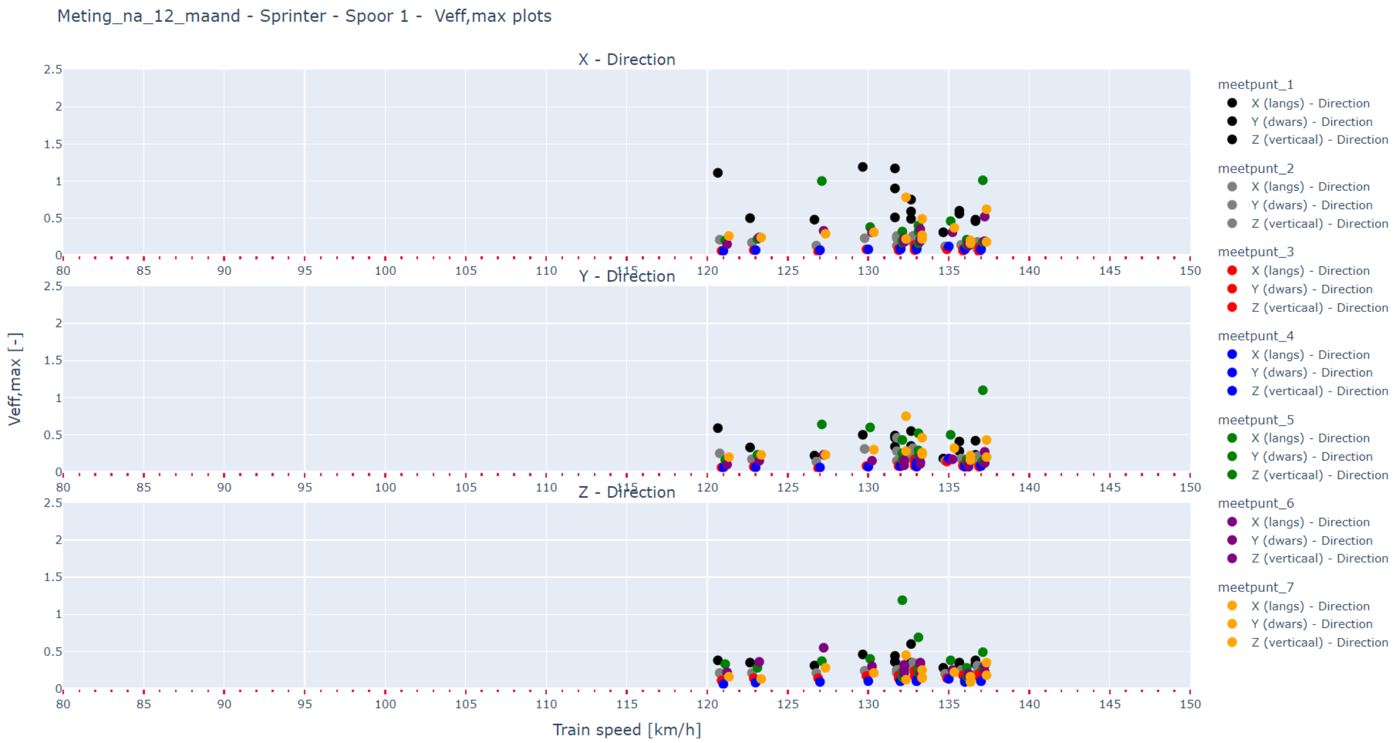

Figure 36 Vibration measurement data set (Veff, max vs. train speed) 12 months after track modification - Sprinter trains - Track 1

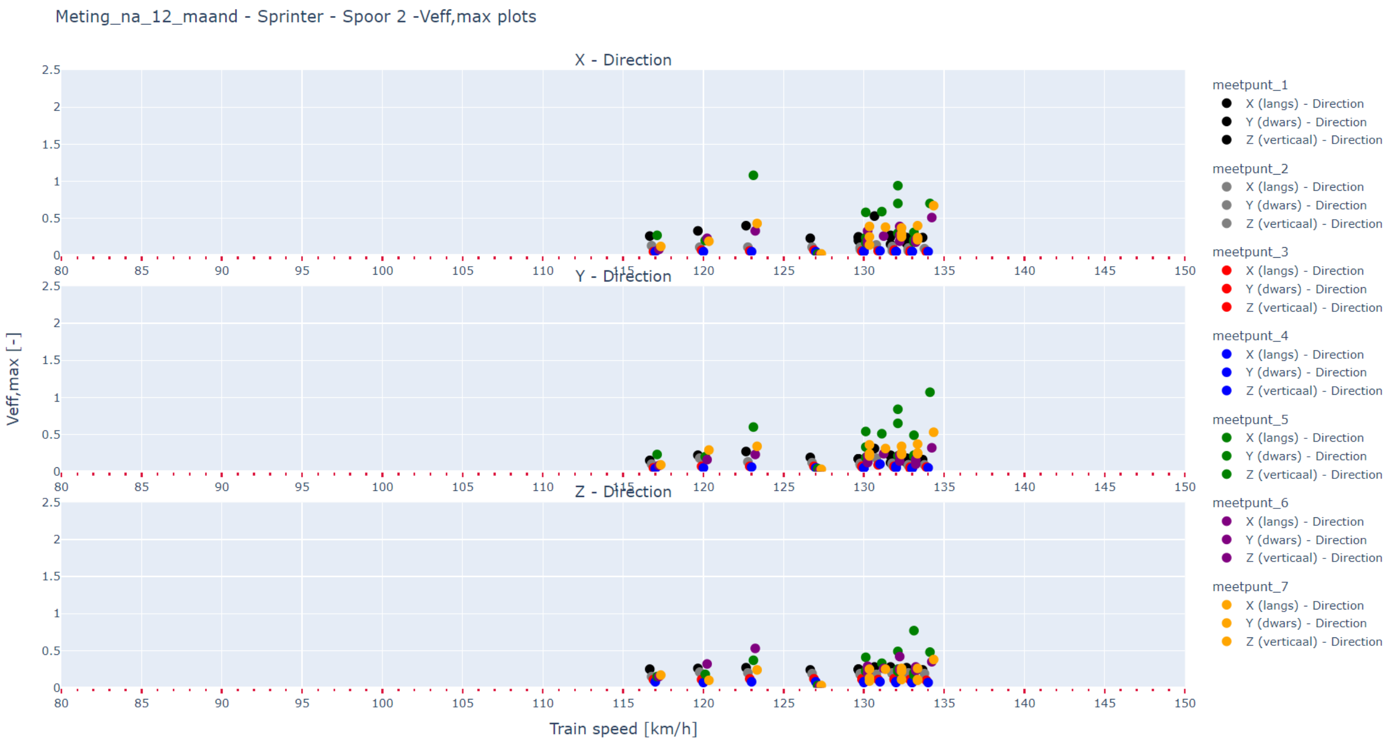

Figure 37 Vibration measurement data set (Veff, max vs. train speed) 12 months after track modification - Sprinter trains - Track 2

Figure 38 Vibration measurement data set (Amplitude vs. octave bands) 12 months after track modification - Sprinter trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Train type: TRAXX

The detailed results of different vibration measurement data sets before and after track modifications for TRAXX trains are shown below.

Measurement data before track modifications

Measurement data set 1

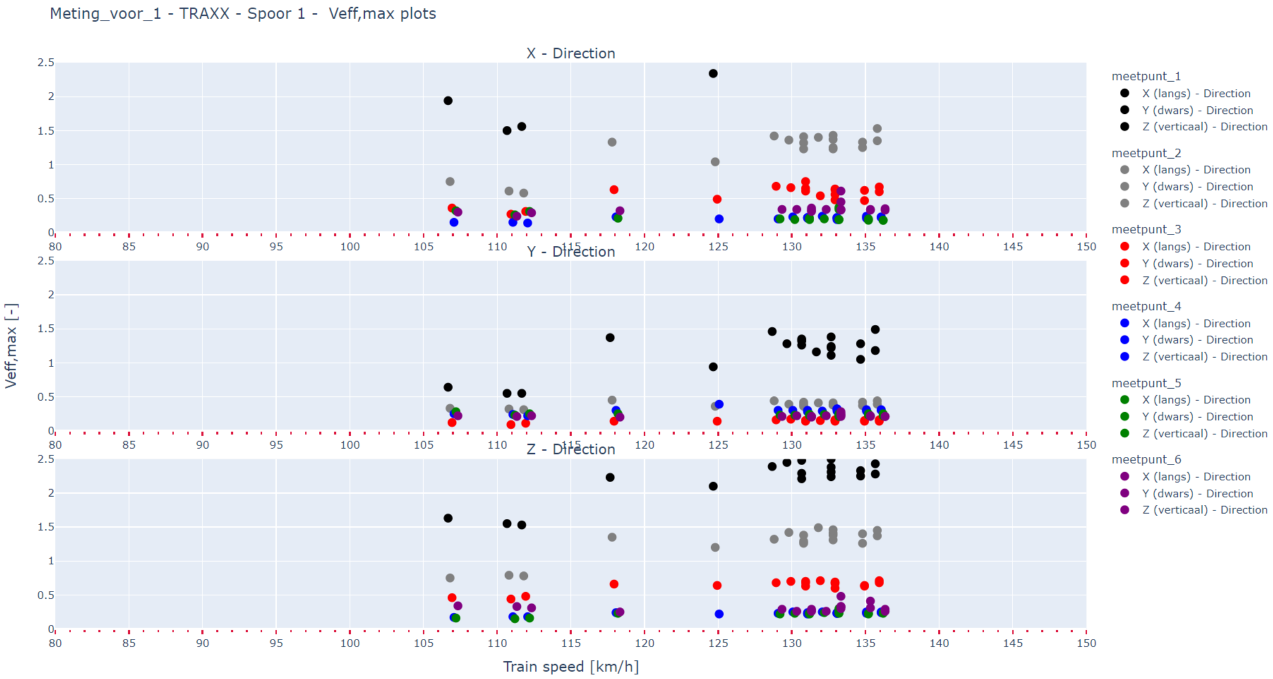

Figure 39 Vibration measurement data set 1 (Veff, max vs. train speed) before track modification - TRAXX trains - Track 1

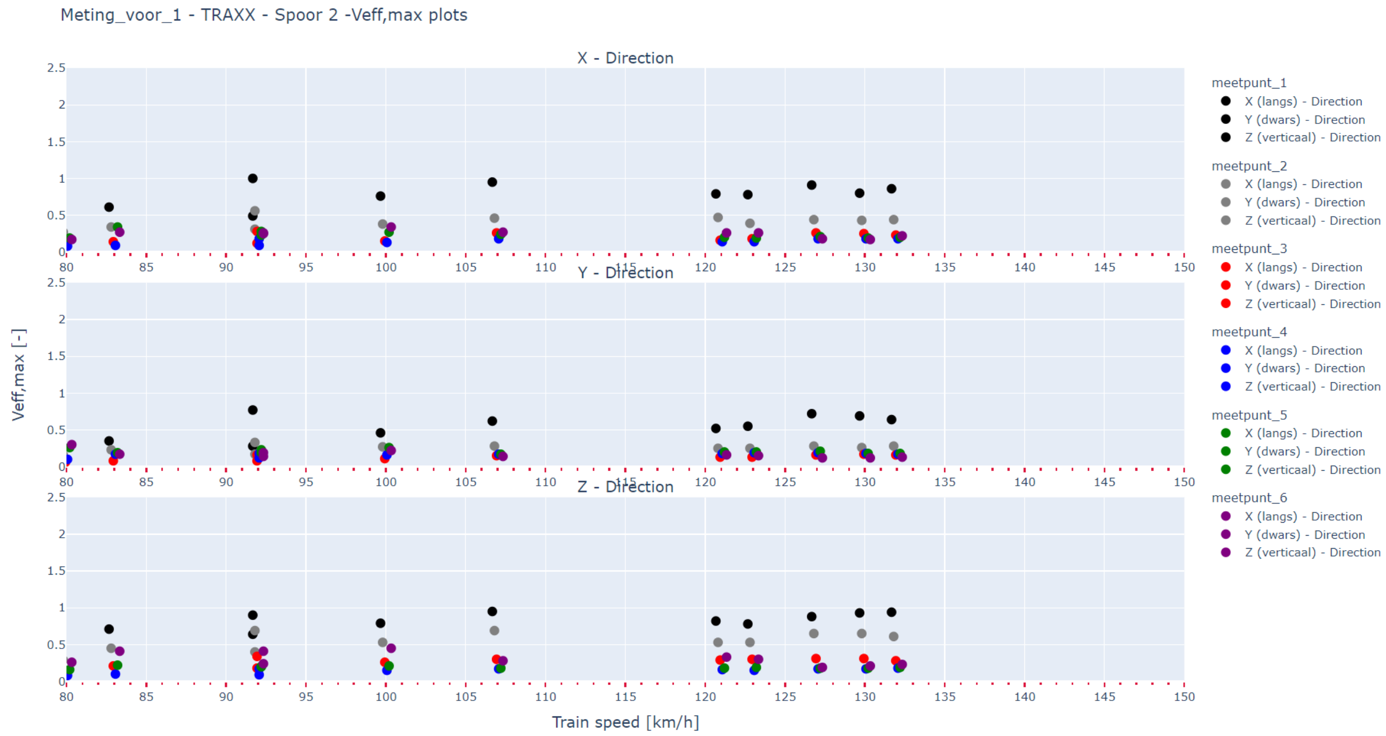

Figure 40 Vibration measurement data set 1 (Veff, max vs. train speed) before track modification - TRAXX trains - Track 2

Figure 41 Vibration measurement data set 1 (Amplitude vs. octave bands) before track modification - TRAXX trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measurement data set 2

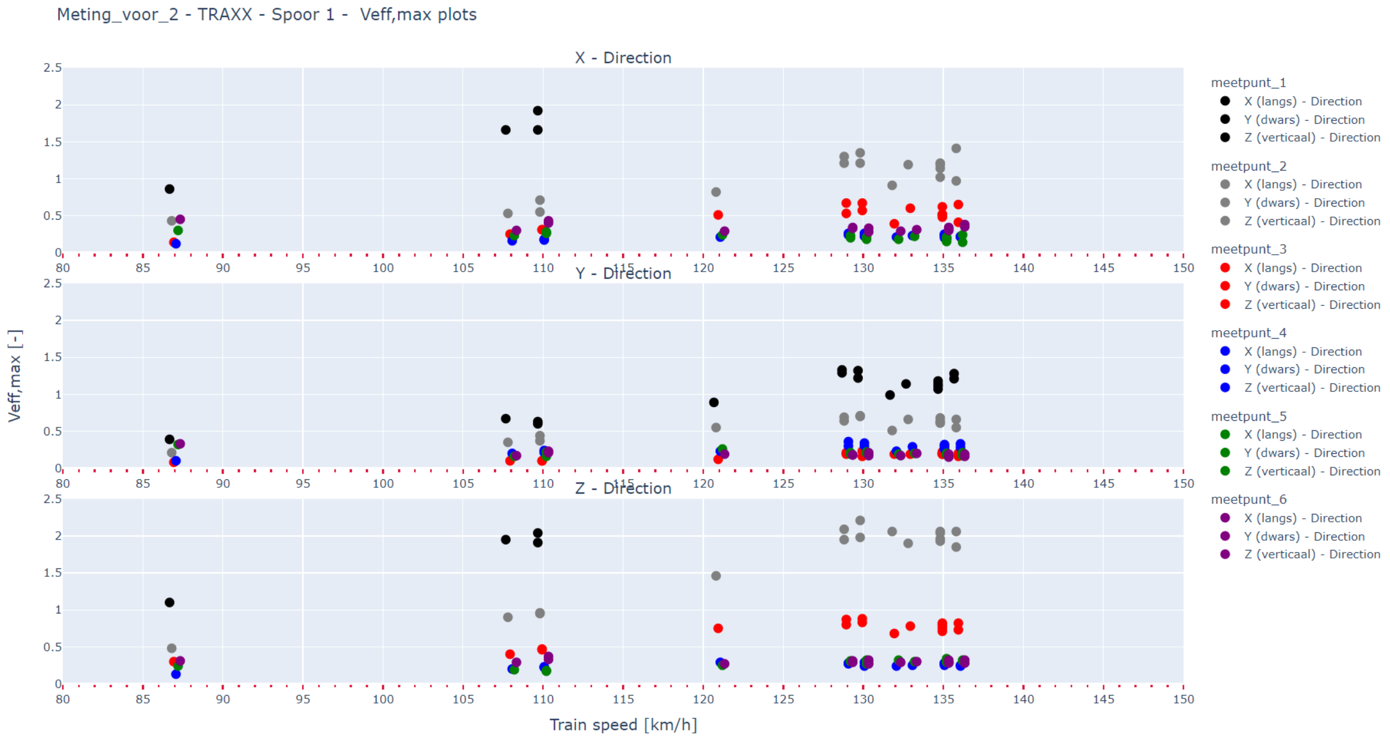

Figure 42 Vibration measurement data set 2 (Veff, max vs. train speed) before track modification - TRAXX trains - Track 1

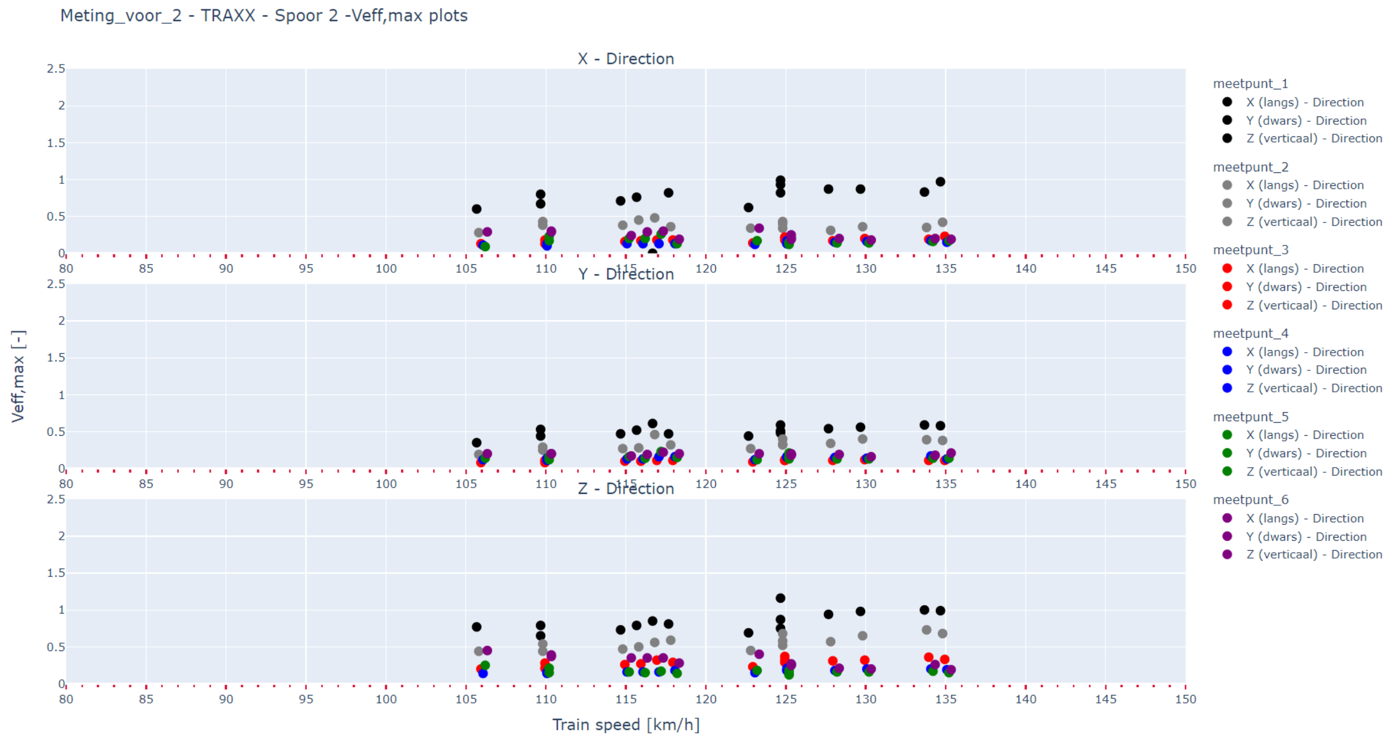

Figure 43 Vibration measurement data set 2 (Veff, max vs. train speed) before track modification - TRAXX trains - Track 2

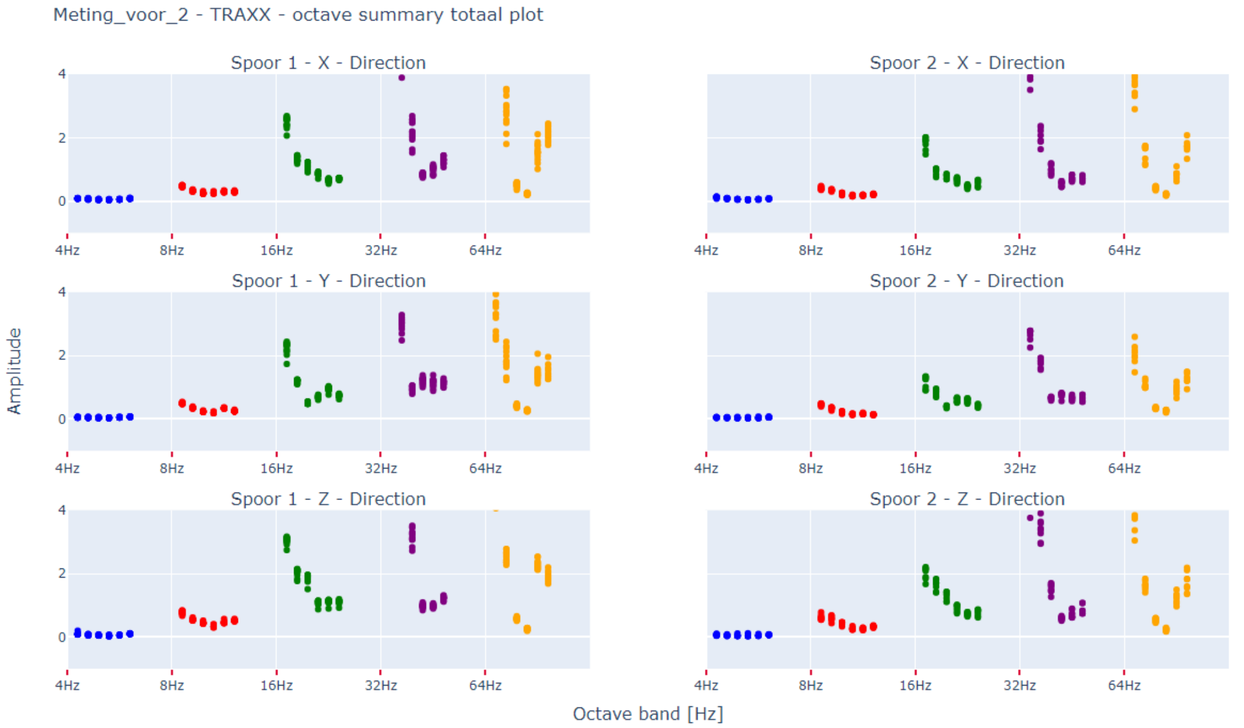

Figure 44 Vibration measurement data set 2 (Amplitude vs. octave bands) before track modification - TRAXX trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measurement data after track modifications

Measured directly after track modifications

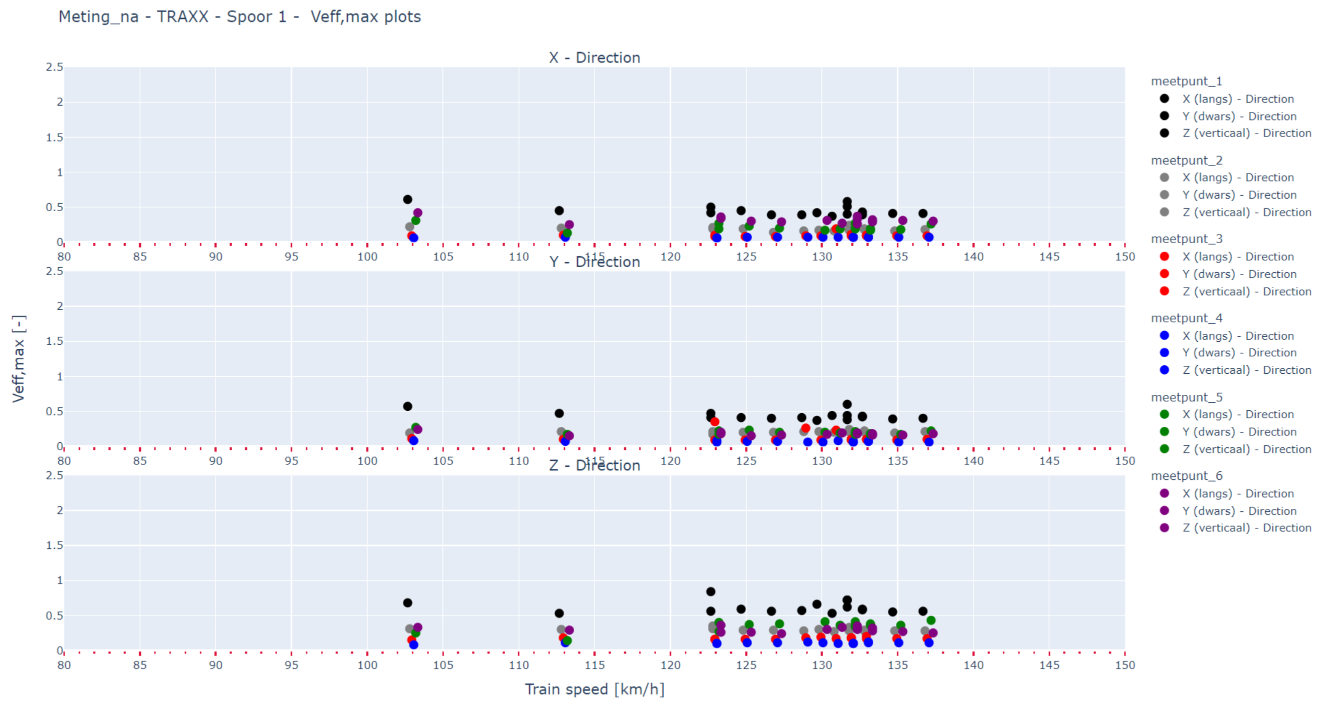

Figure 45 Vibration measurement data set (Veff, max vs. train speed) directly after track modification - TRAXX trains - Track 1

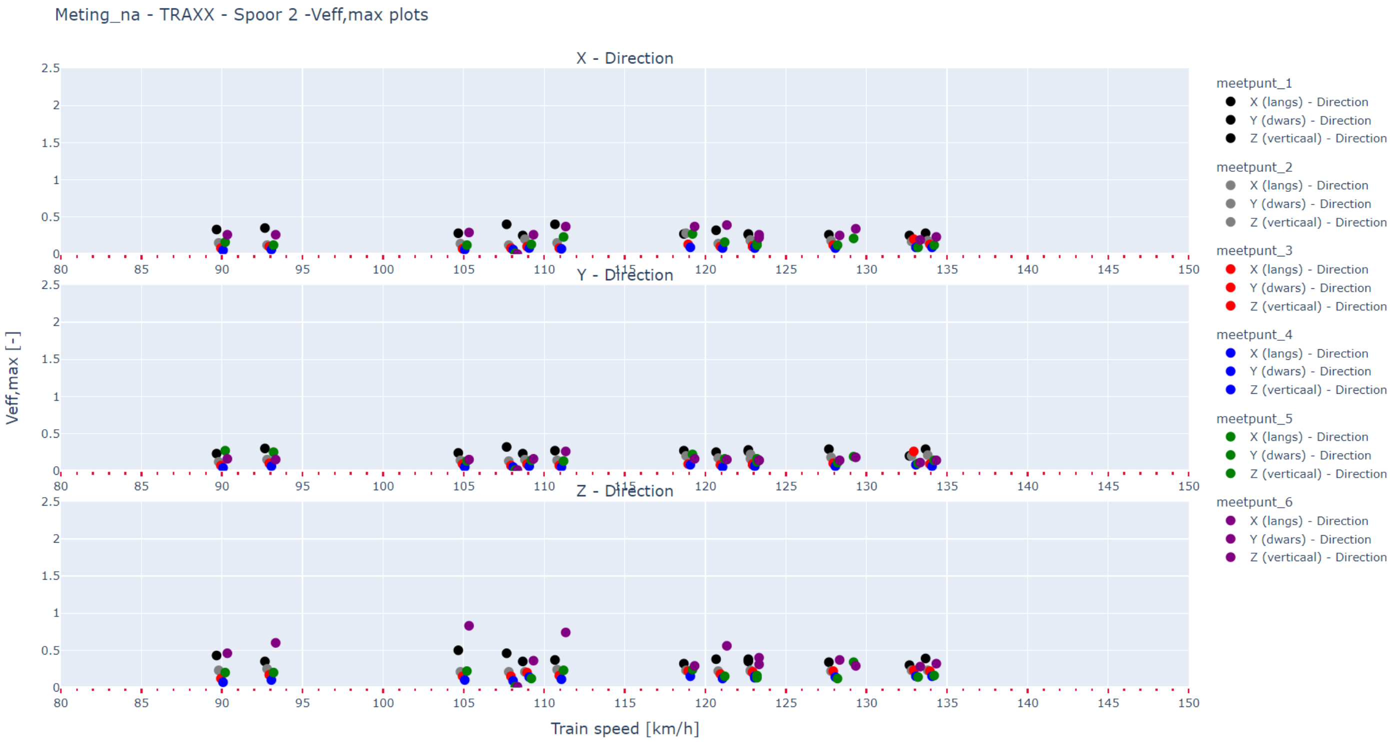

Figure 46 Vibration measurement data set (Veff, max vs. train speed) directly after track modification - TRAXX trains - Track 2

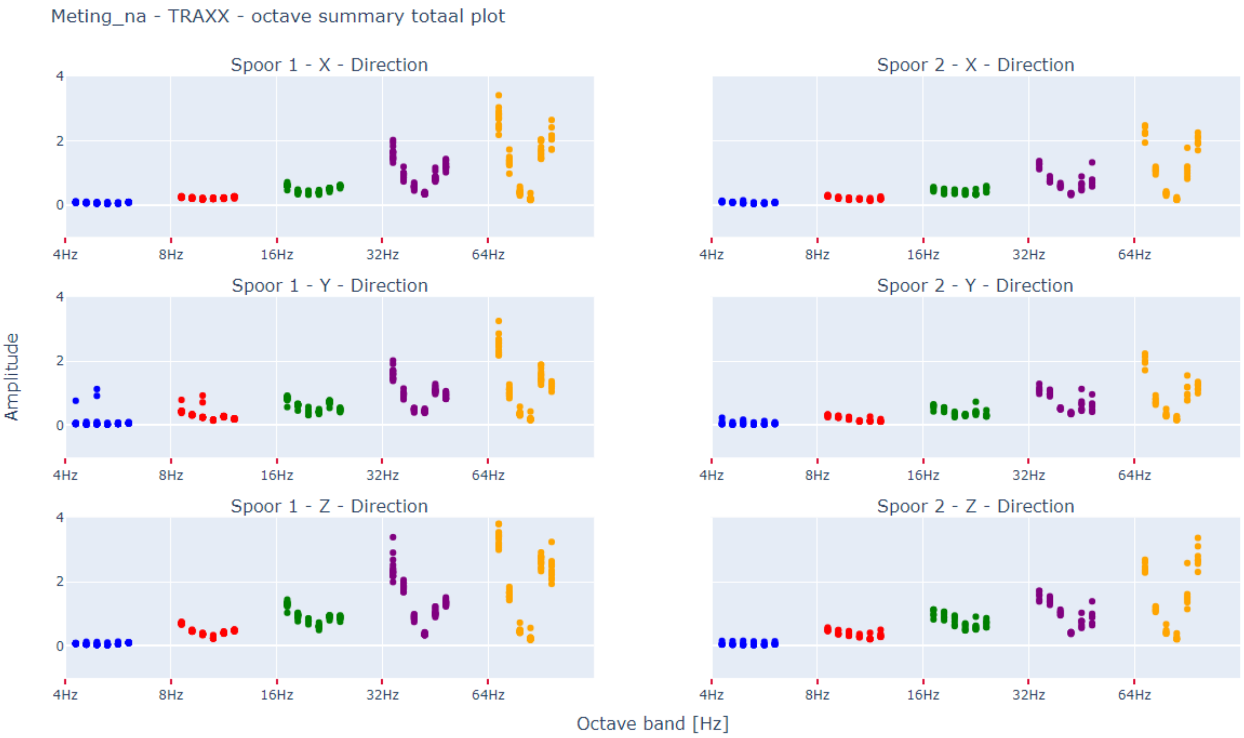

Figure 47 Vibration measurement data set (Amplitude vs. octave bands) directly after track modification - TRAXX trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measured 6 months after track modifications

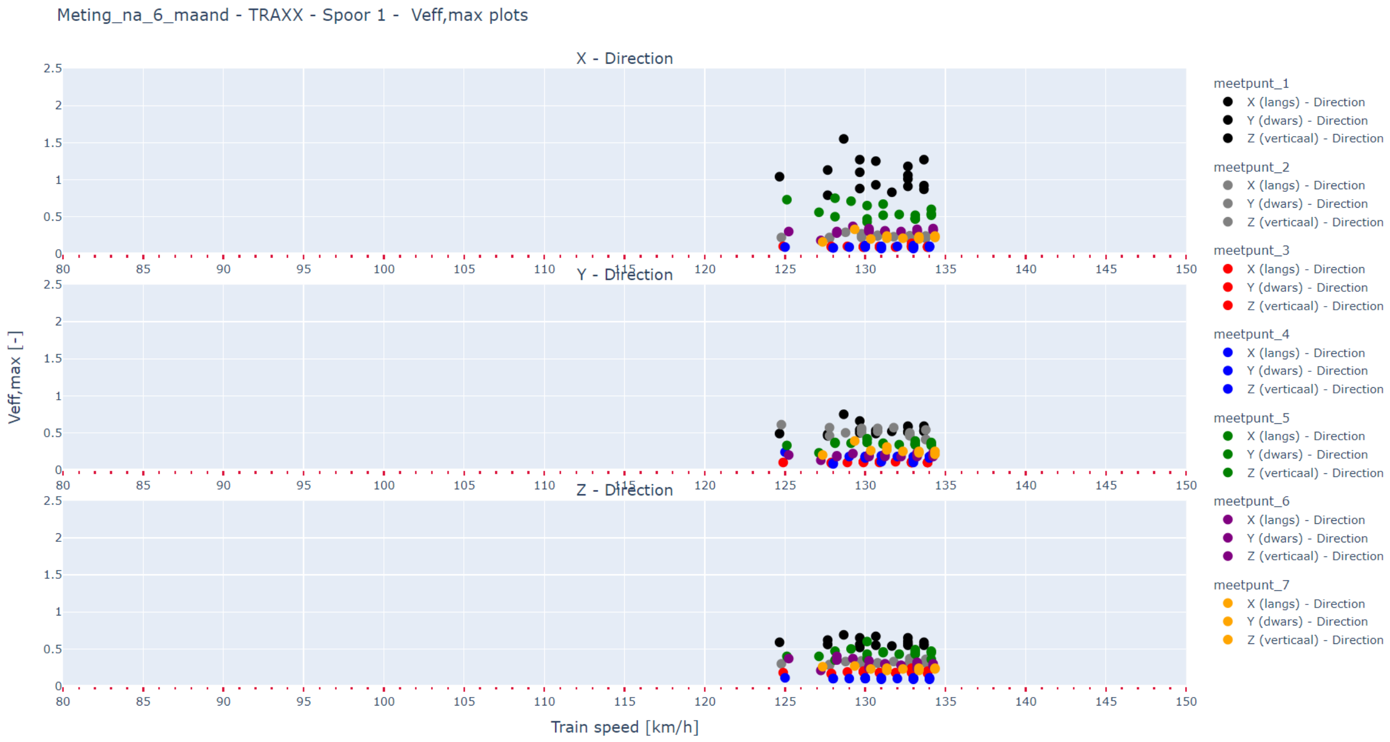

Figure 48 Vibration measurement data set (Veff, max vs. train speed) 6 months after track modification - TRAXX trains - Track 1

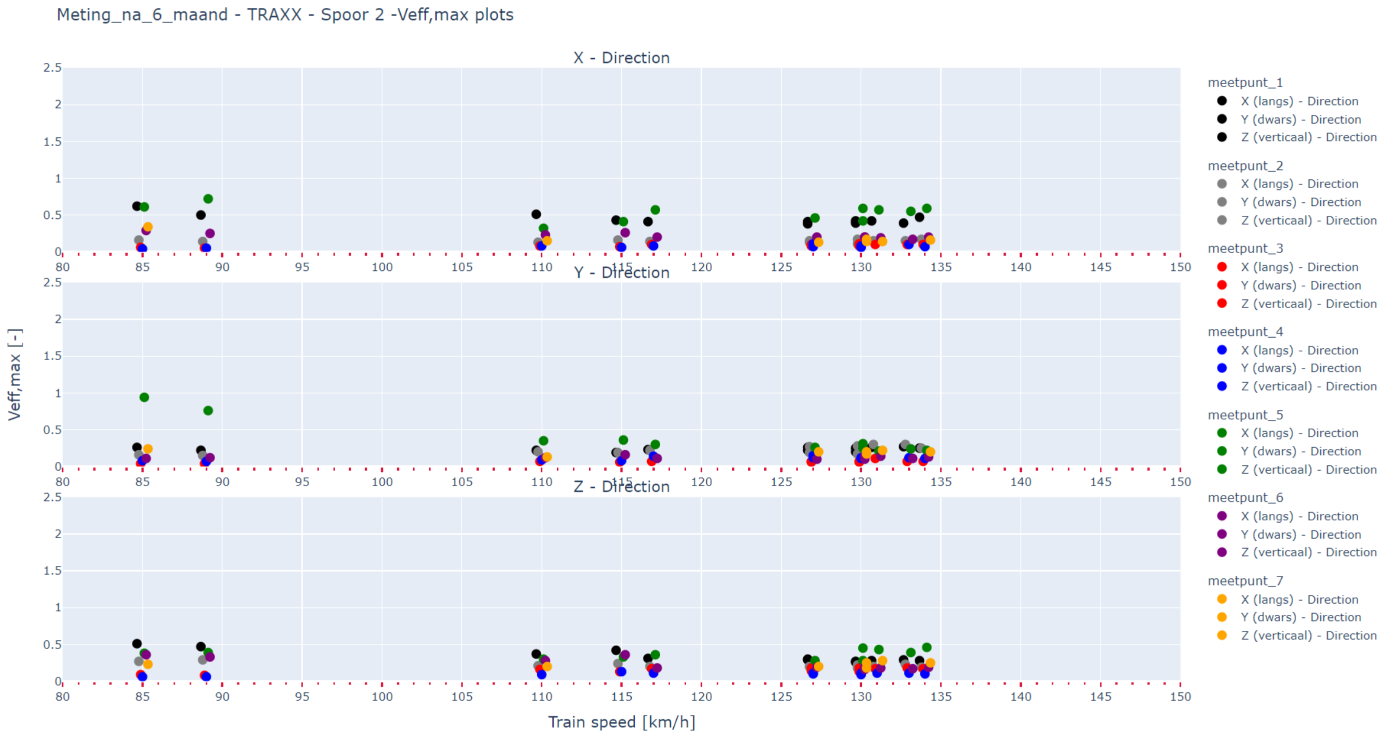

Figure 49 Vibration measurement data set (Veff, max vs. train speed) 6 months after track modification - TRAXX trains - Track 2

Figure 50 Vibration measurement data set (Amplitude vs. octave bands) 6 months after track modification - TRAXX trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measured 12 months after track modifications

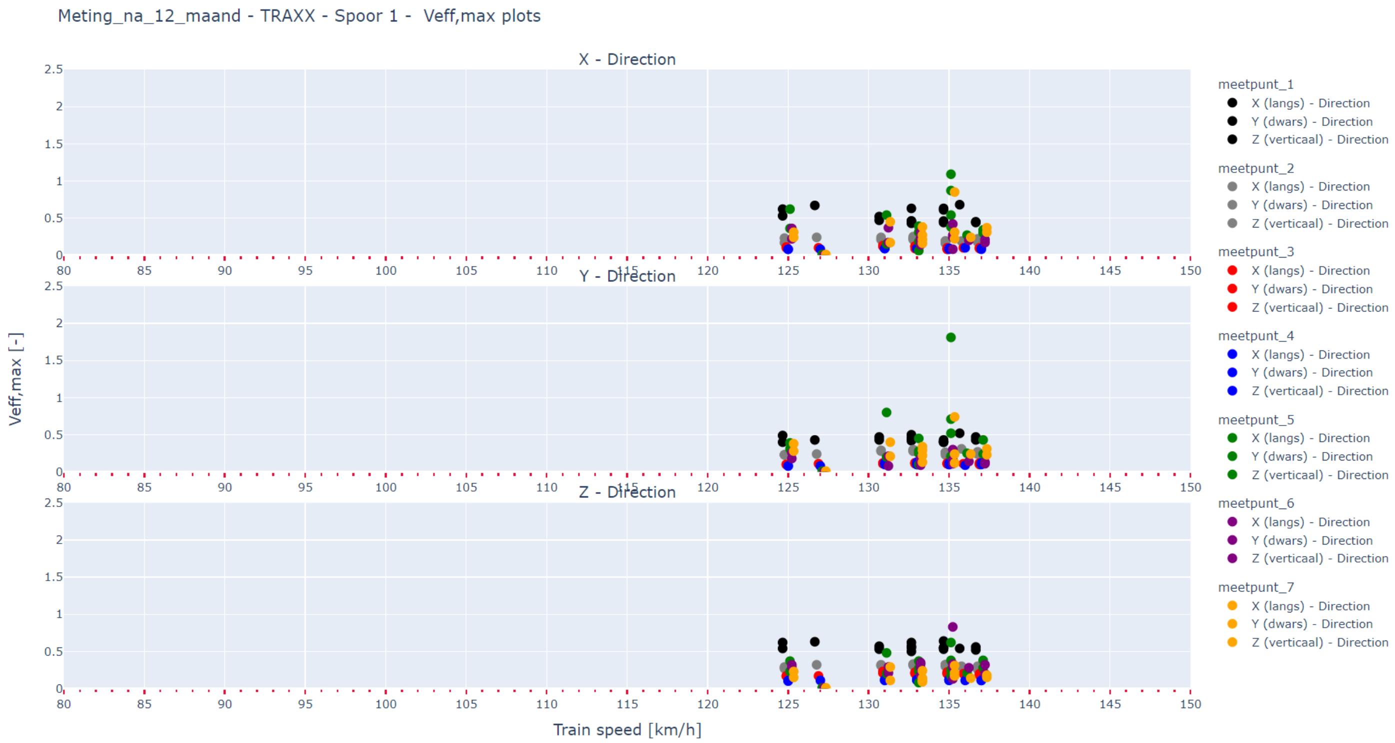

Figure 51 Vibration measurement data set (Veff, max vs. train speed) 12 months after track modification - TRAXX trains - Track 1

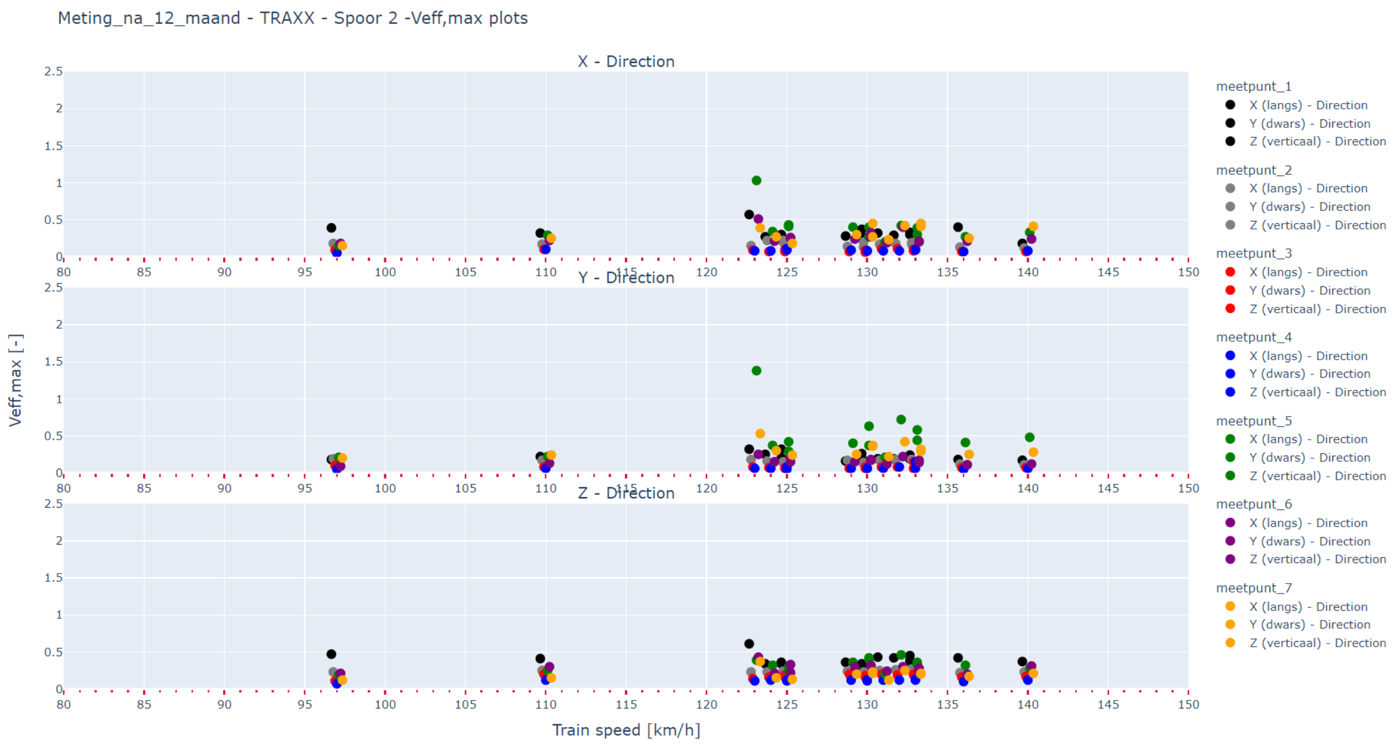

Figure 52 Vibration measurement data set (Veff, max vs. train speed) 12 months after track modification - TRAXX trains - Track 2

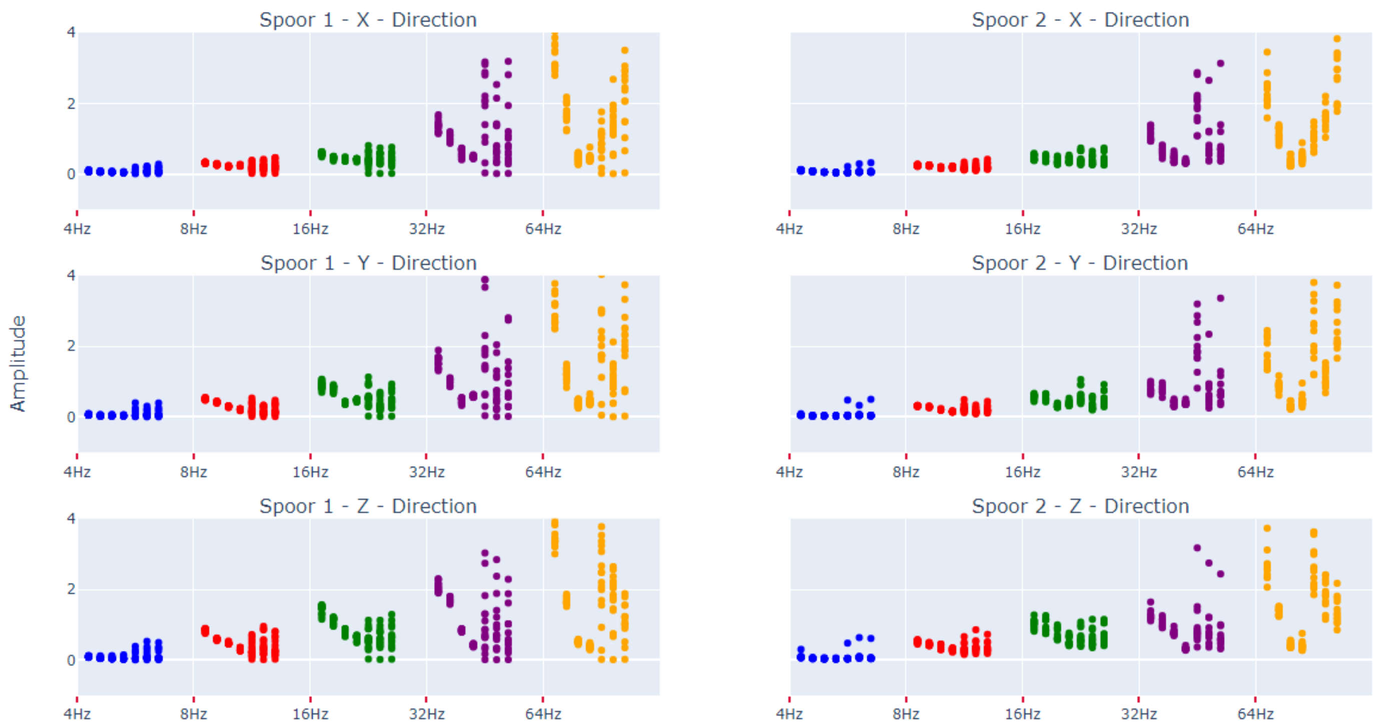

Figure 53 Vibration measurement data set (Amplitude vs. octave bands) 12 months after track modification - TRAXX trains - Tracks 1 and 2, shown in the left and right figures, respectively.

ARCADIS

Train type: VIRM

The detailed results of different vibration measurement data sets before and after track modifications for VIRM trains are shown below.

Measurement data before track modifications

Measurement data set 1

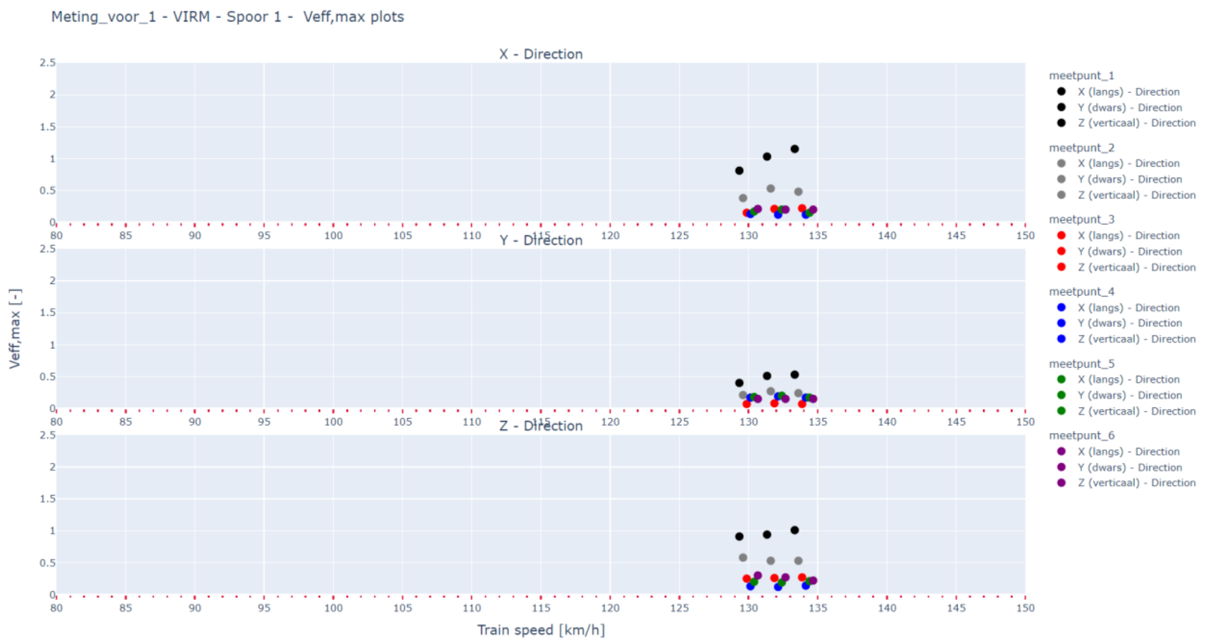

Figure 54 Vibration measurement data set 1 (Veff, max vs. train speed) before track modification - VIRM trains - Track 1

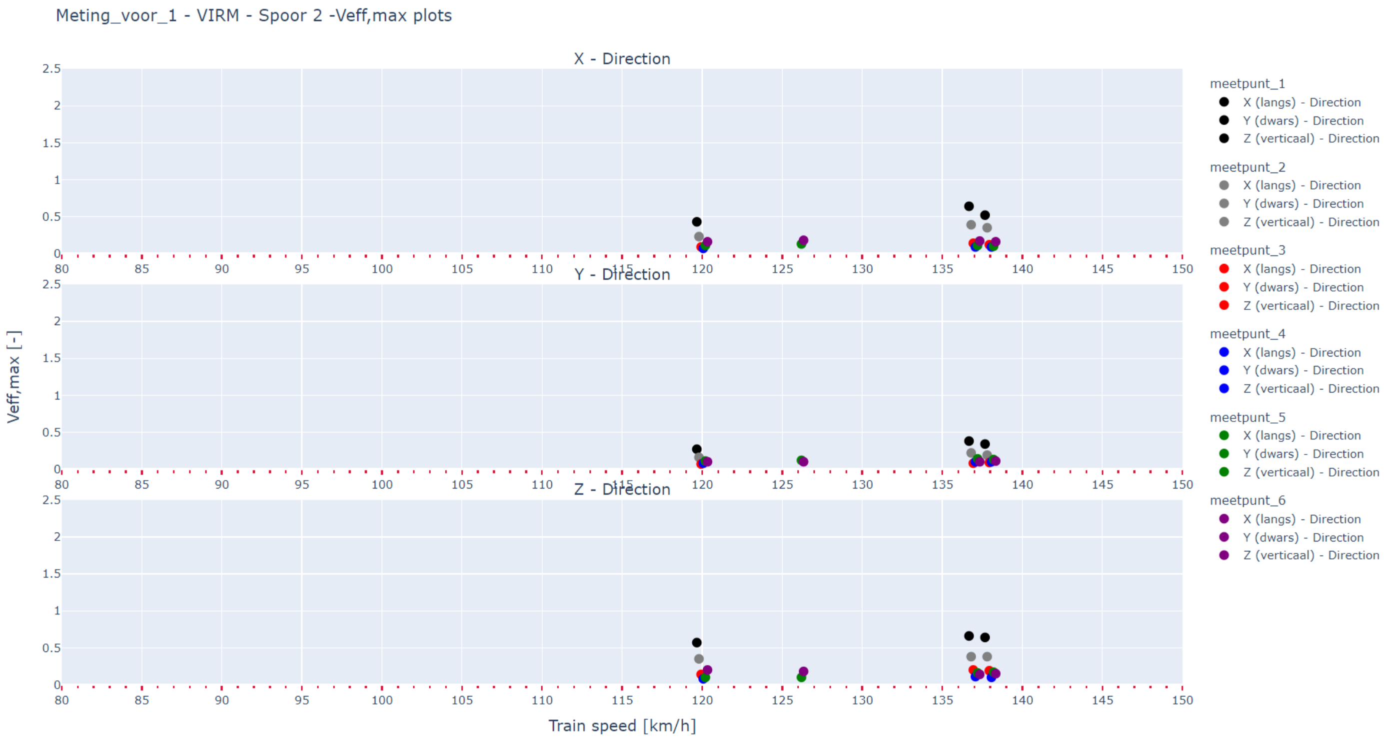

Figure 55 Vibration measurement data set 1 (Veff, max vs. train speed) before track modification - VIRM trains - Track 2

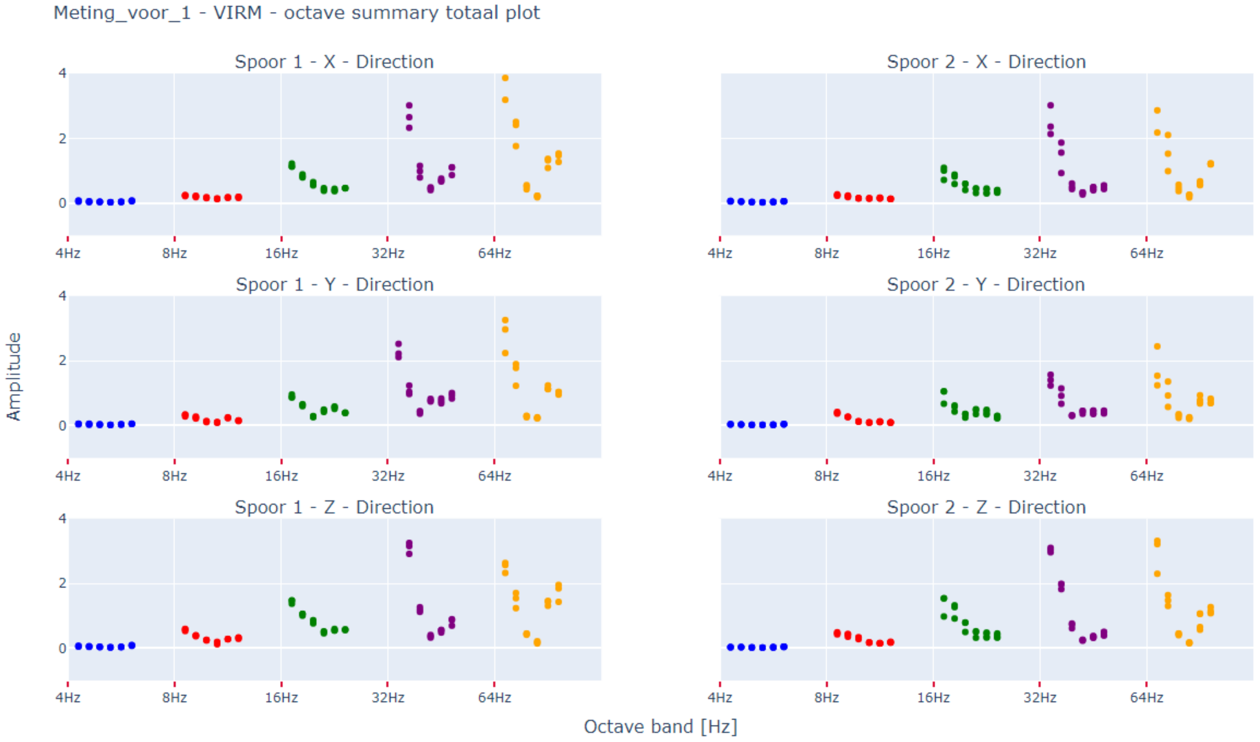

Figure 56 Vibration measurement data set 1 (Amplitude vs. octave bands) before track modification - VIRM trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measurement data set 2

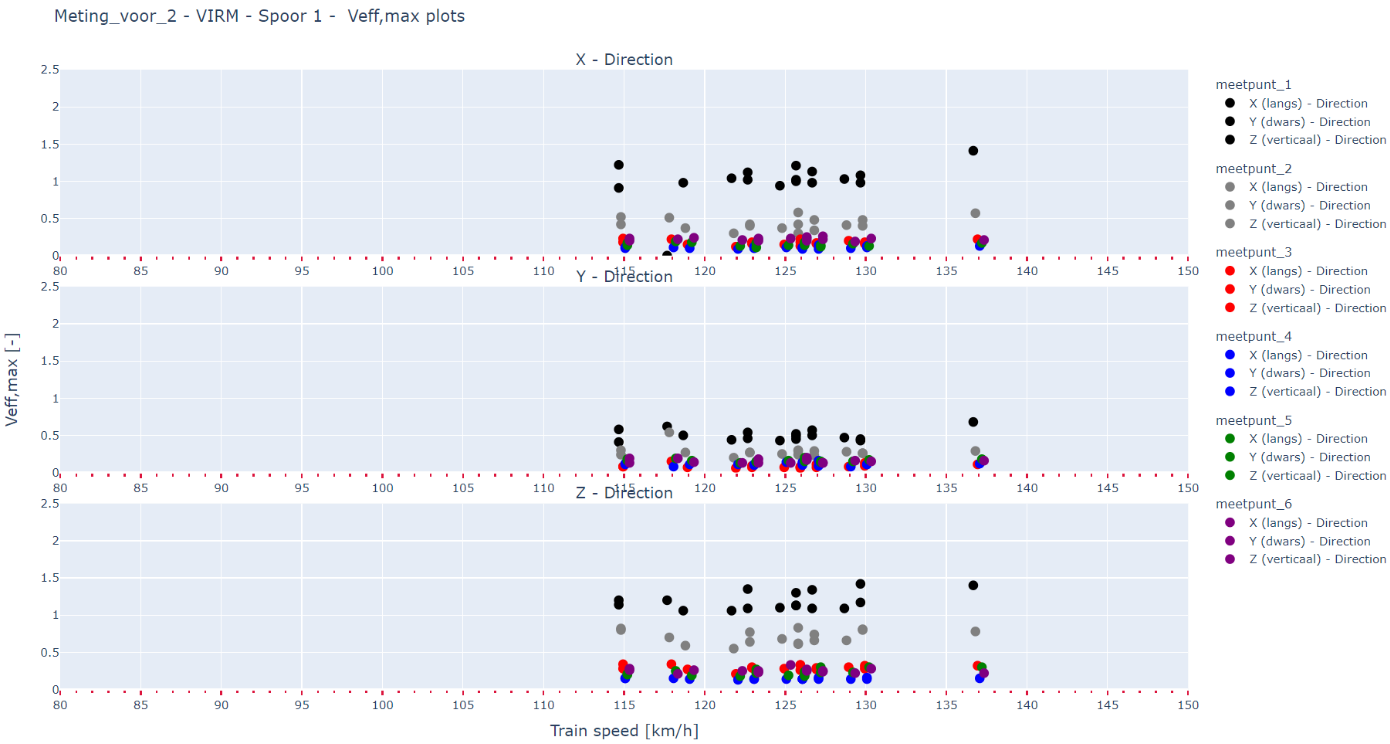

Figure 57 Vibration measurement data set 2 (Veff, max vs. train speed) before track modification - VIRM trains - Track 1

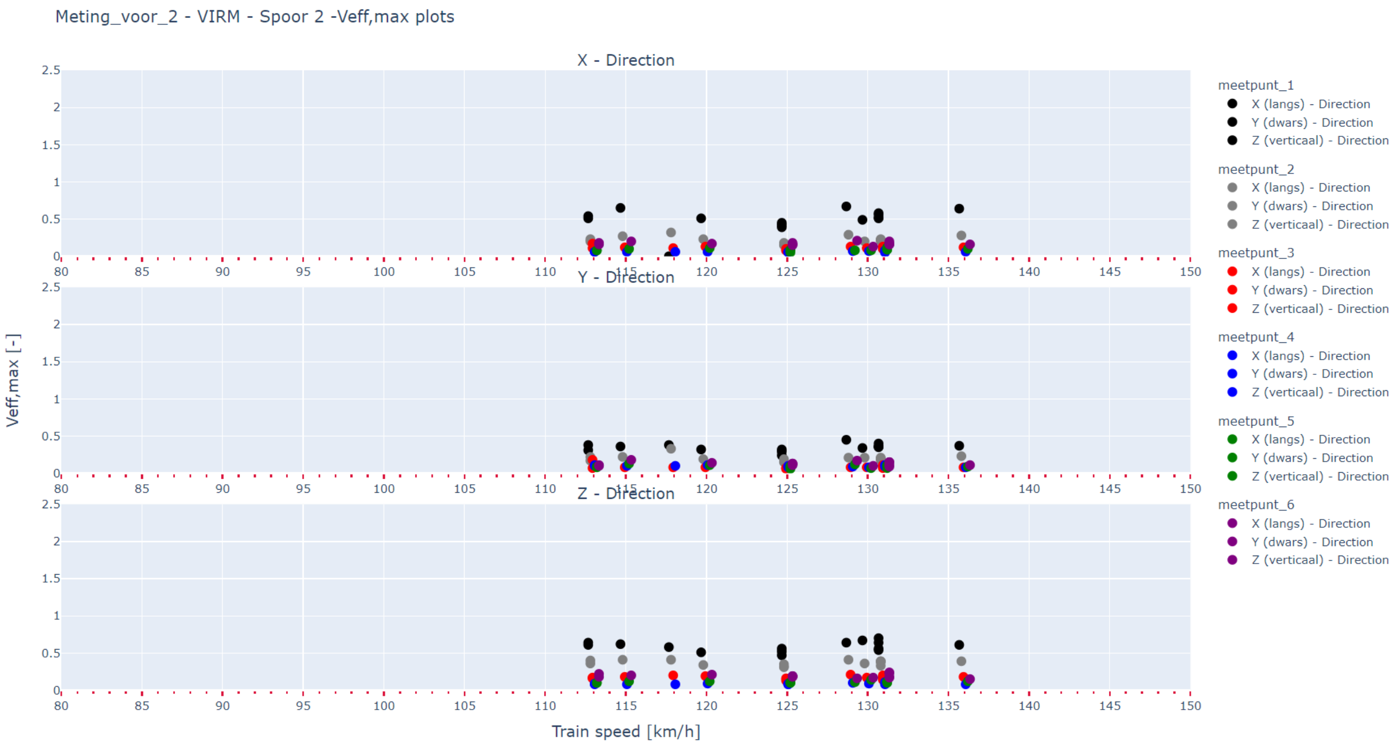

Figure 58 Vibration measurement data set 2 (Veff, max vs. train speed) before track modification - VIRM trains - Track 2

Figure 59 Vibration measurement data set 2 (Amplitude vs. octave bands) before track modification - VIRM trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measurement data after track modifications

Measured directly after track modifications

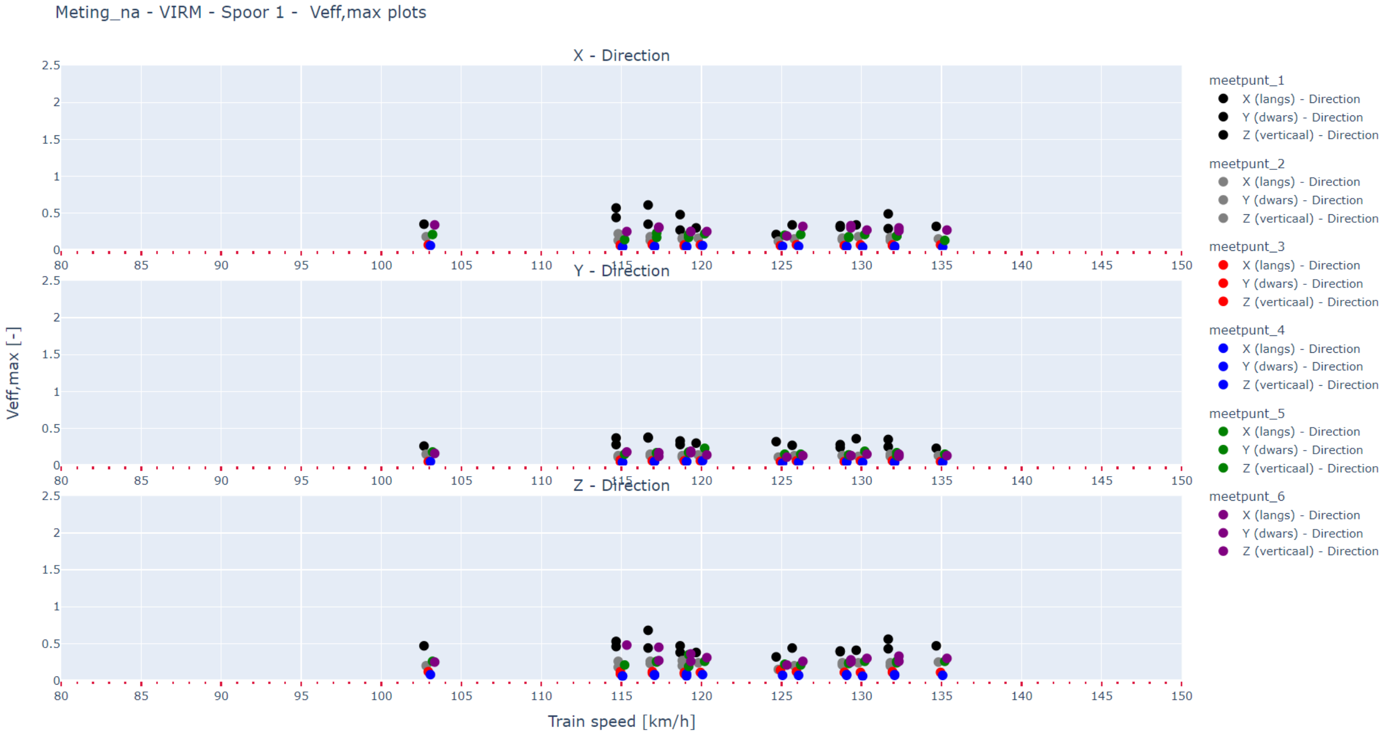

Figure 60 Vibration measurement data set (Veff, max vs. train speed) directly after track modification - VIRM trains - Track 1

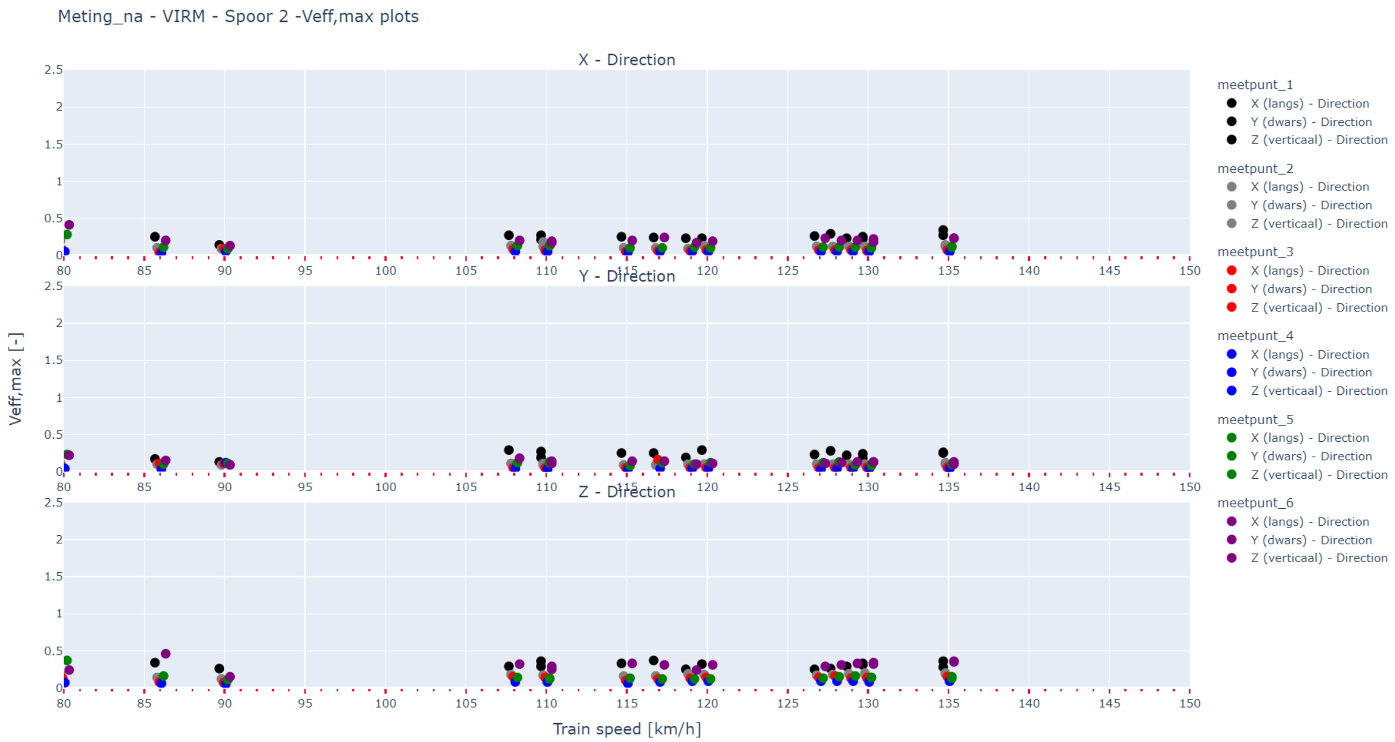

Figure 61 Vibration measurement data set (Veff, max vs. train speed) directly after track modification - VIRM trains - Track 2

Figure 62 Vibration measurement data set (Amplitude vs. octave bands) directly after track modification - VIRM trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measured 6 months after track modifications

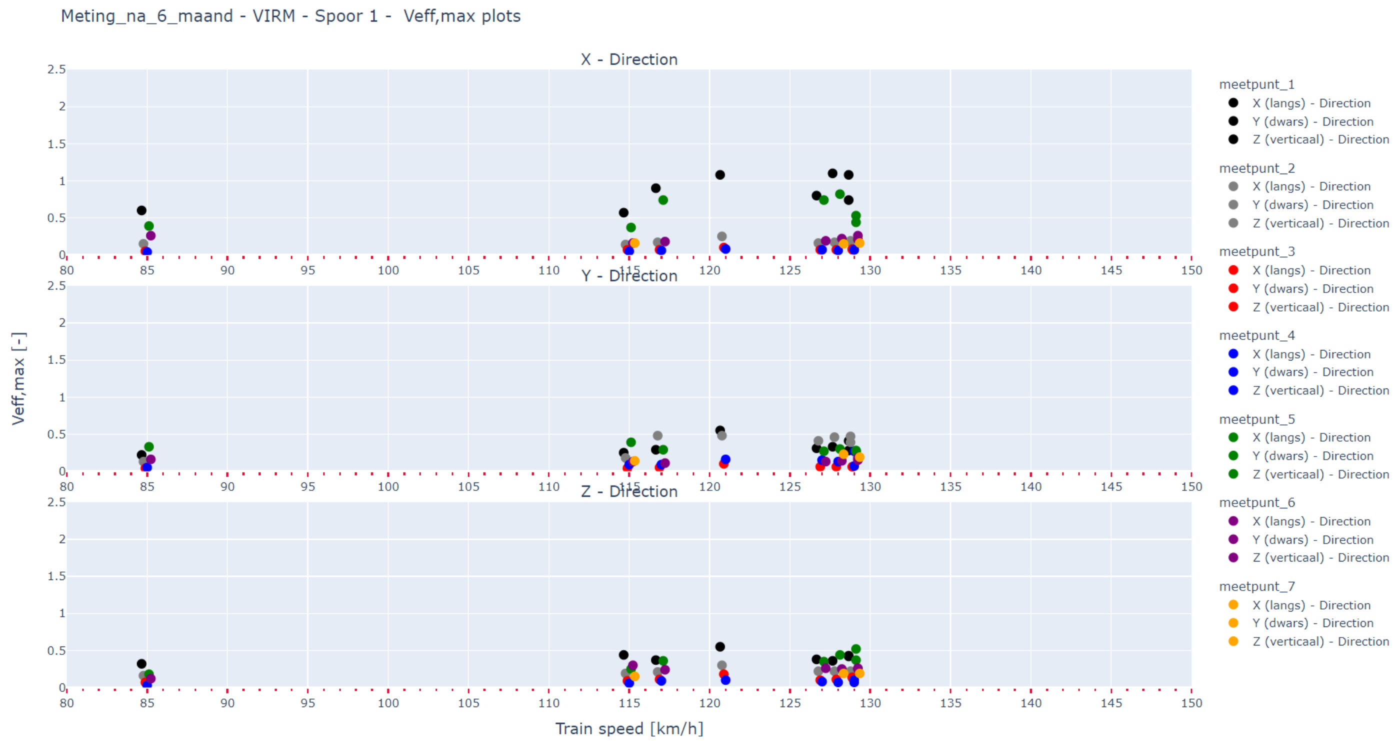

Figure 63 Vibration measurement data set (Veff, max vs. train speed) 6 months after track modification - VIRM trains - Track 1

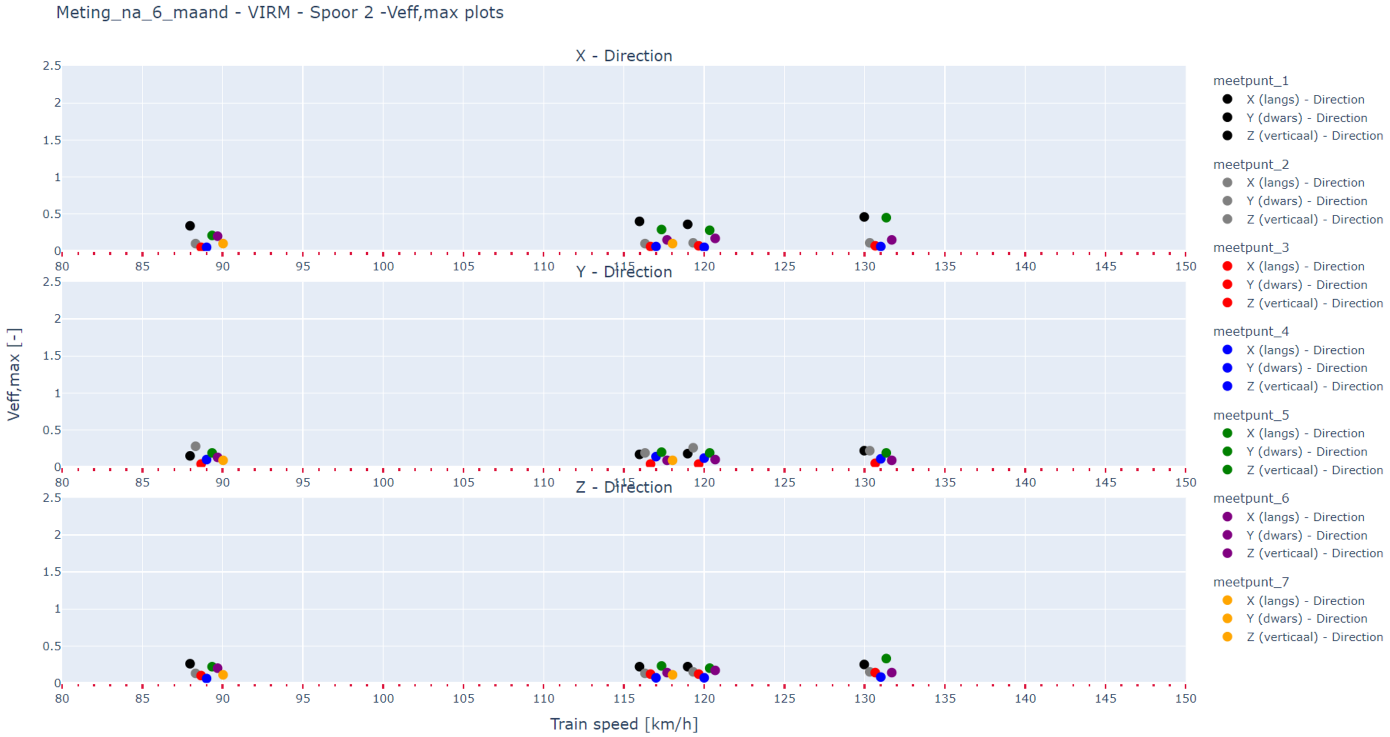

Figure 64 Vibration measurement data set (Veff, max vs. train speed) 6 months after track modification - VIRM trains - Track 2

Figure 65 Vibration measurement data set (Amplitude vs. octave bands) 6 months after track modification - VIRM trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Measured 12 months after track modifications

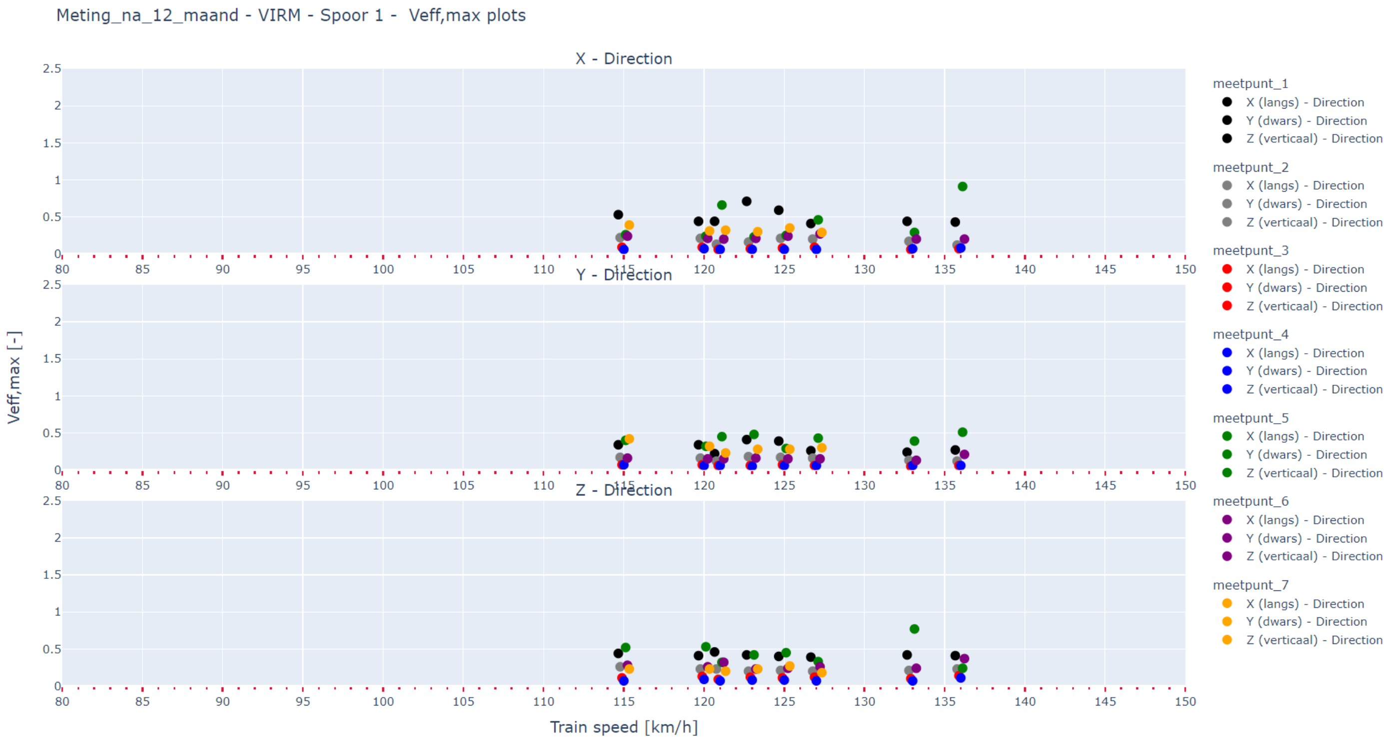

Figure 66 Vibration measurement data set (Veff, max vs. train speed) 12 months after track modification - VIRM trains - Track 1

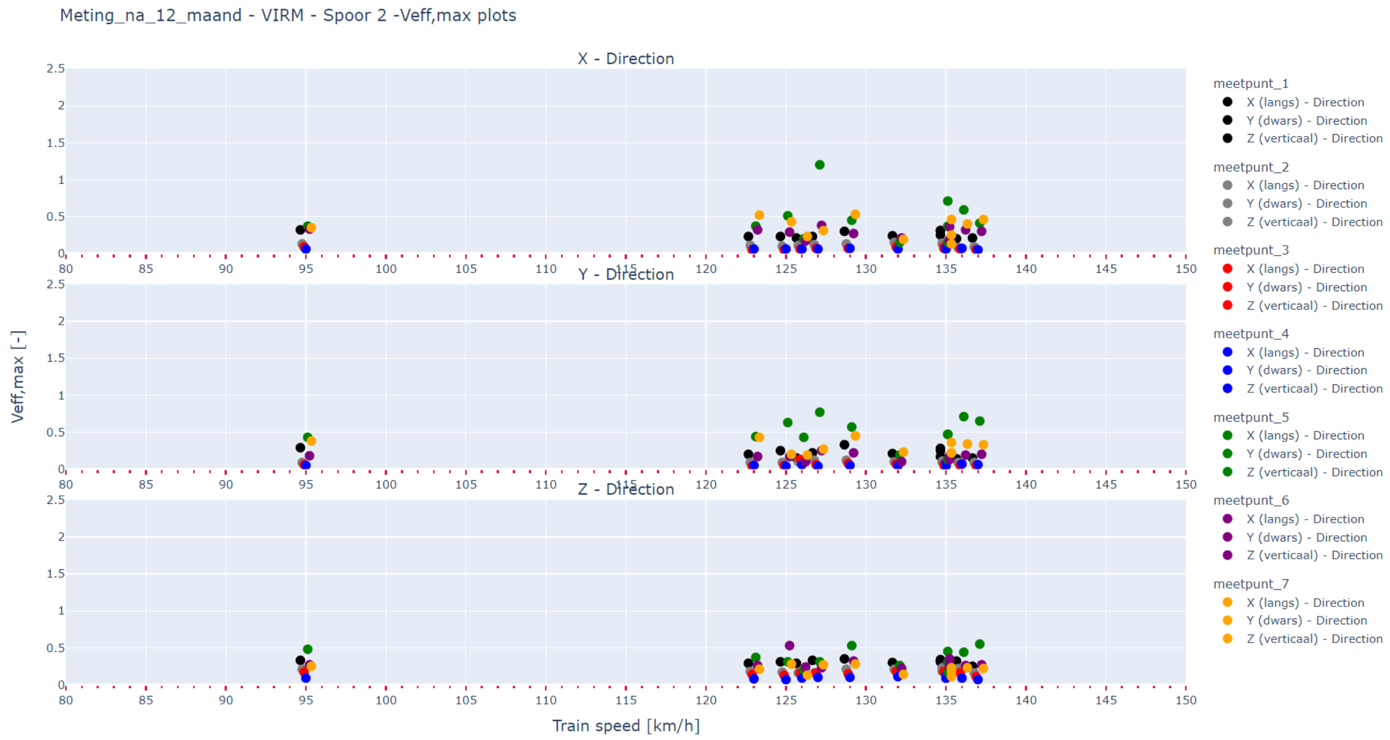

Figure 67 Vibration measurement data set (Veff, max vs. train speed) 12 months after track modification - VIRM trains - Track 2

Figure 68 Vibration measurement data set (Amplitude vs. octave bands) 12 months after track modification - VIRM trains - Tracks 1 and 2, shown in the left and right figures, respectively.

Appendix C Historical track geometry data results – Dorst

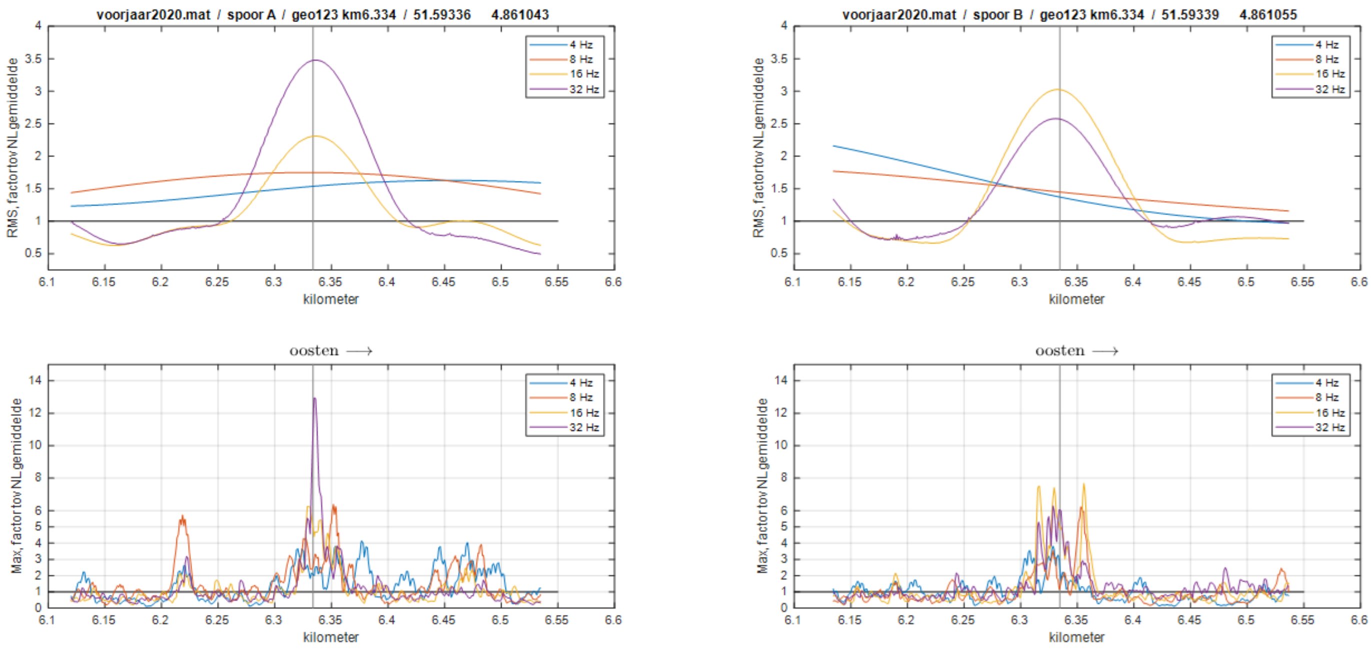

Figure 69 RMS and Max values for both tracks from spring 2020 track geometry measurement data

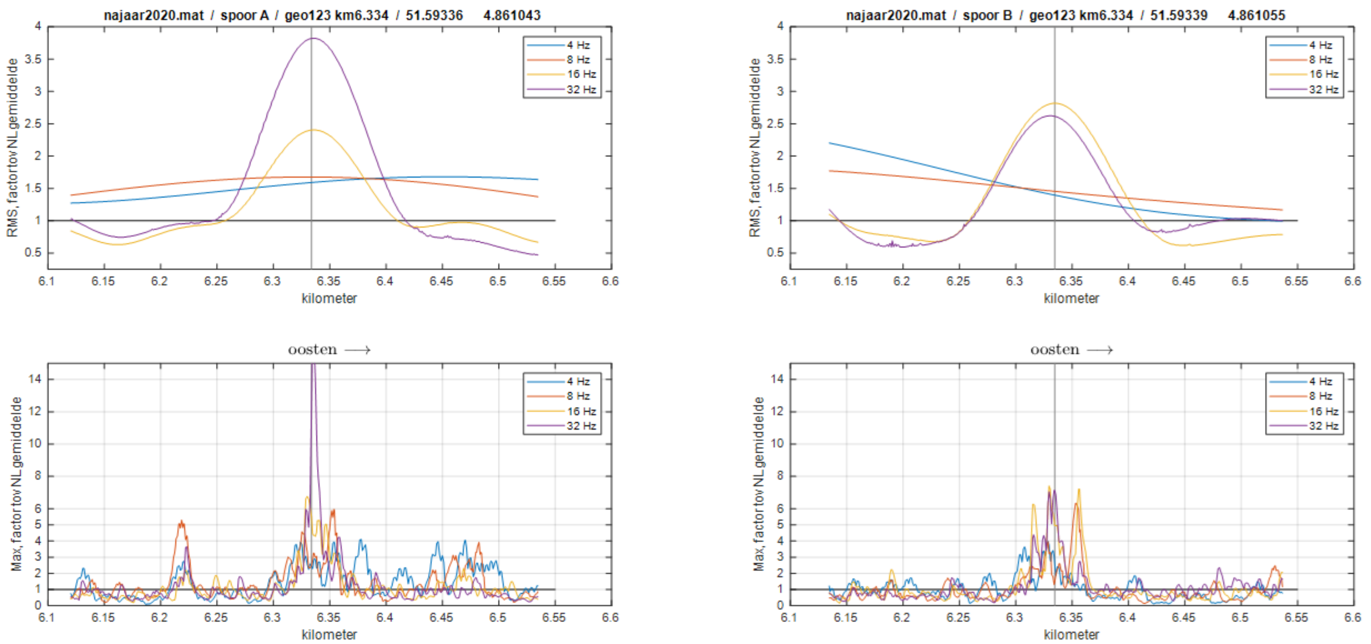

Figure 70 RMS and Max values for both tracks from fall 2020 track geometry measurement data

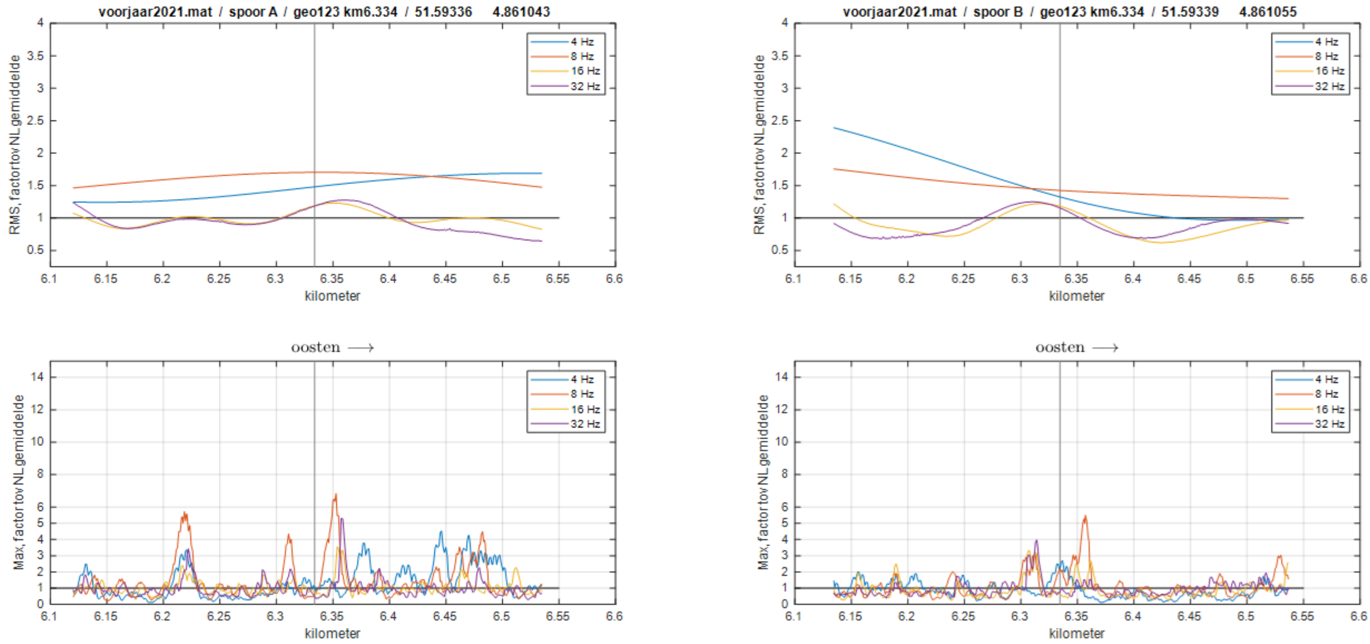

Figure 71 RMS and Max values for both tracks from spring 2021 track geometry measurement data

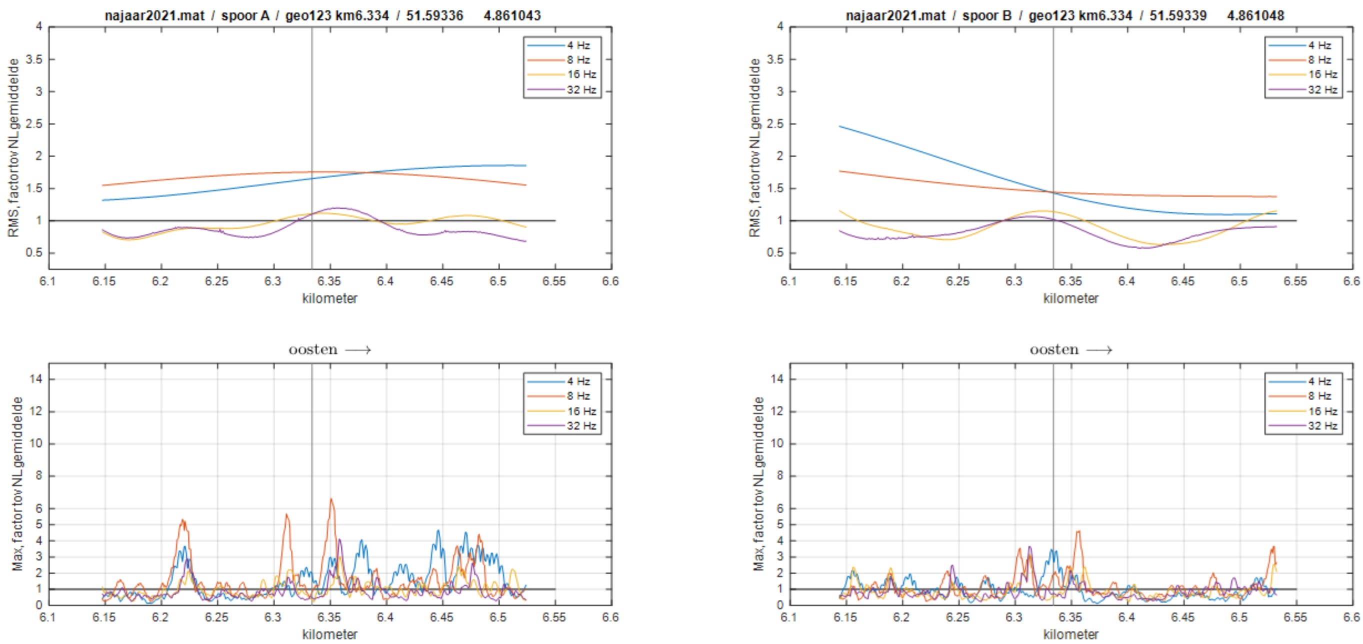

Figure 72 RMS and Max values for both tracks from fall 2021 track geometry measurement data

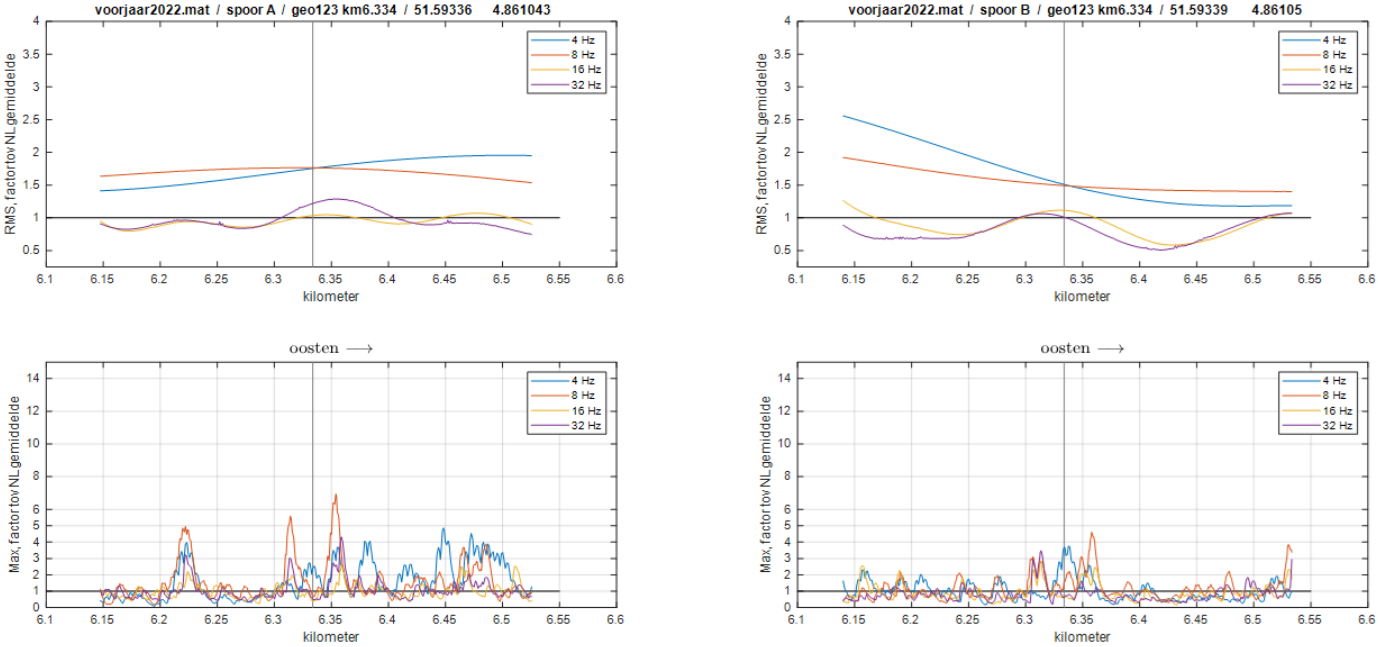

Figure 73 RMS and Max values for both tracks from spring 2022 track geometry measurement data

Colophon

ASSESSMENT OF A RAILWAY VIBRATION QUALITY INDICATOR
THROUGH AN ANALYSIS OF FIELD VIBRATION MEASUREMENT DATA

CLIENT
ProRail

AUTHOR
Saeed Hosseinzadeh & Rahman Özdemir

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