Altissimo Consulting

# Road surface noise – Influence of axle motion on CPX level

*Prepared for*
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# 1 Summary of findings

The vibration of the sprung and unsprung components of the CPX trailer was measured during annual CPX measurements of the Christchurch state highway network. The measurement and analysis details are provided in the following report.

Across all surfaces higher vibration levels resulted in higher CPX levels, but no correlation was found within a surface. Surfaces such as chipseal had higher vibration and CPX levels than porous asphalt. No relationship between overall or third octave CPX and vibration levels was identified within individual surface types.

The presence of audible 'undulations' in the recorded CPX audio has been noted during previous measurements. The low frequency components of the vibration data were evaluated in locations where these audible events were identified. No relationship was found between the low frequency vibrations and these audible events. Additionally, no relationship between the CPX level and these audible events was identified.

A potential source for the audible 'undulations' is vertical bouncing of the trailer. The low frequency limit of the accelerometers prevented assessing this motion. The height will be measured during future CPX measurements. This data will be used to identify any relationship between these audible events and the trailer motion.

The vibration data can be used to automatically detect discontinuities such as potholes, bumps or joints in the surface. These events are frequently missed by the operator during CPX measurements and in the subsequent postprocessing. Further development will be required to implement the automatic detection algorithm including;

- removal of electrical interference
- tuning of detection parameters
- implementing real-time processing

# 2 Experimental design

The motion of the trailer was evaluated by measuring the vibration of the sprung and un-sprung components of the trailer using a pair of accelerometers. These measurements were performed when undertaking annual CPX measurements on the local Canterbury roads. The locations measured are presented in Table 1.

Table 1 Road surface noise measurement sites

| Site | Highway | Road IDs |
|---|---|---|
| Western Belfast Bypass | SH1 | 1715/1716 |
| Johns Road | SH1 | 3588/3589, 3663/3664, 3650/3656 |
| Russley Road | SH1 | 3736/3735 |
| Christchurch Southern Motorway | SH18 | 3319/3318 |
| Main South Road | SH1 | 1710 |

## 2.1 Key research questions

The key questions that this research aimed to answer were:

- Is there are relationship between the average vibration and the CPX level within a specific surface type?
- Does motion of the trailer affect the measured CPX level? This is specific to low frequency bouncing or similar motion.
- Can the measured vibration be used to automatically identify discontinuities in the road surface?

## 2.2 Instrumentation

The acceleration was measured using two PCB 602D01 accelerometers. The specifications of these accelerometers are:

- Sensitivity: (±10%) 100mv/g
- Frequency Range: 0.5Hz to 8kHz
- Measurement range: ±50g

The location of the accelerometers is shown in Figure 1 and Figure 2. Both accelerometers were single axis and are oriented in the vertical direction. Both accelerometers were bolted to a cylindrical steel block, that is in-turn bolted to the components to be measured.

The accelerometer data was captured with the existing CPX National Instruments data acquisition system. The accelerometer data was recorded simultaneously with the CPX audio measurements and stored in a 4 channel .wav file with the two audio channels. The accelerometers are sampled at 50kHz which matches the sampling rate of the microphones.

The naming of the accelerometer channels is:

- Channel 0: Sprung mass
- Channel 1: Unsprung mass

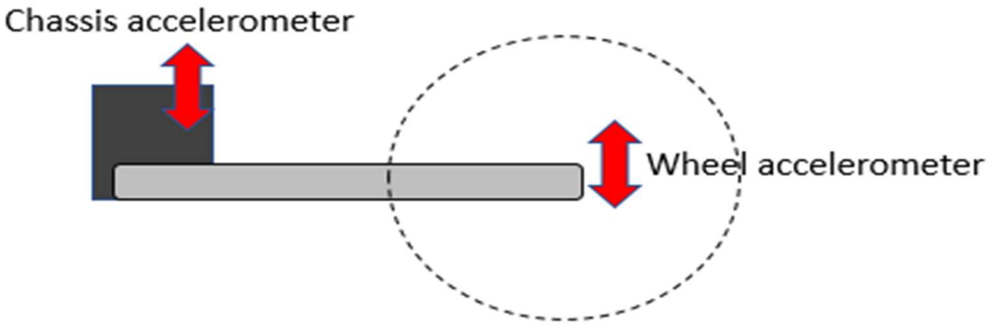



Figure 1 Layout of accelerometers

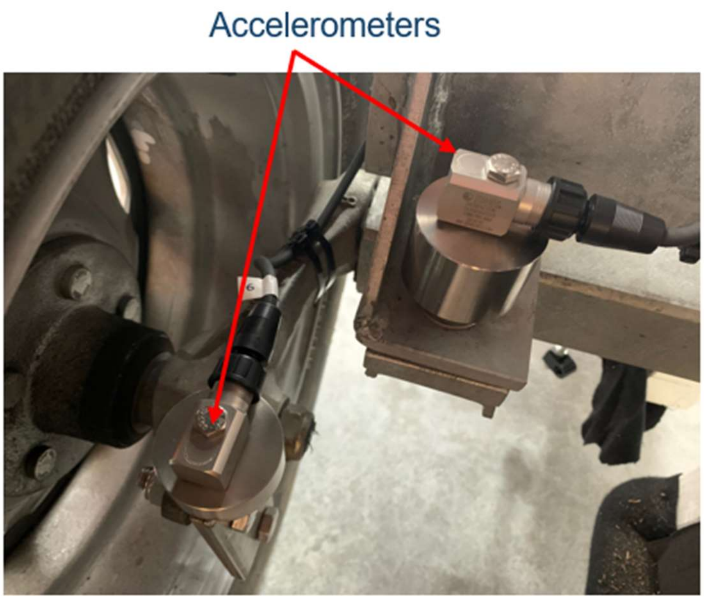



Figure 2 Accelerometers installed on CPX trailer

# 3 Measurement issues

The raw data acquired during testing was adversely affected by electrical noise, which caused 'spikes' in the measured acceleration. This electrical noise altered the averaged vibration across the measurements and required pre-processing to remove it from the vibration data. Due to time constraints on the use of the CPX trailer the source of this electrical interference was not identified. During the winter 2020 maintenance period further work will be done to identify and remove the source of this noise.

These anomalies were removed prior to evaluating the research questions using the following methodology. This methodology was developed iteratively and is not optimised or robust. The priority for future work should be the identification and removal of the source of electrical noise, rather than the development of a more accurate algorithm.

1. A high-pass filter was applied to remove any DC offset
2. The gradient of the vibration data was calculated using a second order central difference calculation (implemented in the *numpy.gradient* function[1])
3. Gradient values that lay more than 3.5 standard deviations from the mean were identified and 500 samples around these points were erased. This was effective in removing the longer duration effects caused by the spikes.

The result of applying the filtering process described above in Figure 3. This incorporates both the filtering and the peak removal.

The data lost varied between each measurement location. The proportion of data lost due to these spikes was approximately 9% for the sprung mass (Channel 0) and 20% for the unsprung mass, the data loss is summarised in Table 2.

Table 2 Evaluation of data removed due to electrical noise

| Road ID | Measurement ID / Run Number | Channel | Total number of measurement points | Number removed | Percentage removed |
|---|---|---|---|---|---|
| 1715 | 146_6 | 0 | 16588556 | 1436148 | 8.6% |
| | | 1 | 16588556 | 3656350 | 22.0% |
| | 146_10 | 0 | 15743208 | 1404983 | 8.9% |
| | | 1 | 15743208 | 3732377 | 23.7% |
| | 146_14 | 0 | 16274117 | 1489045 | 9.1% |
| | | 1 | 16274117 | 4136361 | 25.4% |
| | 139_3 | 0 | 23192188 | 1774820 | 7.7% |
| | | 1 | 23192188 | 4372884 | 18.9% |
| | 139_4 | 0 | 16368139 | 1621797 | 8.9% |
| | | 1 | 16368139 | 3290222 | 20.1% |
| | 139_6 | 0 | 23493423 | 2121546 | 9.0% |
| | | 1 | 23493423 | 5147058 | 21.9% |

[1] https://numpy.org/doc/stable/reference/generated/numpy.gradient.html?highlight=gradient#numpy.gradient

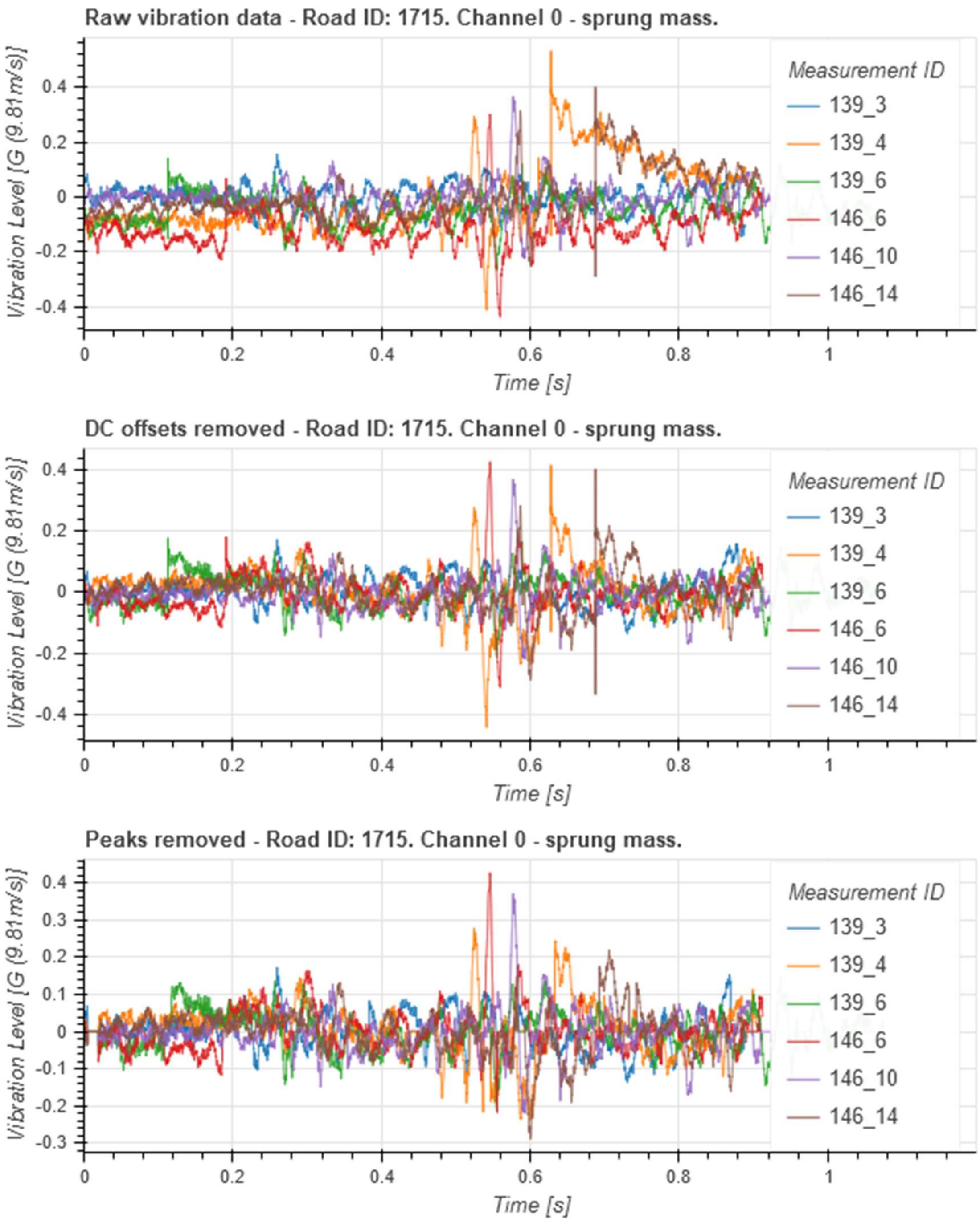



Figure 3  Electrical noise in accelerometer signals

# 4 Experimental results

## 4.1 Overall relationship between trailer vibration and CPX level

The 20m CPX level was compared to both the sprung and unsprung vibration levels averaged over each 20m segments. This averaging was performed after the electrical anomalies had been removed. The decibel value of the vibration level was used for plotting the correlation plots, and was calculated using the following equation:

$$V(dB) = 10 \times \log_{10}|V|$$

Across all surfaces a higher vibration level resulted in a higher noise level, this is especially clear between EPA and chipseal, as shown in Figure 4 below. The surface types have been drawn from the RAMM database. It should be noted that there is a section of EPA14 is currently covered in/replaced by chipseal due to the works on the Waimakariri bridge


Figure 4 Example of correlation between CPX level and vibration level

Within each surface type there was no clear relationship between the measured vibration level and the CPX level. The correlation plots for each site tested are presented in Appendix A.

### 1.1.1 Third octave correlations

A third octave band filter was applied to the vibration data between 100Hz and 5kHz. This was plotted against the corresponding third octave CPX level. The same trends present in the overall correlation analysis were seen in all frequency bands. No clear correlations were noted in any of the third octave bands.

## 4.2 Detection of discontinuities

The vibration data was evaluated as a mechanism for detecting discontinuities in the road. This detection could be used to exclude this data from CPX level calculations.

Locations with known bridge joints were used to characterise the vibration and noise behaviour around significant discontinuities. A rapid increase in the vibration level was associated with a bridge joint. The following graphs show the bridge joints on the Western Belfast Bypass as identified using the RAMM surface database data.

These bridge joints are typically manually flagged by the operator when performing the CPX measurements. Additionally, the CPX level calculation identifies the location of any surface joints in RAMM and automatically flags these locations for removal. Despite the higher rate of data loss, the unsprung mass vibration (channel 0) was found to be more effective at detecting discontinuities than the sprung mass vibration.

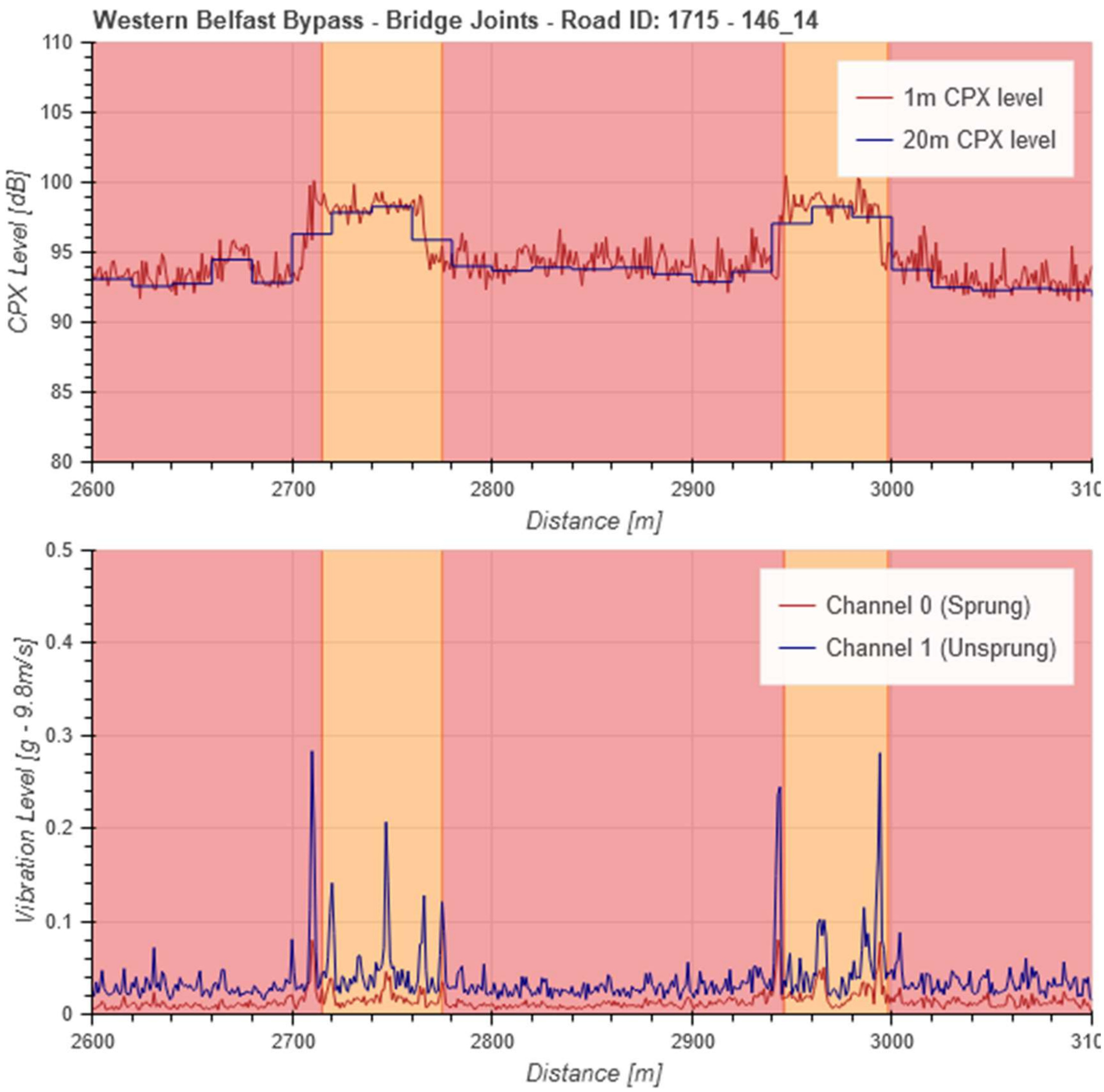



Figure 5 Vibration response due to bridge joints on Western Belfast Bypass

Peaks that were greater than 5 standard deviations from the mean vibration were identified on Western Belfast Bypass and Main South Road. The longitudinal plots with the identified peaks are provided in Appendix B. The audio recordings at these peaks was manually reviewed and the findings are summarised in Table 3.

Table 3 Identified peaks

| Road ID | Measurement ID / Run Number | Number of detections | Number correct | Number incorrect | Audible discontinuities missed |
|---|---|---|---|---|---|
| 1715 | 146_6 | 7 | 5 | 2 | 0 |
| 1715 | 146_10 | 8 | 6 | 2 | 0 |
| 1715 | 146_14 | 18 | 12 | 4 | 1 |
| 1716 | 147_1 | 15 | 7 | 8 | 0 |
| 1716 | 147_1 | 12 | 8 | 4 | 0 |
| 1716 | 147_1 | 5 | 4 | 1 | 0 |
| 1710 | 144_1 | 13 | 9 | 4 | 2 |

The vibration data can be utilised to detect discontinuities in the road surface, provided that the electrical interference is rectified or post processed. Of the events detected by the measured vibration approximately 95% of these were audible discontinuities. The vibration detection method had false positive rate of approximately 35%, which corresponded to a loss of 70m of measured surface over 5.5km of tested surface for the example presented.

The current methodology used to remove discontinuities is manual flagging of events during the measurements, and automatic removal of road surface joints using the RAMM surface data. The audible discontinuities that were missed had not been flagged manually in the CPX measurements and would therefore have not been removed in the current process for calculating the CPX level.

Further testing and improvements to the measurement system will be required to enable this functionality, including:

- Removing sources of electrical noise. This is especially important as the unsprung channel was better at detecting discontinuities, but also suffered from the highest data loss rate due to the electrical noise.
- Identifying a robust parameter for discontinuity detection and optimising this parameter for accuracy. A range of peak or edge detection algorithms exist, and these should be investigated.
- Quantifying the impact of removing these discontinuities on the measured CPX level

### 4.3 Low frequency vibration and CPX level

There are audible low frequency fluctuations present in the CPX measurement audio. This occurs after known discontinuities such as bridge joints, but also occurs in areas where there is no clear discontinuity in the surface.

A number of these events were manually located on Main South Road. Main South Road was selected as it is SMA or Chipseal, removing any confounding factors from porous asphalt. The vibration data was cleaned using the methodology described in Section 3. The following process was then applied to extract the average low frequency vibration data:

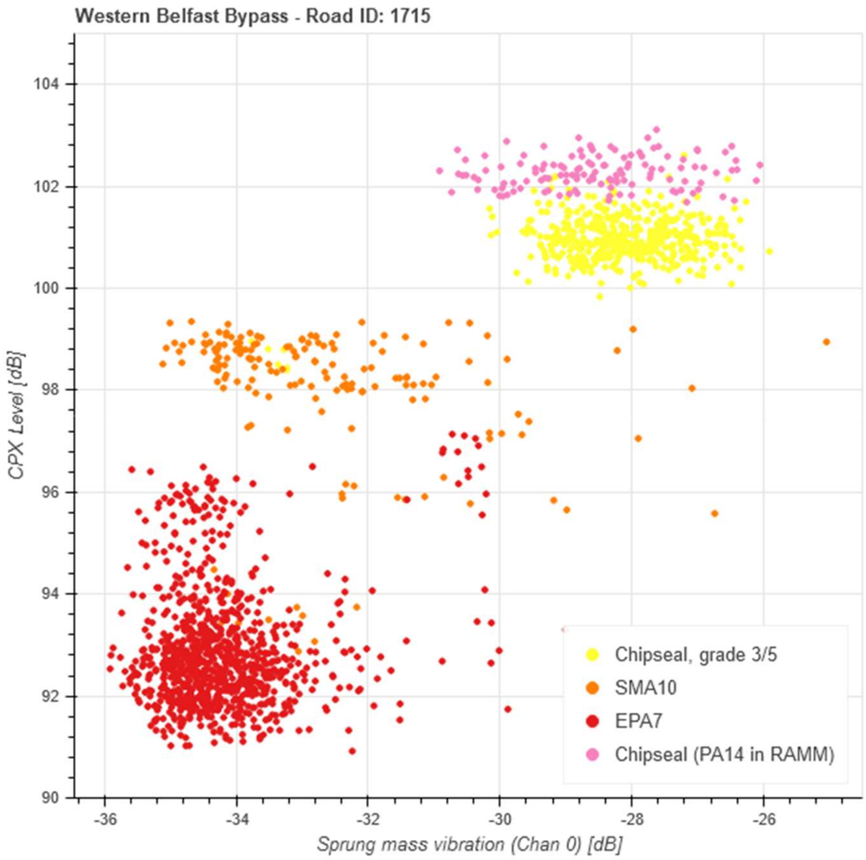
1. A band pass filter between 2Hz and 10Hz was applied. This range was selected as the audible fluctuations have a frequency of approximately 2-4Hz.
2. The absolute resulting vibration levels were averaged over each 1m segment of road, this allowed direct comparison with the 1m CPX level data.

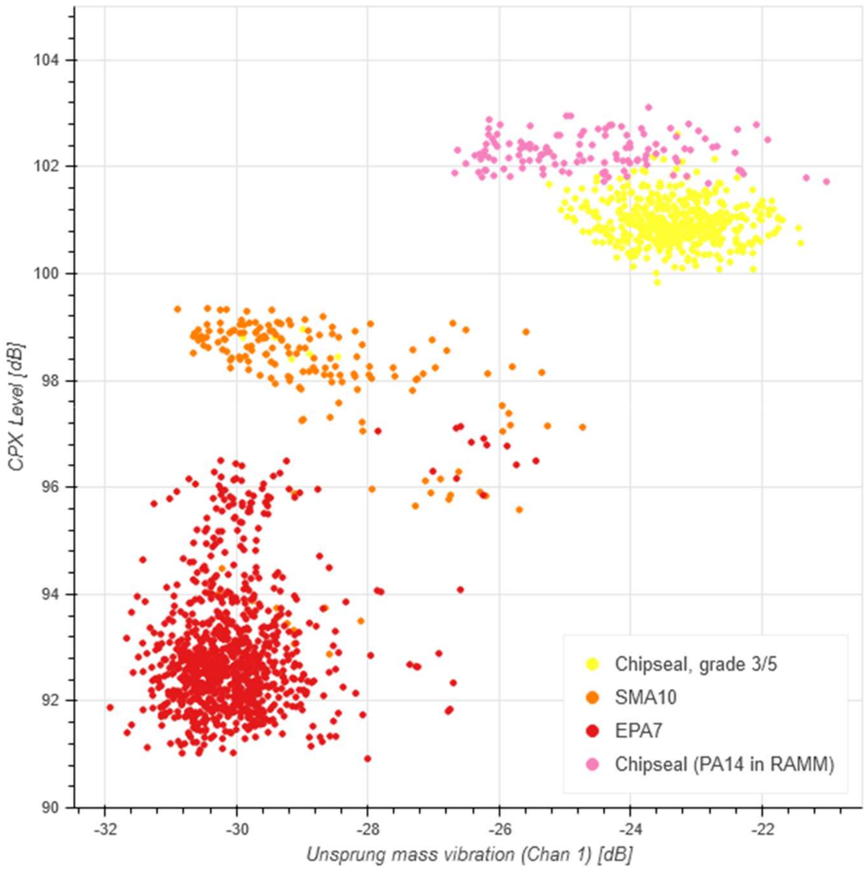
The results of these calculations are presented in Appendix C. No difference in the low frequency vibration levels were noted at the location of these events when compared to areas without these audible events. There was not correlation between the low frequency vibration and the 1m or 20m CPX levels.

There is no change in the 20m CPX level at locations where these events occur, as such these events do not impact the results of CPX measurements. Further measurements of the trailer ride height will be performed in future testing, this will establish if these audible events are due to the trailer 'bouncing'.

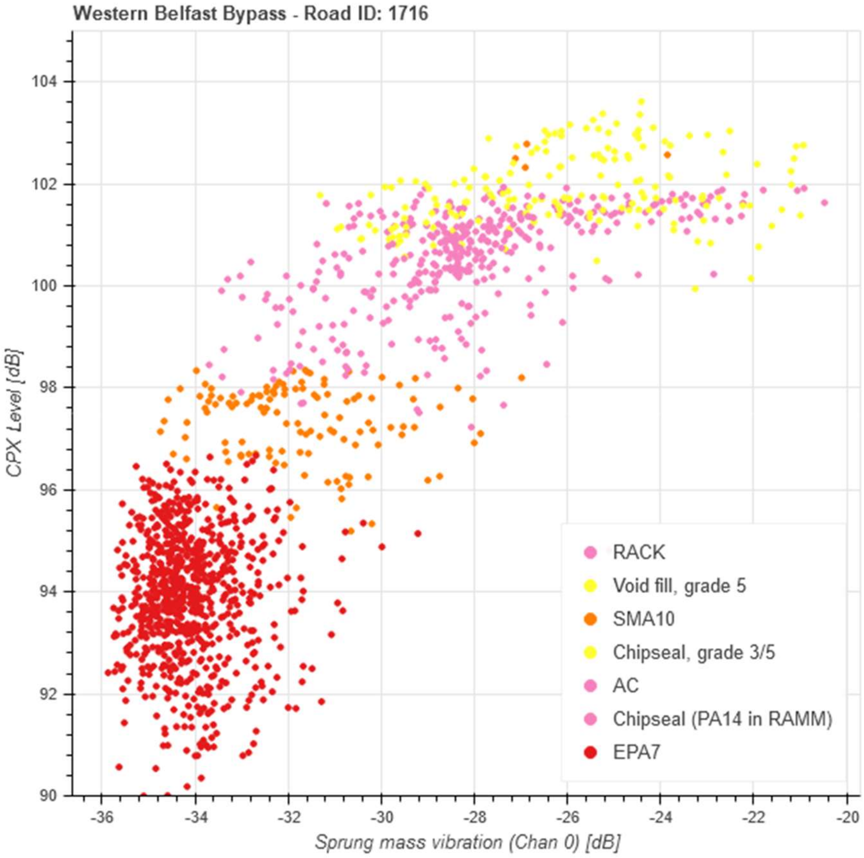
# Appendix A
# Overall Vibration to CPX Level Correlations

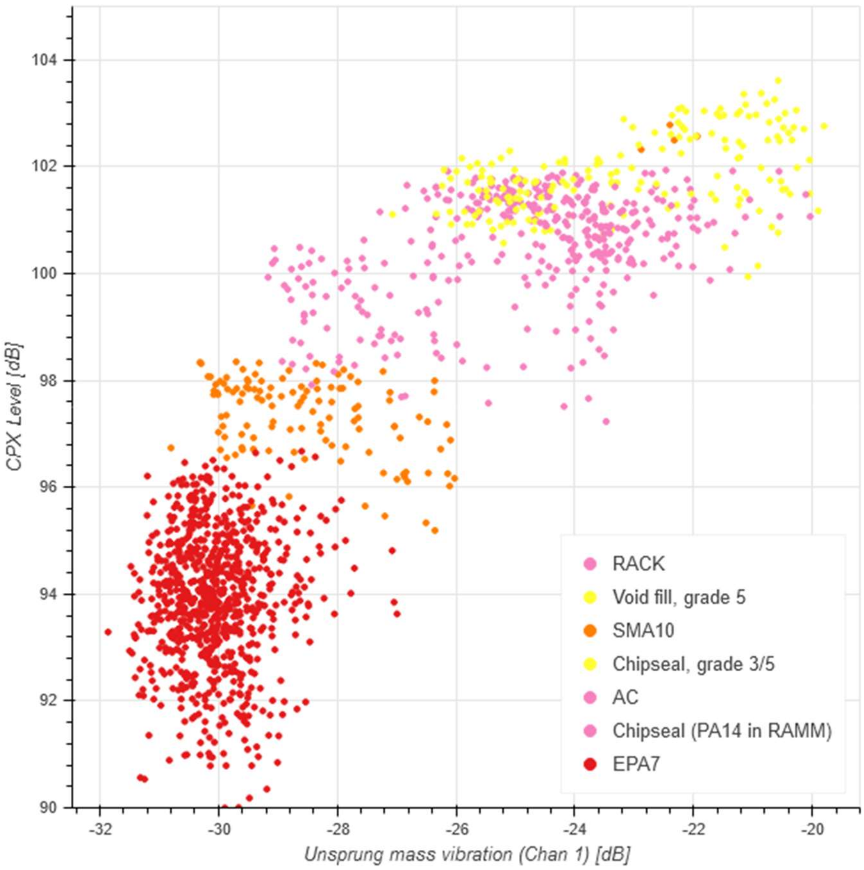
## A.1 Western Belfast Bypass – SH1 - Northbound



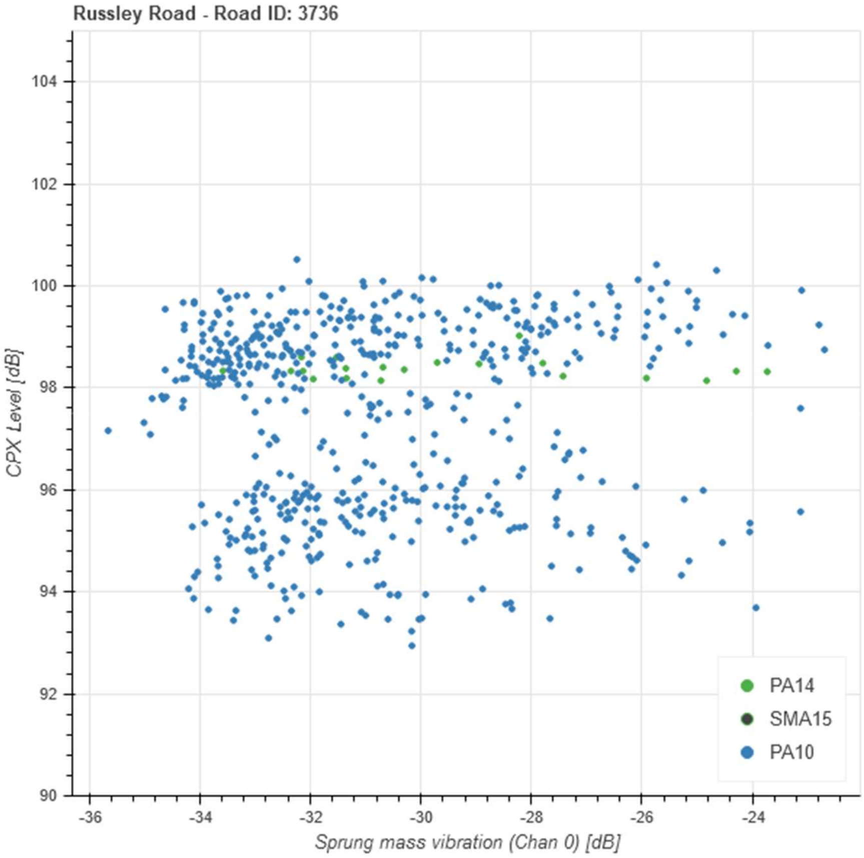



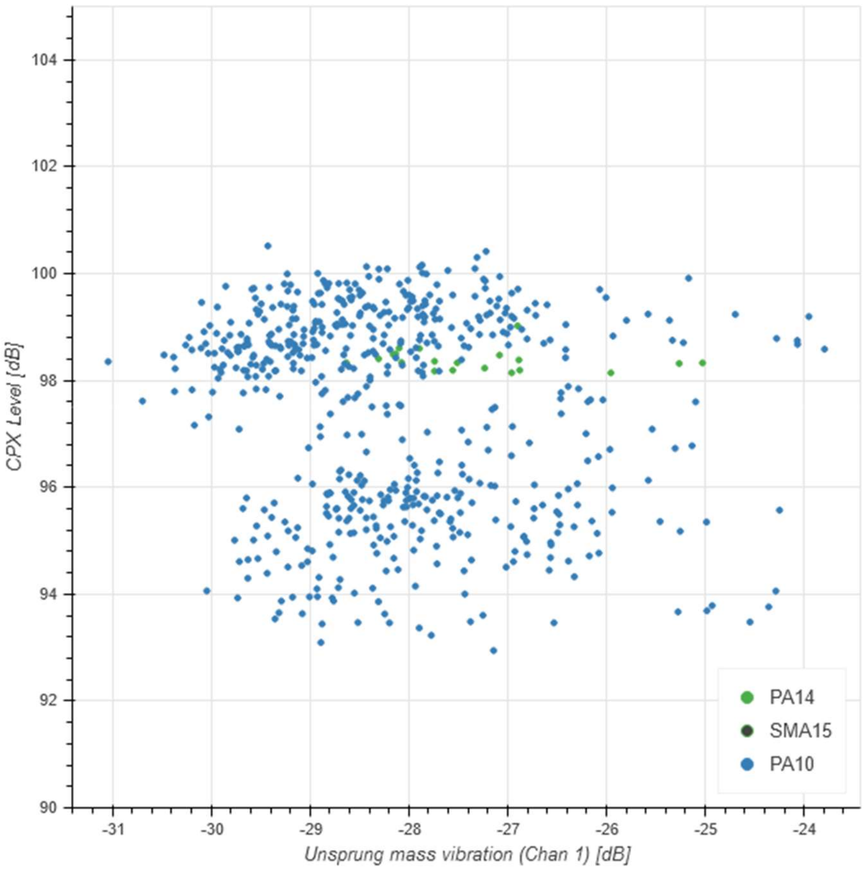
## A.2 Western Belfast Bypass – SH1 - Southbound



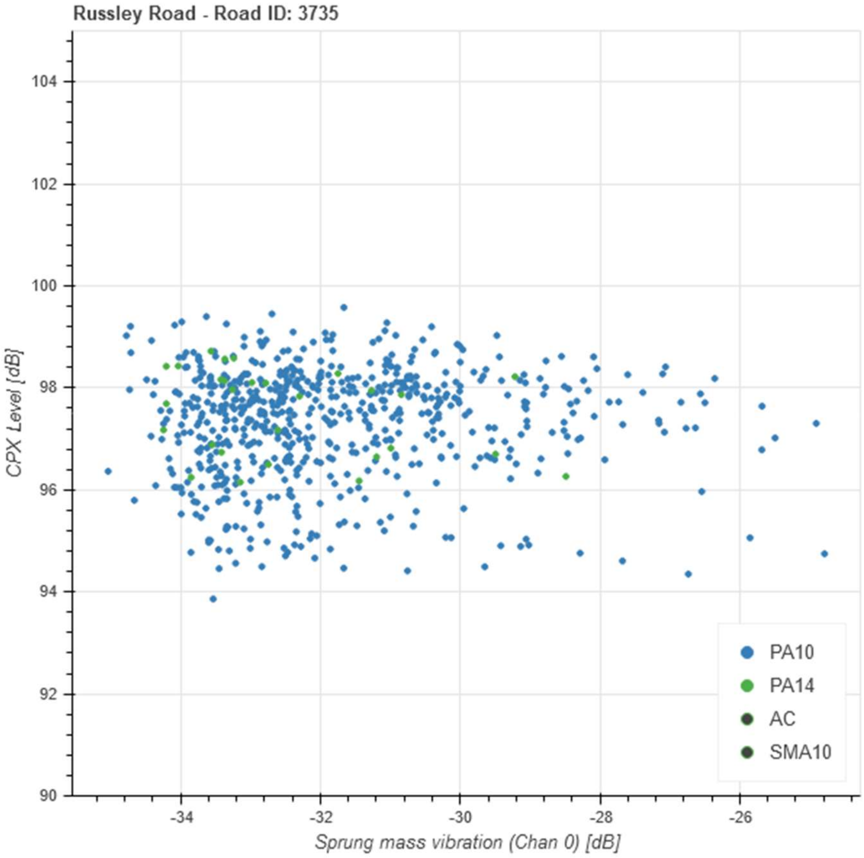



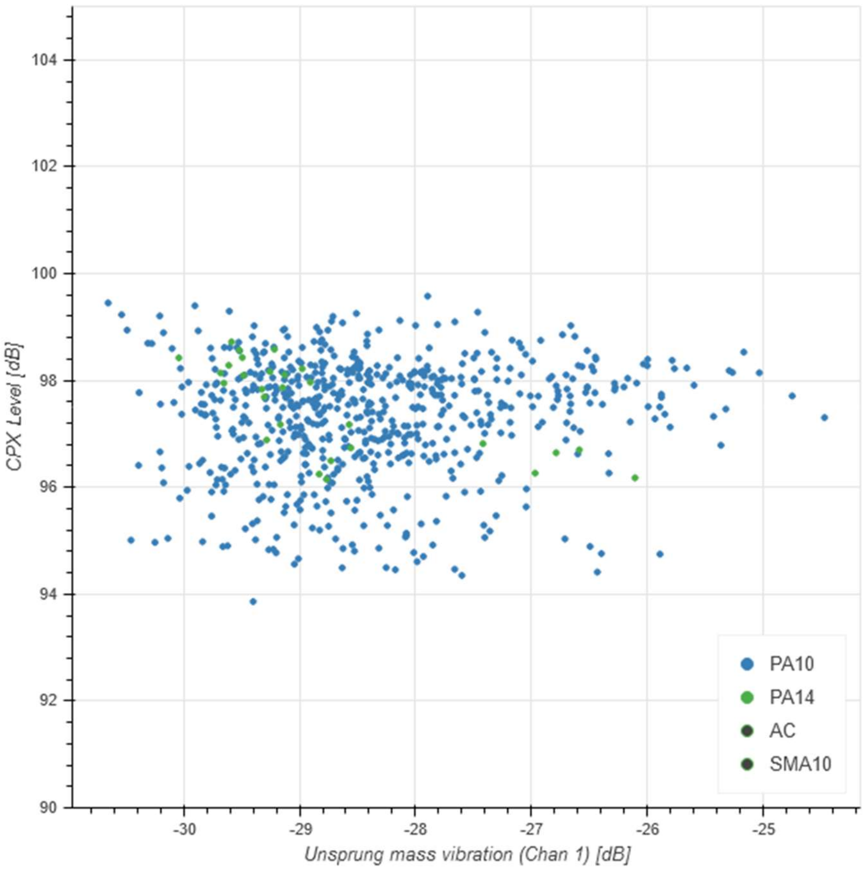
## A.3 Russley Road – SH1 - Northbound



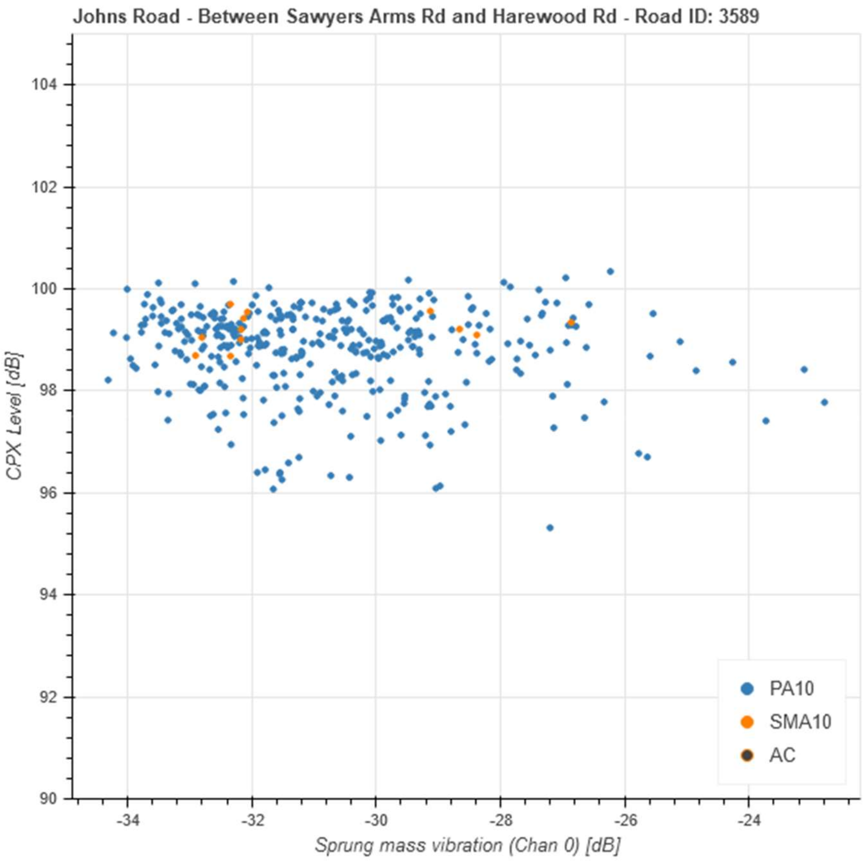



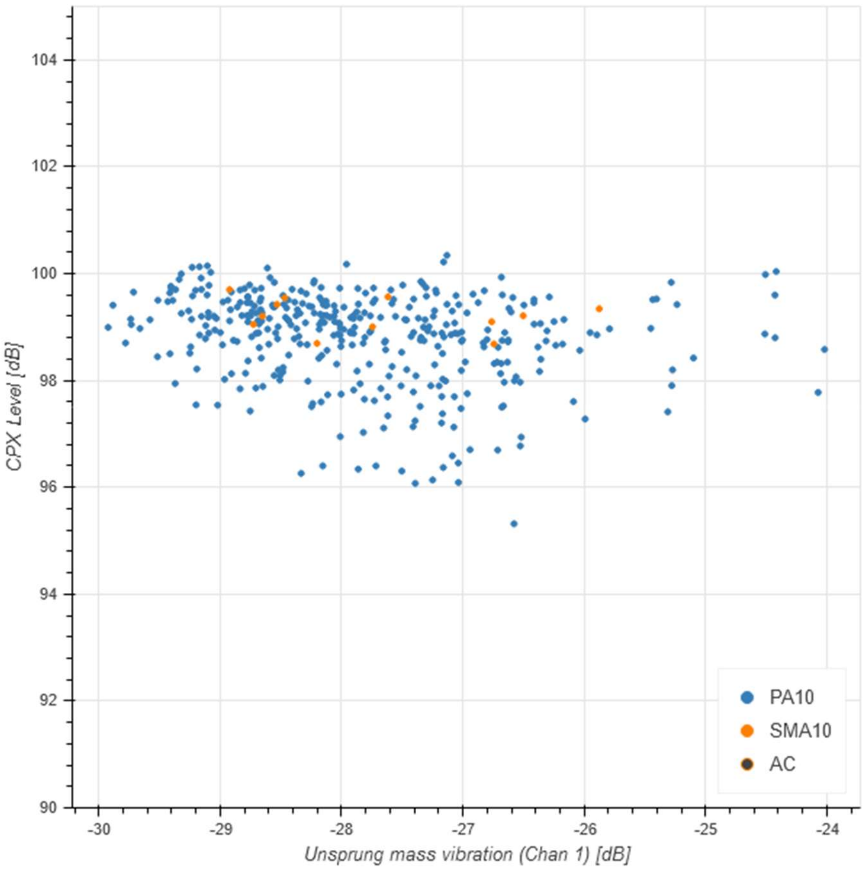
## A.4 Russley Road – SH1 - Southbound



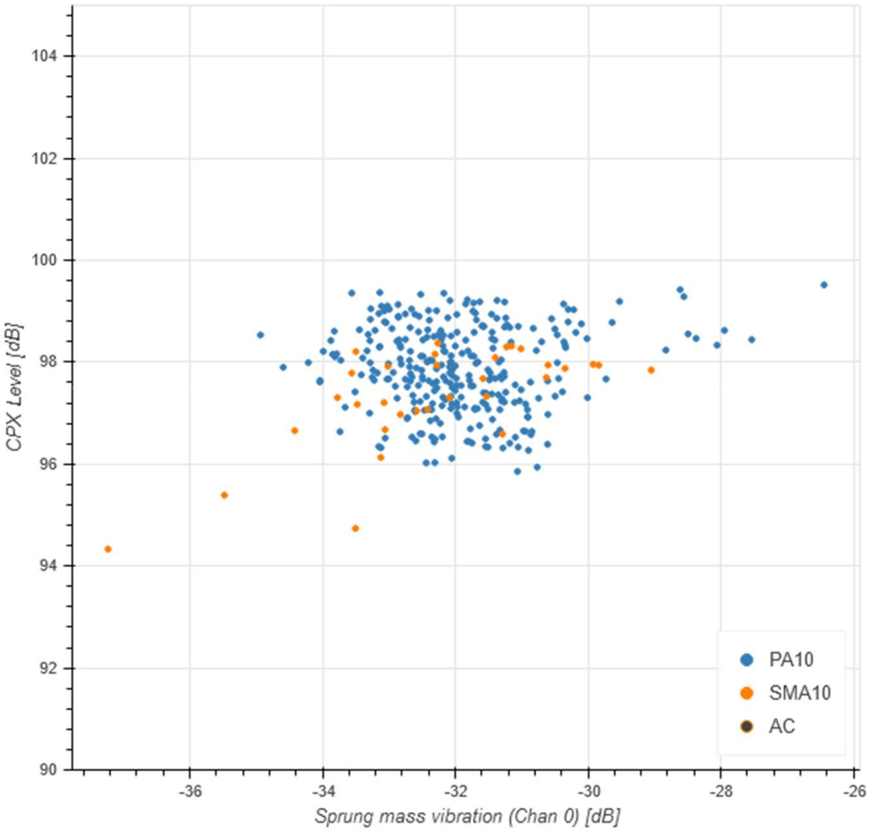
## A.5 Johns Road between Sawyers Arms Rd and Harewood Rd – SH1 - Northbound

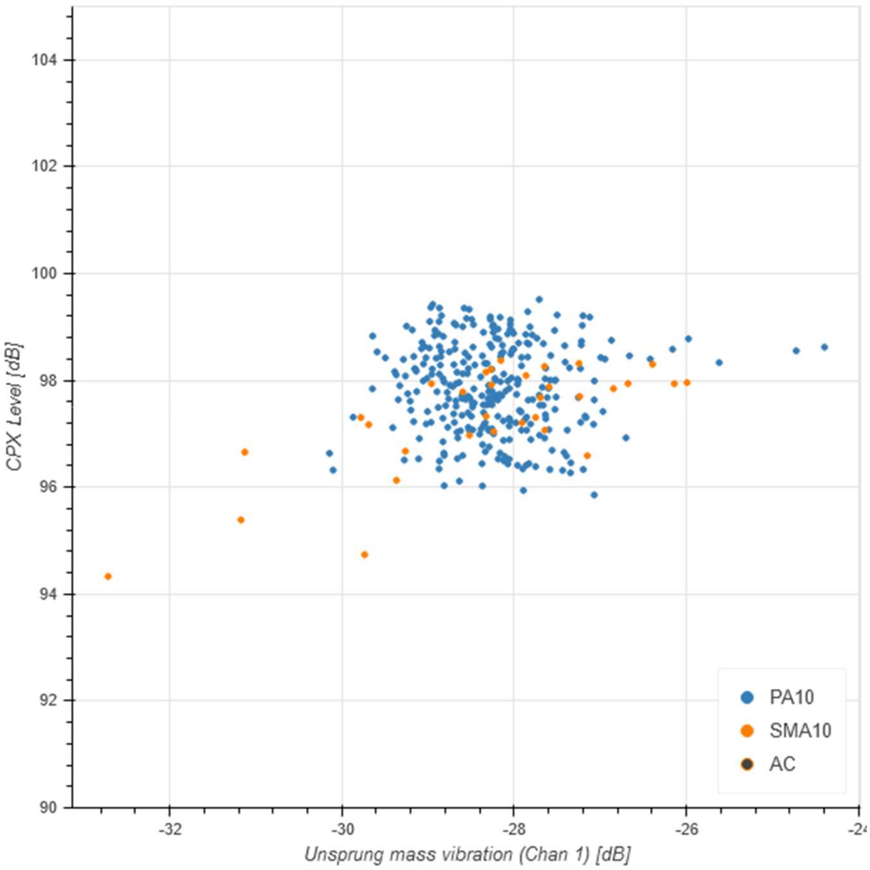


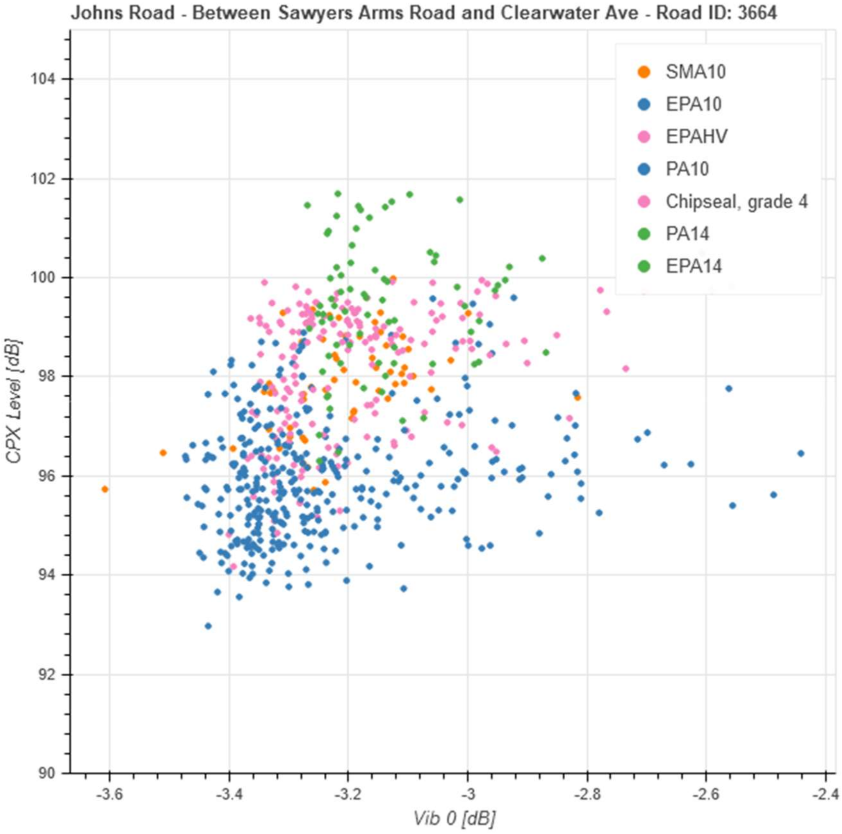
## A.6 Johns Road between Sawyers Arms Rd and Harewood Rd – SH1 - Southbound

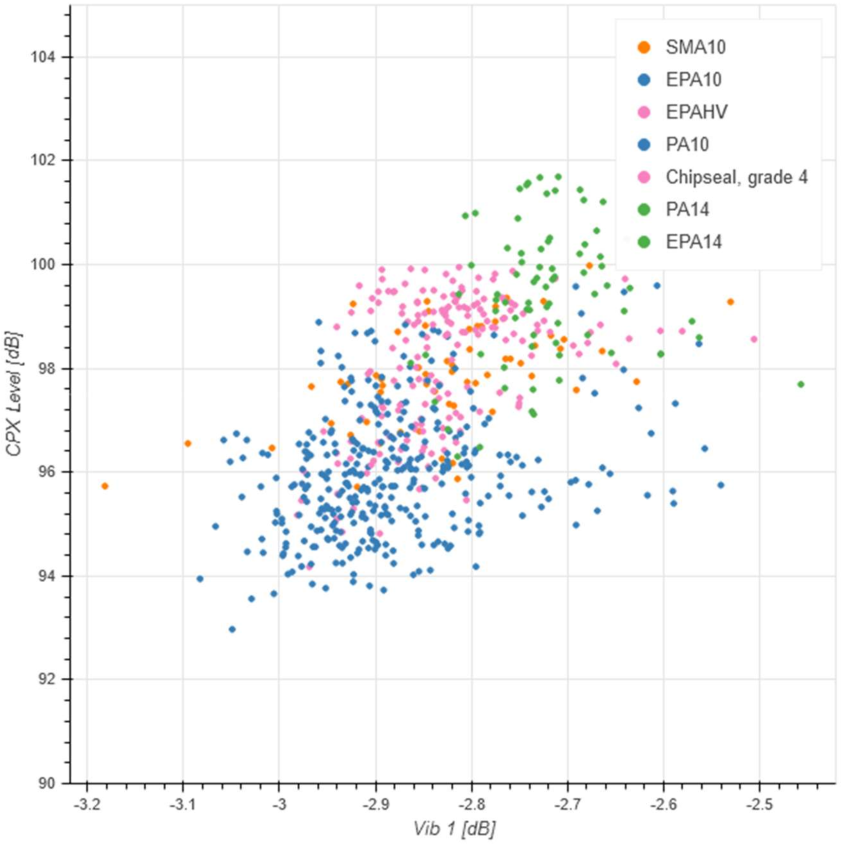
Johns Road - Between Sawyers Arms Rd and Harewood Rd - Road ID: 3588



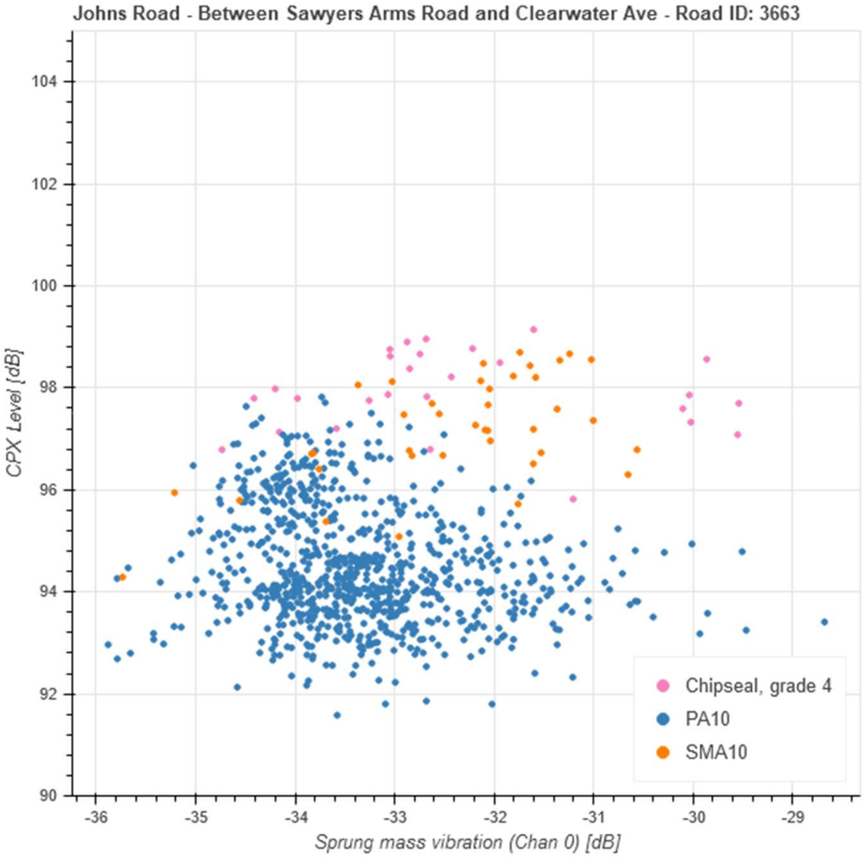



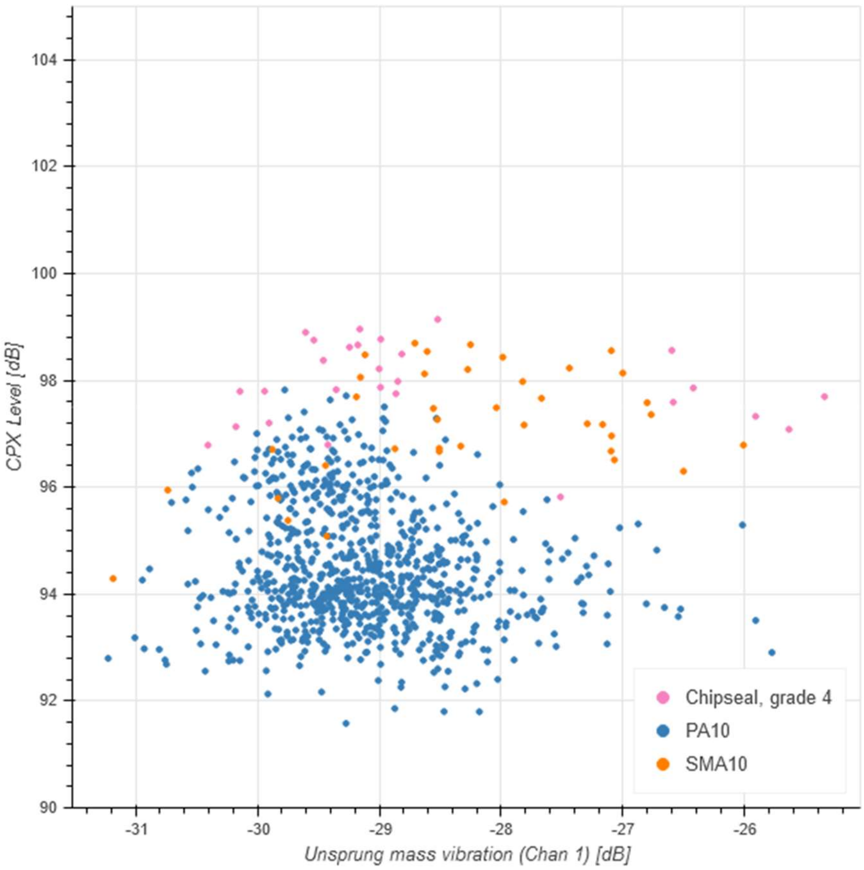
## A.7 Johns Rd between Sawyers Arms Rd and Clearwater Ave - SH1 - Northbound



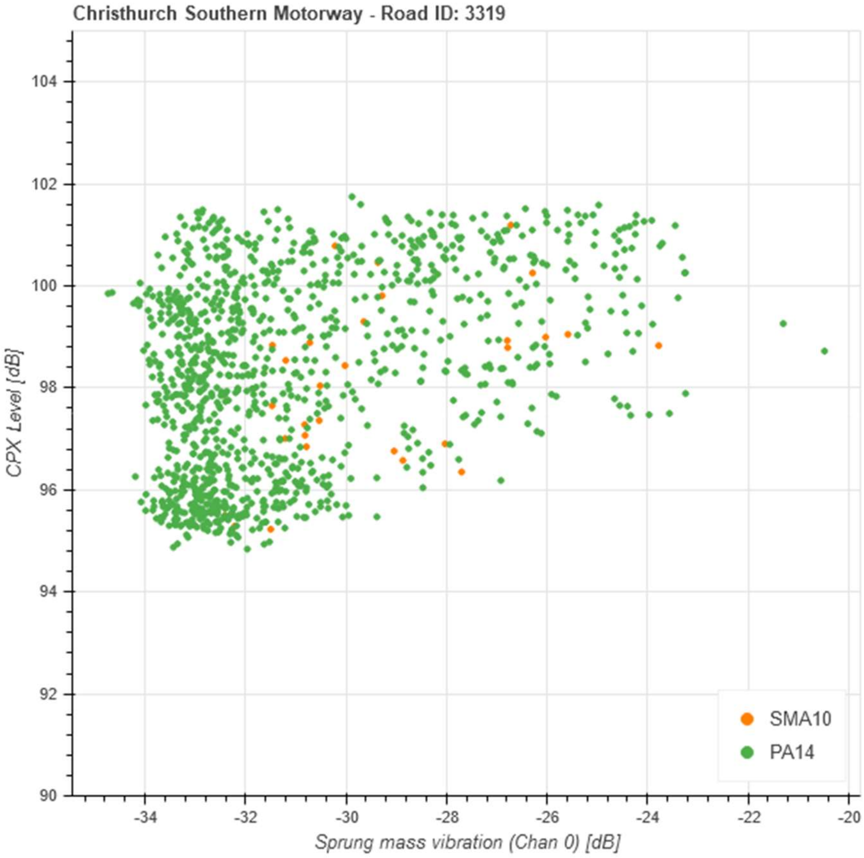



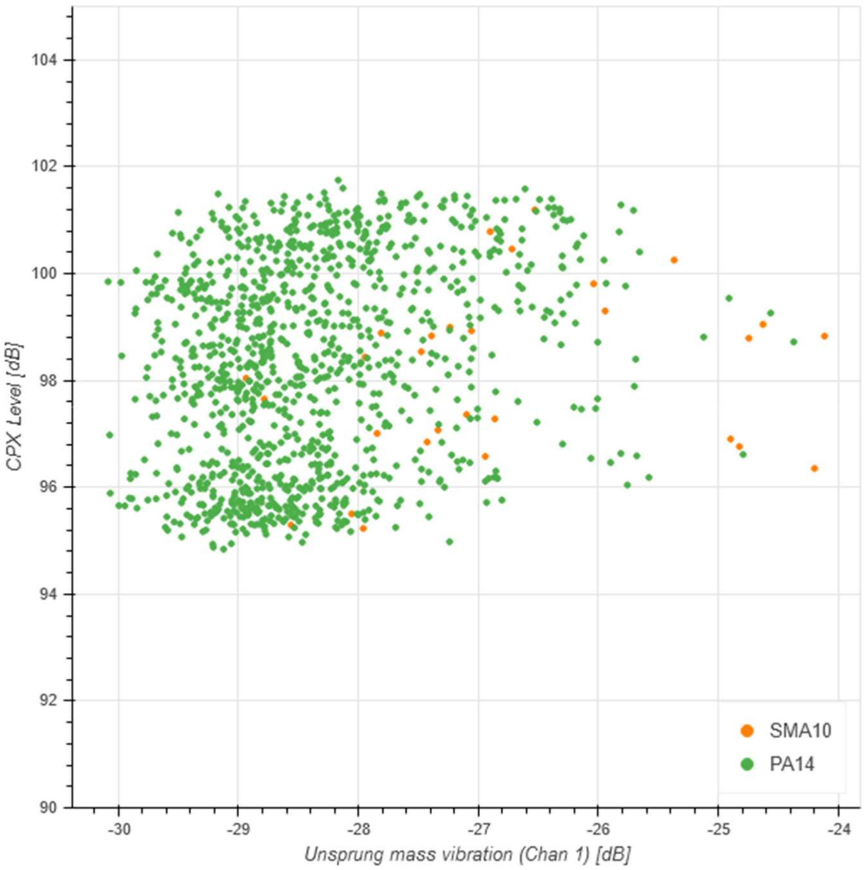
## A.8 Johns Rd between Sawyers Arms Rd and Clearwater Ave - SH1 - Southbound



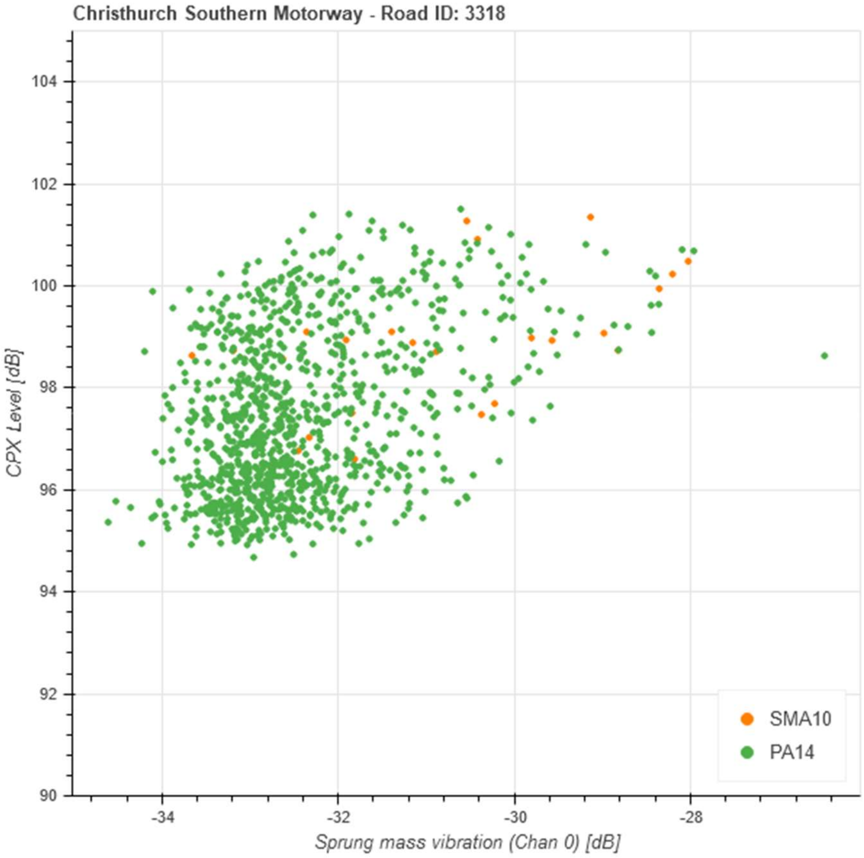



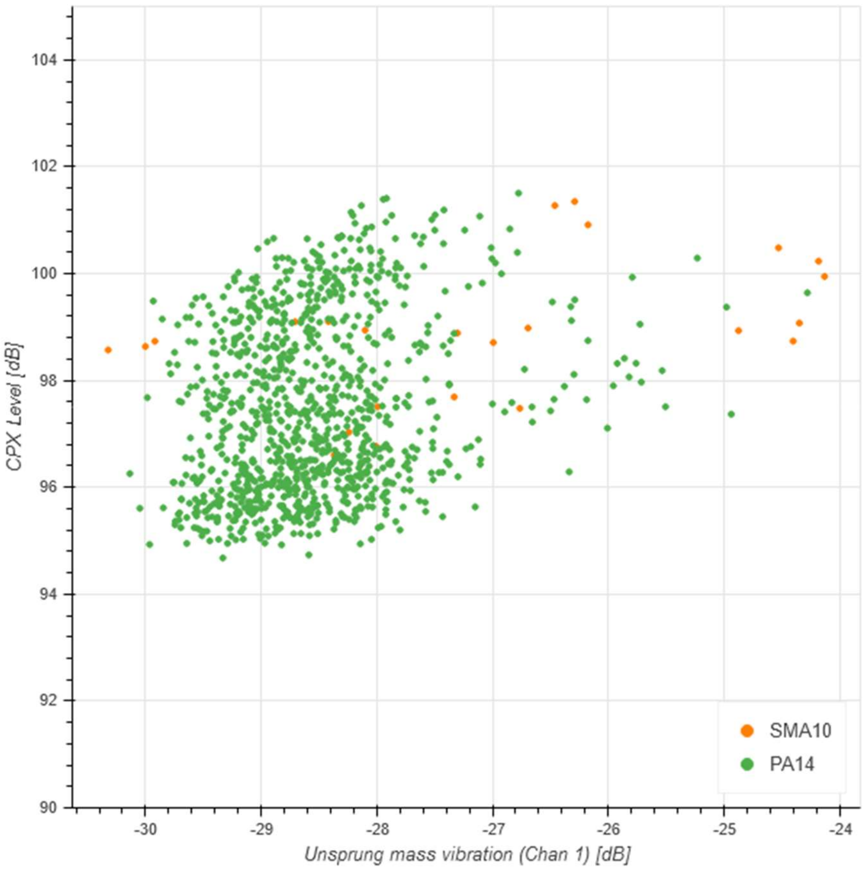
## A.9 Christchurch Southern Motorway - SH1 - Eastbound



## A.10 Christchurch Southern Motorway - SH1 - Westbound

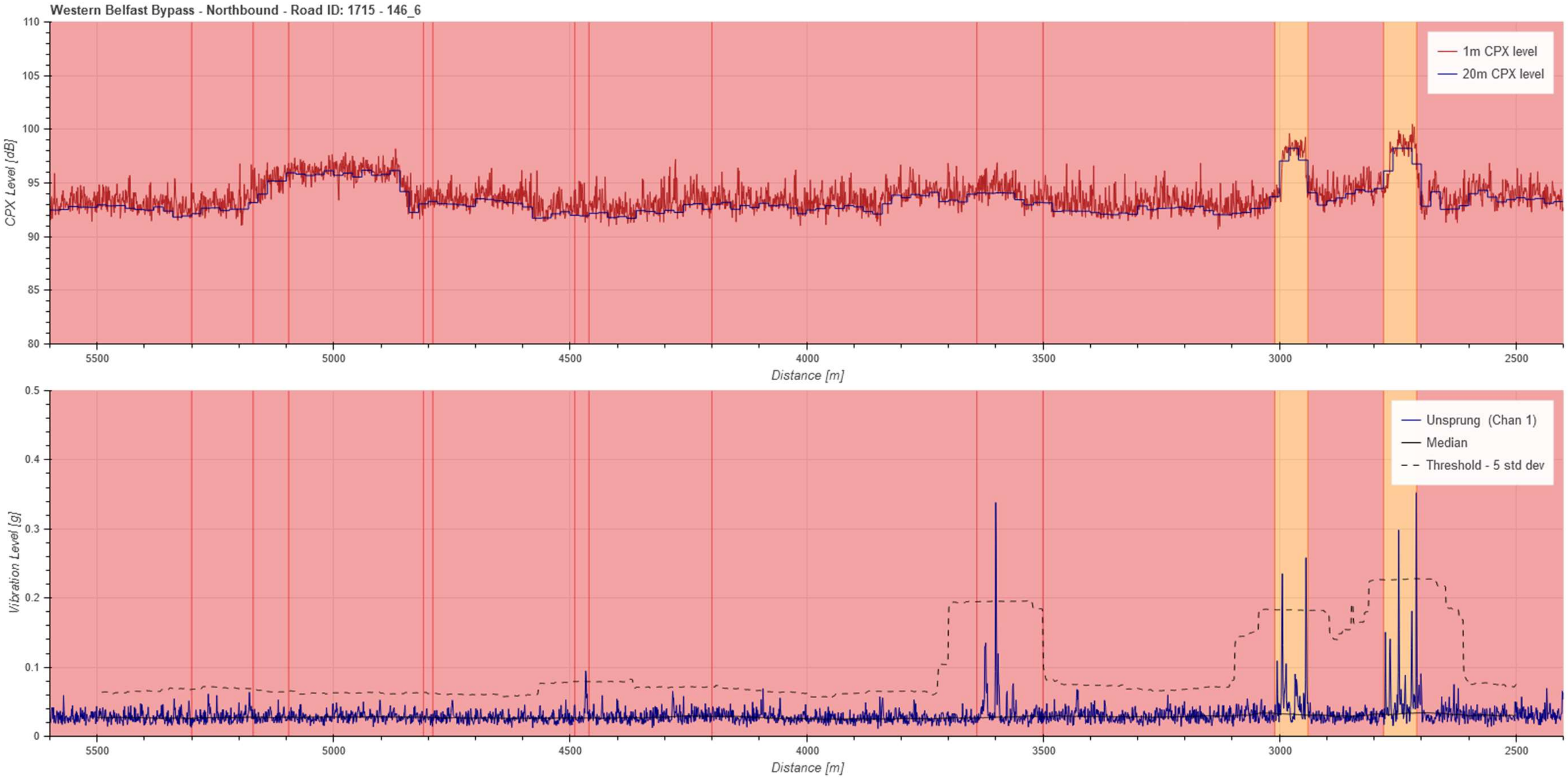


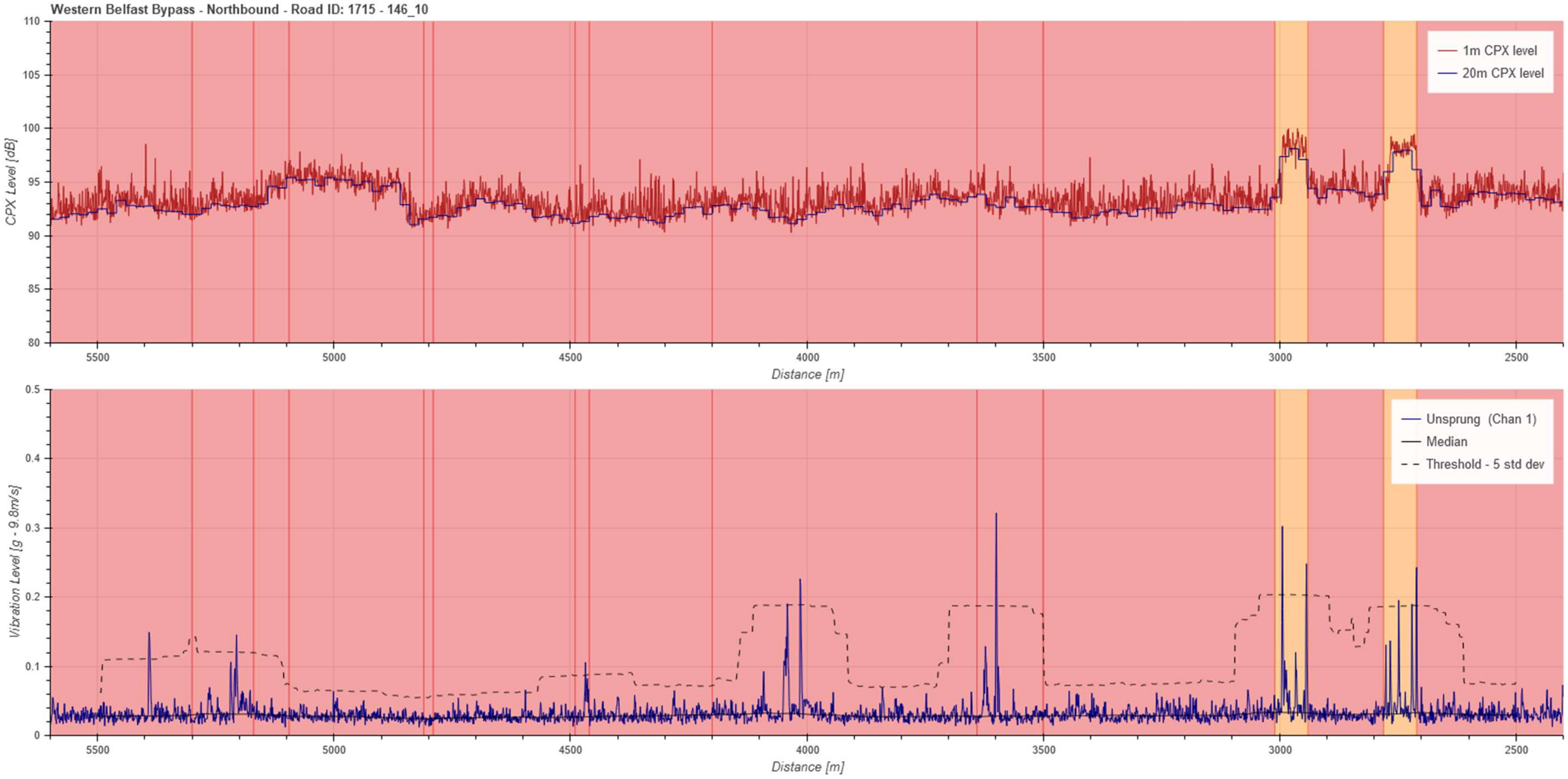



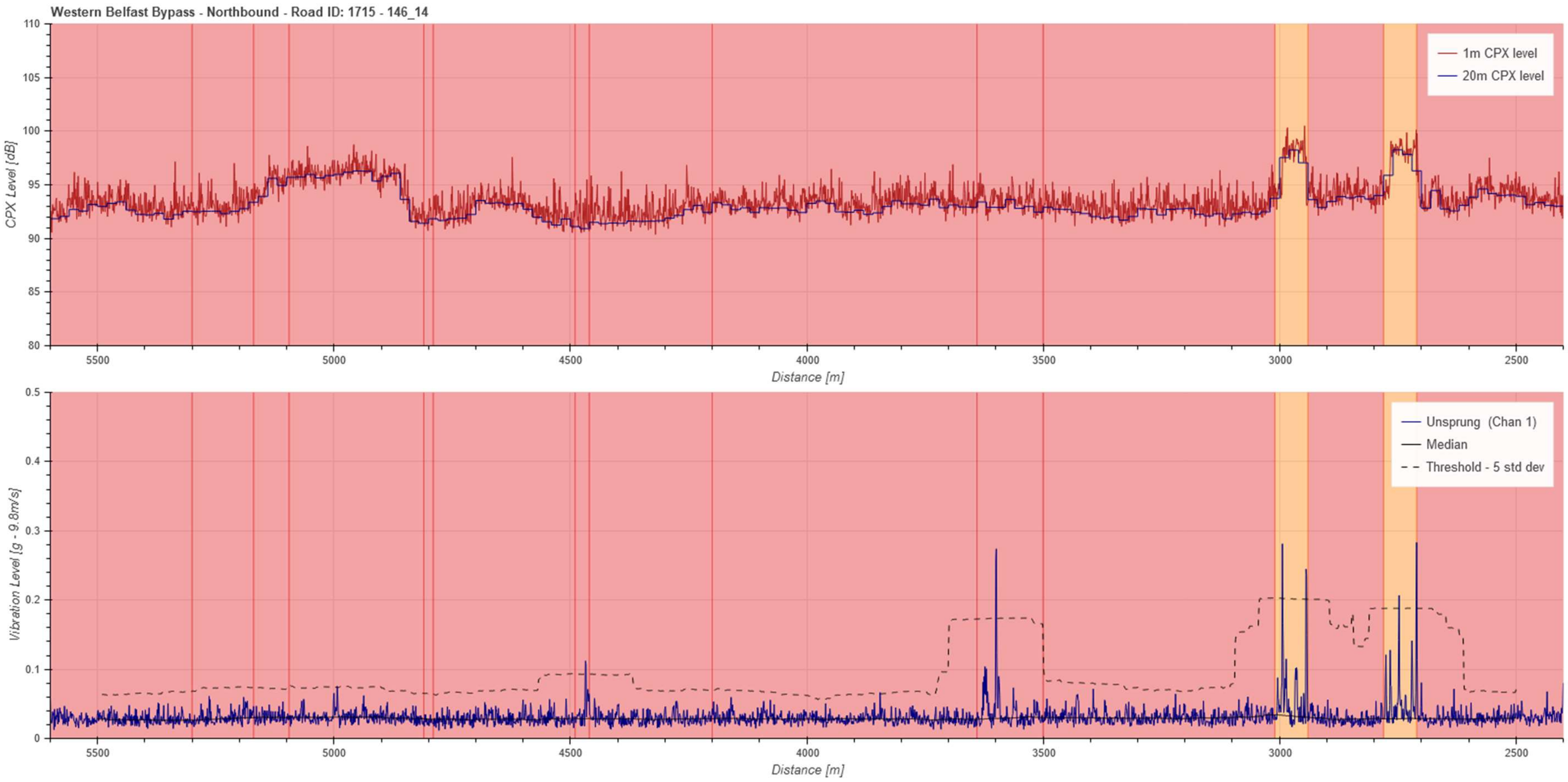
# Appendix B
# Detailed Peak Detection Plots

## B.1 Western Belfast Bypass – SH1 - Northbound

- The vertical red lines on these graphs are changes in the surface type in RAMM, the first changes are the three thickness trials on Western Belfast Bypass and the associated ramps.
- The events flagged using the current post processing method on this section are the joints identified in RAMM.




Western Belfast Bypass - Northbound - Road ID: 1715 - 146_10
1m CPX level
20m CPX level
CPX Level [dB]
Distance [m]
Unsprung (Chan 1)
Median
Threshold - 5 std dev
Vibration Level [g - 9.8m/s]
Distance [m]

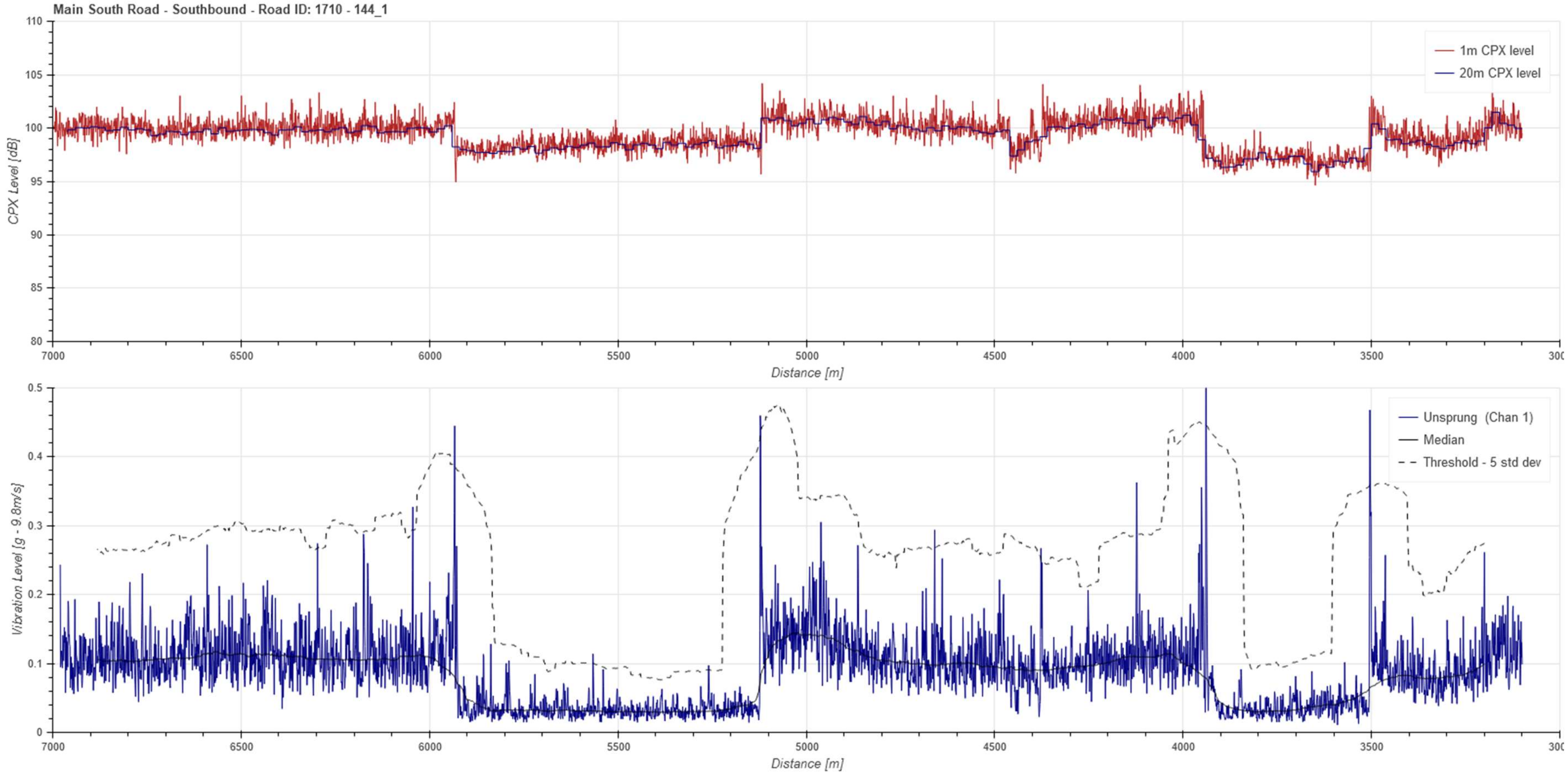

Western Belfast Bypass - Northbound - Road ID: 1715 - 146_14
1m CPX level
20m CPX level
CPX Level [dB]
Distance [m]
Unsprung (Chan 1)
Median
Threshold - 5 std dev
Vibration Level [g - 9.8m/s]
Distance [m]

## B.2 Western Belfast Bypass – SH1 - Southbound


Western Belfast Bypass - Southbound - Road ID: 1716 - 147_5
1m CPX level
20m CPX level
CPX Level [dB]
Distance [m]
Unsprung (Chan 1)
Median
Threshold - 5 std dev
Vibration Level [g - 9.8m/s]

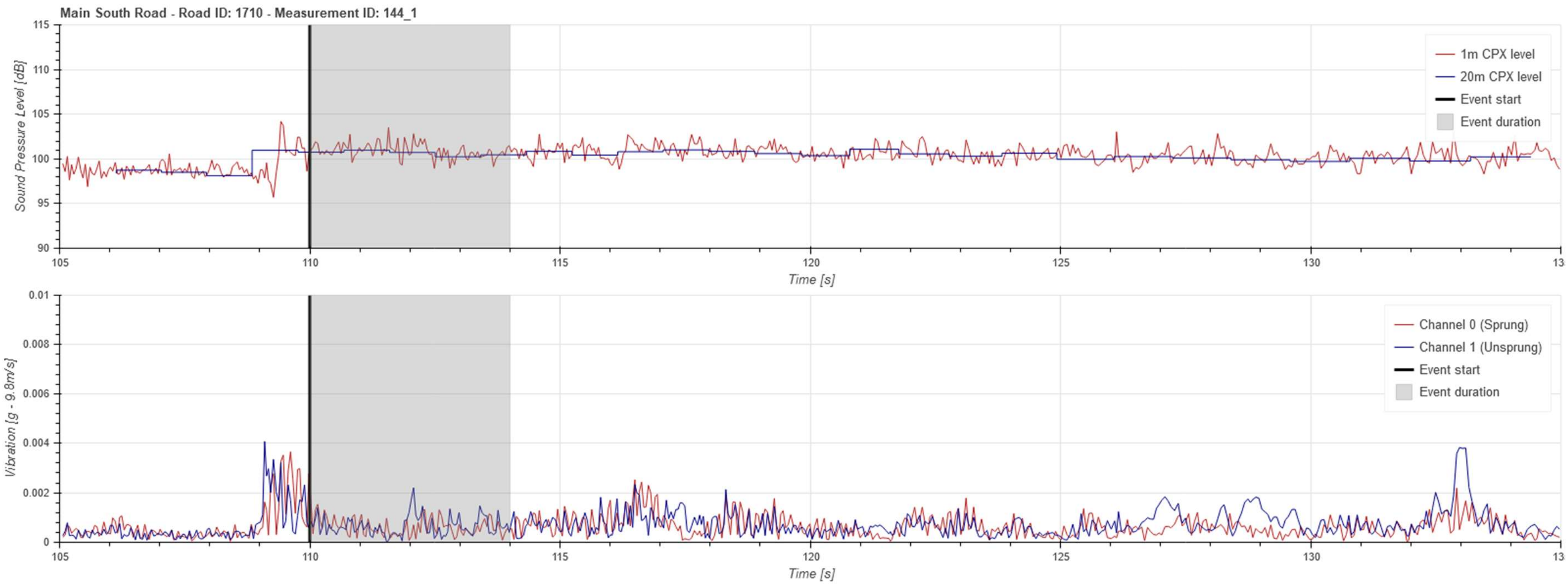

Western Belfast Bypass - Southbound - Road ID: 1716 - 147_9
CPX Level [dB]
110
105
100
95
90
85
80
2500
3000
3500
4000
4500
5000
5500
Distance [m]
1m CPX level
20m CPX level
Vibration Level [g - 9.8m/s]
0.5
0.4
0.3
0.2
0.1
0
2500
3000
3500
4000
4500
5000
5500
Distance [m]
Unsprung (Chan 1)
Median
Threshold - 5 std dev

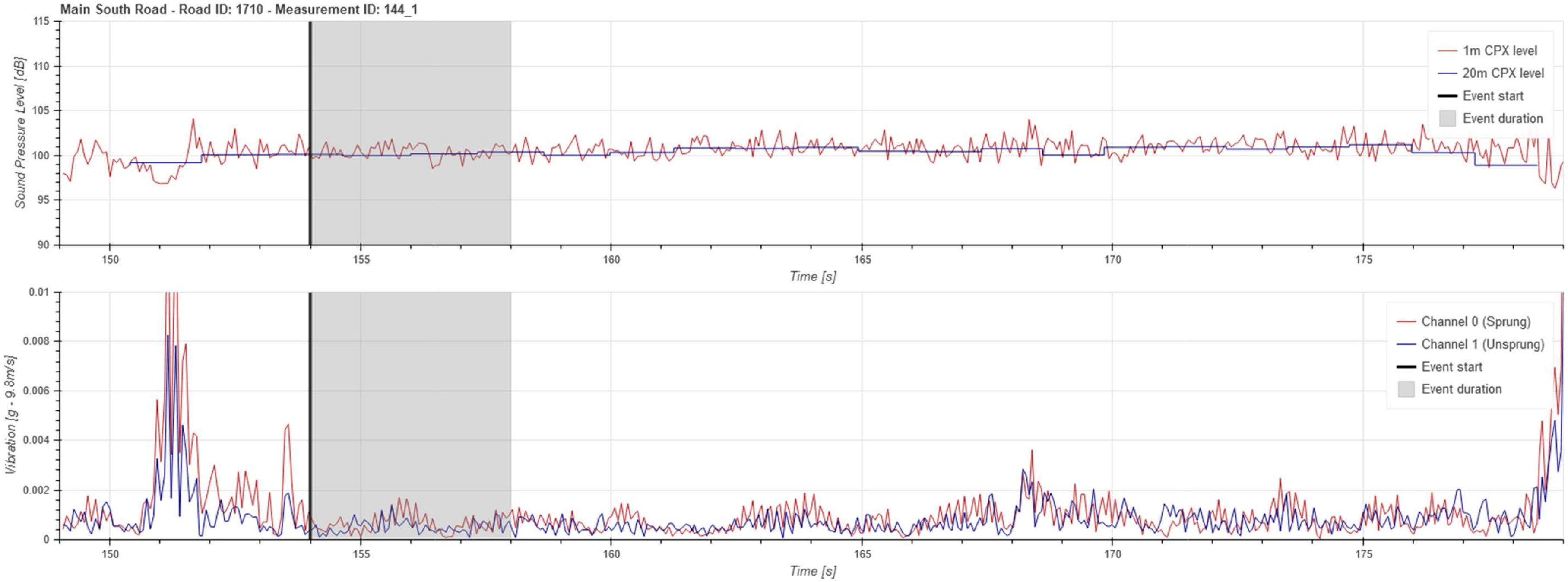
## B.3 Main South Road – SH1 - Southbound

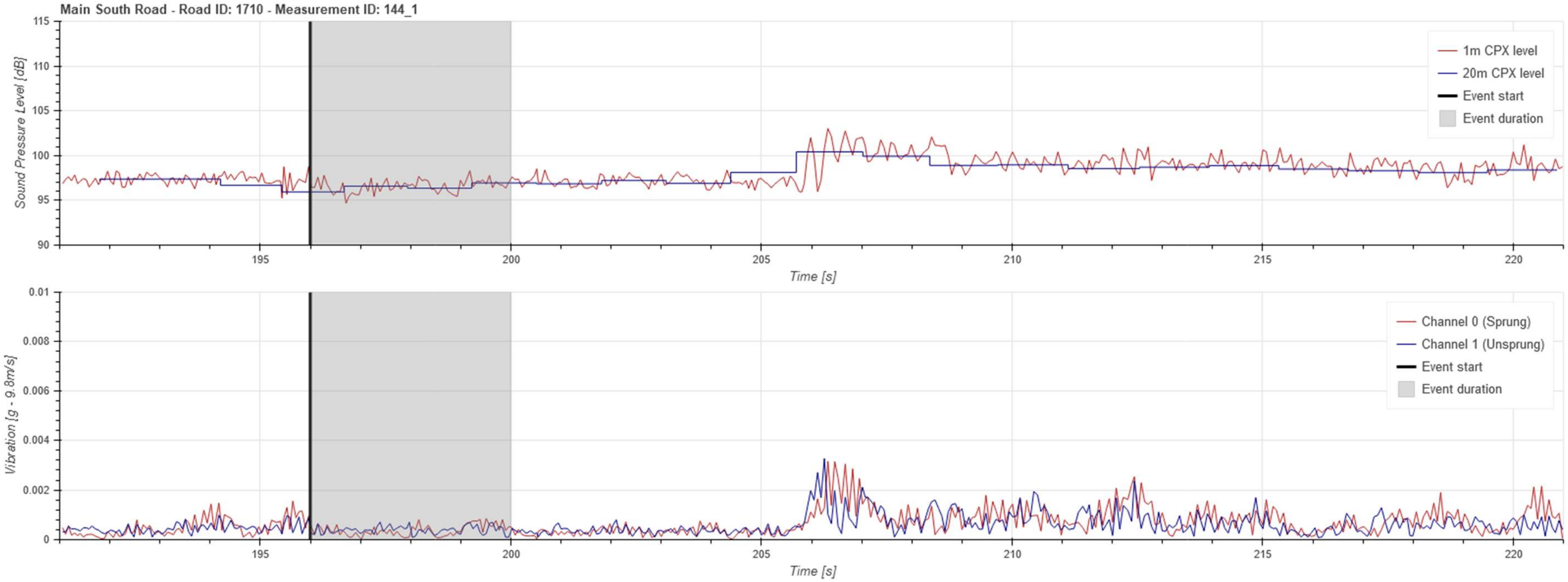


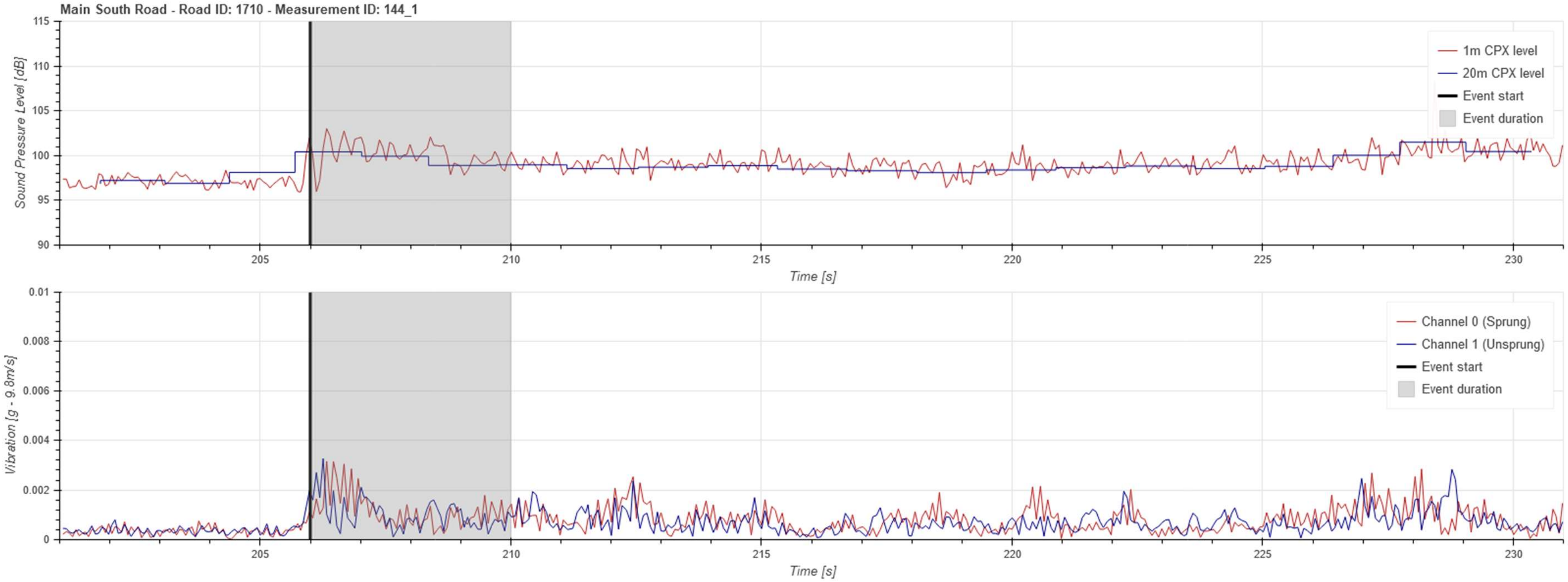
# Appendix C
# Low frequency fluctuations

## C.1 Main South Road – SH1 – Southbound




Main South Road - Road ID: 1710 - Measurement ID: 144_1
Sound Pressure Level [dB]
Time [s]
1m CPX level
20m CPX level
Event start
Event duration
Vibration [g - 9.8m/s]
Channel 0 (Sprung)
Channel 1 (Unsprung)


Main South Road - Road ID: 1710 - Measurement ID: 144_1
Sound Pressure Level [dB]
115
110
105
100
95
90
195
200
205
210
215
220
Time [s]
1m CPX level
20m CPX level
Event start
Event duration
Vibration [g - 9.8m/s]
0.01
0.008
0.006
0.004
0.002
0
Time [s]
Channel 0 (Sprung)
Channel 1 (Unsprung)
Event start
Event duration


Main South Road - Road ID: 1710 - Measurement ID: 144_1
Sound Pressure Level [dB]
115
110
105
100
95
90
205
210
215
220
225
230
Time [s]
1m CPX level
20m CPX level
Event start
Event duration
Vibration [g - 9.8m/s]
0.01
0.008
0.006
0.004
0.002
0
205
210
215
220
225
230
Time [s]
Channel 0 (Sprung)
Channel 1 (Unsprung)
Event start
Event duration