Prominence of impulses from road bridge expansion joints

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Summary

Vehicles driving over expansion joints on bridges generate impulsive noise additional to the ordinary vehicle pass-by noise. Neighbours to bridges have complained about annoyance from the many thousands of impulsive sounds 24/7, yet there is no tradition for taking the impulsive sounds into account when measuring or calculating road traffic noise.

For other types of noise – e.g. industrial noise – L_{Aeq} is adjusted with a penalty for prominent impulses. This paper describes measurements and analysis of the impulses from the joints according to the impulse prominence method described in Nordtest Acou 112 and British Standard 4142. Measurements were made before and after improvements of the joints and the road surface. Listening tests with 18 assessors on 64 samples of the impulses were also performed. From the measurements and listening tests it is concluded that the method can be used to quantify the impact on the environment of the impulses from the bridge expansion joints. The procedure is sensitive enough to detect the improvement of the expansion joints and there is high correlation between the physical prominence metric, P and the assessments of the prominence in the listening test ($R^2 = 0.95$ for average values).

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1. Introduction

Noise generated from vehicles driving over bridge expansion joints can be very annoying for the people living near the bridge. The joints generate impulse noise additional to the ordinary vehicle pass-by noise which causes extra annoyance. Inside cars, the excess annoyance is tolerable since it happens only a few times; but depending on the traffic flow it occurs hundreds of times, day and night, for the neighbours to the bridge.

For other types of noise – e.g. industrial noise – L_{Aeq} is adjusted with a penalty for prominent impulses. An objective impulse prominence method described in Nordtest Acou 112 [1] and British Standard 4142 [2] exists. The suitability of this method for this problem was tested and the method was used to enlighten the problem and the performed improvements of the expansion joints by repaving and levelling the road surface at the joints.

2. Purpose

The primary purpose was to measure the effect of the improvement of the joints, if any. Was there a measurable and audible improvement? It was also the purpose to test the impulse prominence method, in particular:

- Will the method work for impulsive sounds in pass-by noise with a sudden onset?
- Will it be sensitive enough to detect the improvement of the joints?
- Will the results correlate with perceptual assessments of the impulses from the expansion joints?

3. Location

The bridge considered is a 2x2 lane motorway bridge with a traffic flow on about 50.000 vehicles a day (yearly average) and with 10-15% heavy vehicles. The motorway is a part of E45 connecting the northern part of Scandinavia with the Central and Southern part of Europe (figure 1).
After a bridge renovation in 2014 the neighbours started complaining over the impulsive noise from the vehicles on the bridge. People living up to 1500 metres from the bridge were complaining. In 2016 the Danish Road Administration decided to investigate the reason for the many complaints by conducting measurements close to the bridge and close to the neighbours' residences.
Later, it was decided to improve the road surface by smoothening the transition zone between the road surface and the expansion joints.

4. Measurements

Measurement campaigns were made before (M1) and after (M2) the improvement work. The campaign M1 in June 2016 showed numerous audible impulses in the noise from the road bridge up to 5-600 metres from the bridge. The measurements were repeated in November 2017 after the improvements (M2) in the exact same measuring positions. Due to the long distances measurements were made with a positive wind component from the bridge towards the measurement positions. Average wind speed M1: 5-6 m/s, SE. M2: 2-3 m/s, SE. This fulfils the requirements for outdoor noise measurements [3].

In the evaluation, measurements in three positions (height: 1.6 m) were performed (P1, P5 and P8, figure 1):

- P1: Close to the road, 4.3 metres from the centre of the nearest lane on the bridge.
- P5: 450 metres from the bridge (P1) in the direction of the nearest residences approx. 600-1000 metres from the bridge (P1).
- P8: A reference position 11 metres from the centre of the nearest lane with no expansion joints, thus characterizing the "ordinary" vehicle noise.

The measurements were made using NoiseLAB Capture 4.0 with ½" microphones (G.R.A.S. type 40E) connected to a hard disc recorder (Sound Devices 744T). On a separate channel voice notes were recorded identifying the type of vehicle.

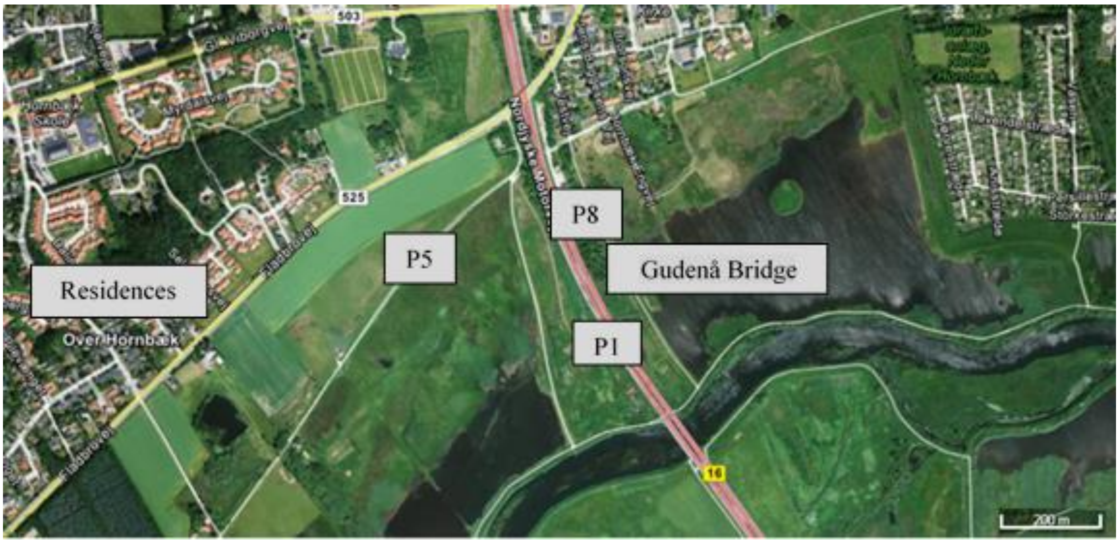

Figure 1. Overview of measurement site and Gudenå Bridge. North is upwards.

5. The Impulse prominence method

The method aims at predicting the prominence of impulsive sounds in correspondence with average subjective assessments. Based on the predicted prominence, P, a graduated adjustment, K_I, to the measured L_{Aeq} is defined. The adjustment depends on how prominent the impulse characteristic is perceived through the continuous part of the noise.

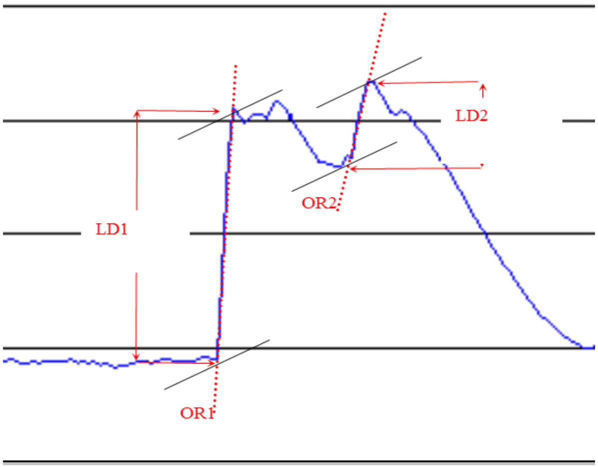

Figure 2. General illustration of the impulse prominence method. The blue curve is the A-weighted sound pressure level with time weighting F as a function of time. LD and OR indicates the Level Difference [dB] and the Onset Rate [dB/s] for each of the shown impulses. The onset starts and ends at slopes of 10 dB/s (black lines).

The method defines the sudden onset of a sound as an impulse.
The prominence metric, P is defined as:

$$P = 3 \cdot \log(OR/[dB/s]) + 2 \cdot \log(LD/[dB]) \quad (1)$$

When measurements are made close to a road the sudden onset of the pass-by noise may (intentionally) also be measured as an impulse, see figure 3.

In the present project this is overcome by manually calculating the level difference and onset rate of the impulses on top of the pass-by onset.

For future measurements this problem can be solved using larger distances to the road, see table 1. This means that smaller onset rates of the pass-by noise itself makes it easier to detect the impulse sound.

Table 1. Minimum microphone distance to vehicles for theoretical onset slope less than 10 dB/s. Double the distance is recommended in practice.

Speed, km/h	50	70	90	110	130
Min. distance, m	7	9	11	14	16

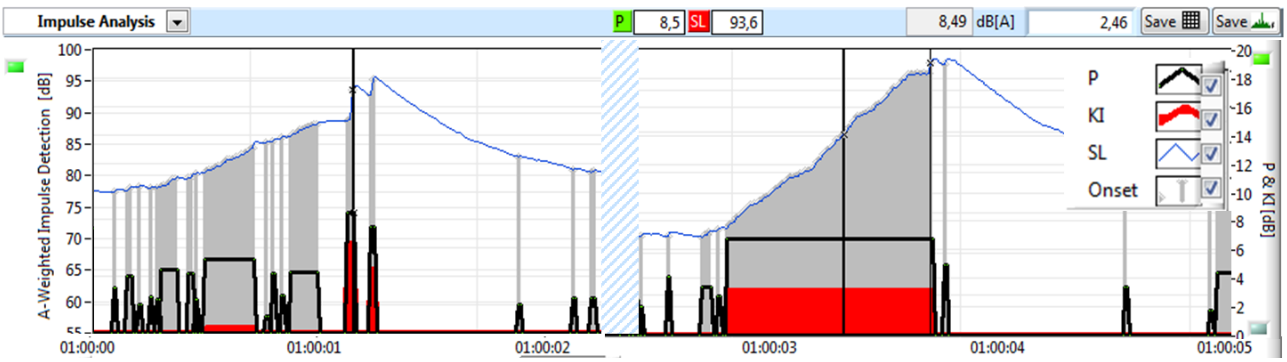

Figure 3. Impulse analysis with the NoiseLab software. Left pass-by illustrates automatically detected impulses. Right pass-by illustrates the onset of the pass-by detected as an impulse. Legend: Blue: A-weighted sound pressure level with time weighting F. Grey: Onset. Black: P. Red K_I.

6. Measurement results

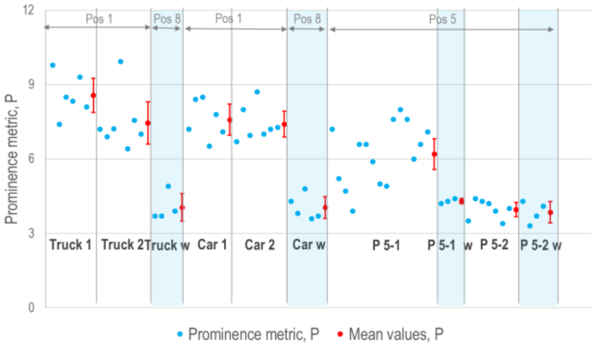

Figure 4. Results of the impulse prominence metric for the 64 pass-bys used in the listening test. Blue points: Measured P-values per sample. Red points: Average values and 95% confidence intervals. Truck 1 and 2, Car 1 and Car 2: Trucks/passenger cars in P1 before and after the improvement. Truck w/Car w: Trucks/passenger cars in P8 without impulses. P5-1 and P5-2: Impulses in P5 before and after. P5-1 w and P5-2 w: Samples with no or barely audible impulses.

The results in figure 4 show high impulse prominence in position P1 (at the bridge joints) for trucks and passenger cars and low prominence in P8 (no joints) indicating that the impulse prominence method works as intended. For the before and after situation there is an improvement for trucks in position (P1) but only a small tendency for improvements for the passenger cars. In the remote position (P5) higher P-values for situations with impulses than for situations without (P5-1 w and P5-2 w) indicates that the method works as intended also in the remote position. The average value indicates a clear improvement in the after situation. It should be noted that the L_{Aeq} of the background noise in the after situations was 6 dB higher than in the before situation which partly may have masked some of the impulses.

Figure 4 also shows large variations in the results from different vehicles both for trucks and for passenger cars. Therefore, measurements on more pass-bys than the ones used for the listening tests were made.

The following results are based on measurements on 200-600 vehicles in each position. All numbers are adjusted from the actual number of vehicles per hour to the average traffic flow of 1500 vehicles per hour so direct comparison is possible.

On the following figures the number of impulses based on an automatic analysis in P-intervals P=2 (1.5-2.5), P=3 (2.5-3.5) etc. are shown.

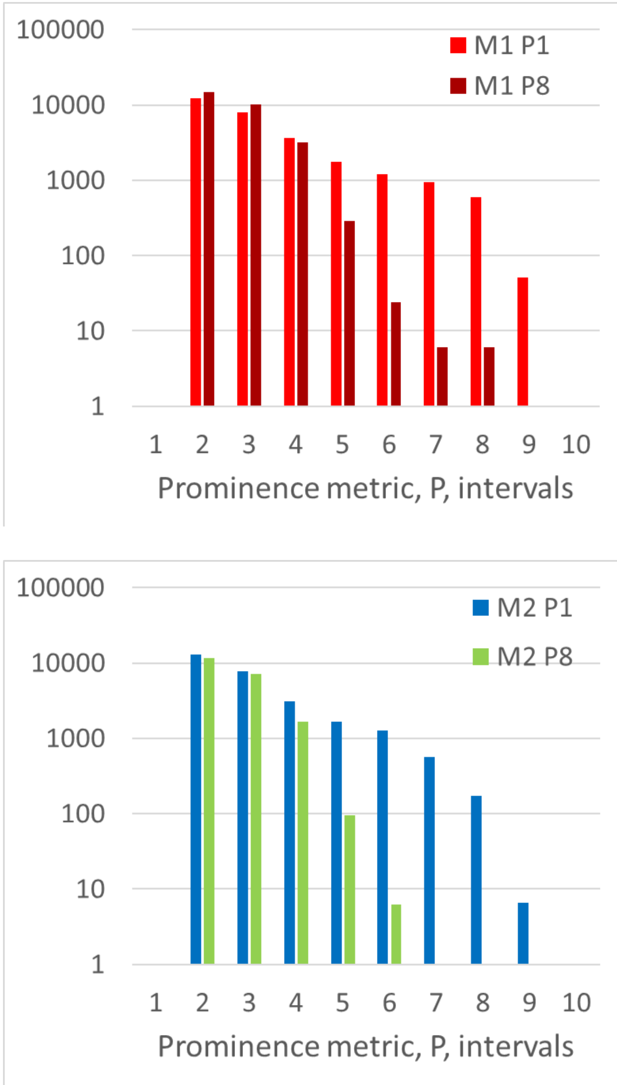

Figure 5. Number of impulses in P1 and P8 per hour for P-values in integer intervals, normalized to 1500 vehicles/hour, before (M1) and after (M2) the improvement.

Figure 5 shows that the number of impulses with P-values 4 and below are essential the same in P1 (with joints) and P8 (without joints). These small pulses may origin from random fluctuations and from the onset of the vehicles passing close by the microphone. The fewer impulses with P-values around 5 in P8 may also be caused by smaller onset rates caused by the larger distance to the road compared to P1. Impulses with P-values 6 and larger may mainly origin from the joints.

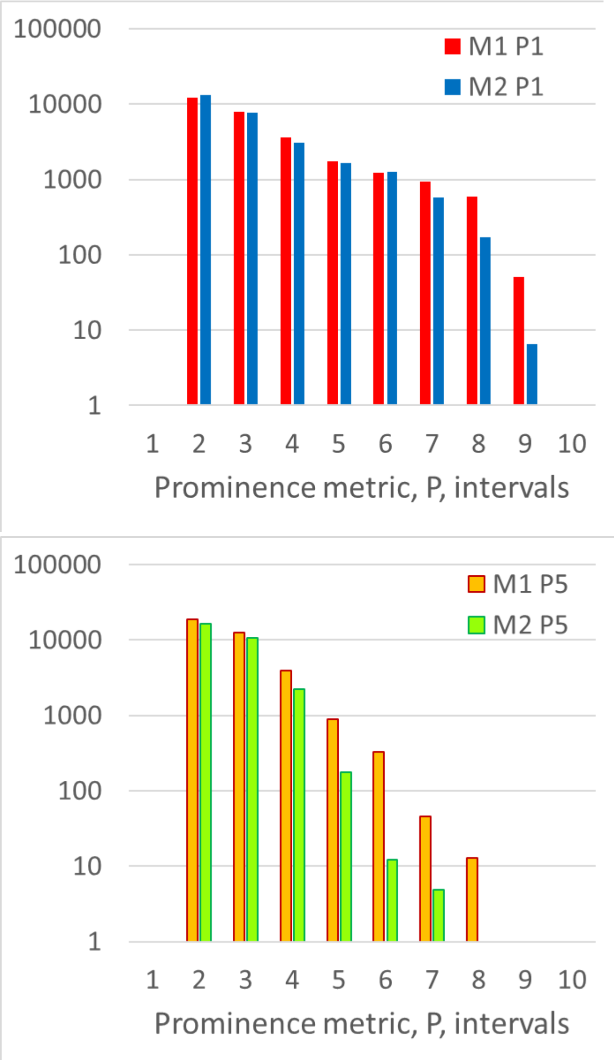

Figure 6. Number of impulses per hour for P-values in integer intervals, normalized to 1500 vehicles/hour, in positions P1 and P5 before (M1) and after (M2) the improvement.

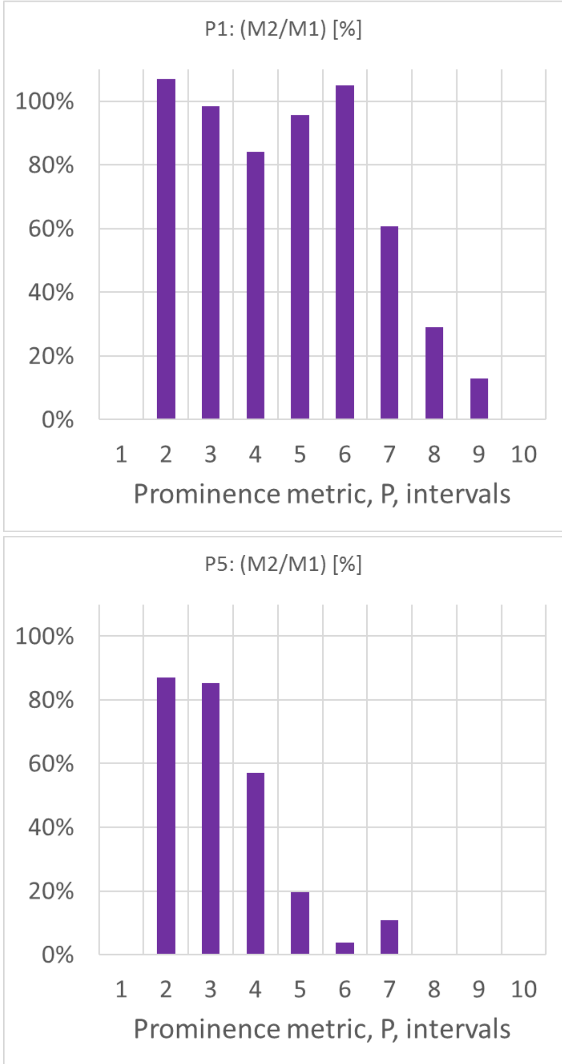

Figure 7. Percentage of change from M1 (before) to M2 (after) in the number of impulses for P-values in integer intervals, in positions P1 and P5.

Figure 6 shows there is a reduction in the number of impulses in P1 for P-values above 6. The reduction in P5 is for P-values above 4-5. Part of the latter is probably caused by the higher background noise level in the situation M2 (after).

The change is illustrated clearly in figure 7. Impulses with P-values below 6 may not relate to the joints, because some of the measurements were performed closer to the road than recommended in table 1. In case of industrial noise, the penalty according to [1] and [2] should be as shown in table 2. Also for this reason impulses with P-values of 6 and above are most important.

Table 2. Relation between the prominence metric, P and the adjustment to L_{Aeq} for prominent impulses.

Prominence metric, P	5	6	7	8	9
K_I, dB	0.0	1.8	3.6	5.4	7.2

From the measurements it is conluded that there has been an essential reduction in the number of prominent impulses. We don't know whether this reduction is satisfactory for the neighbours. The audibility of the impulses is dealt with in the next paragraphs.

7. Listening tests

A listening test was performed on 64 samples of the recordings made on the bridge (P1), near the road (P8), and 450 m from the bridge (P5), see figure 1.

18 assessors (ages 26-69 years, mean: 39 years, 14 men and 4 women) participated. 14 of the assessors were trained in assessing audio systems and 4 were acousticians working in the field of environmental noise.

The sound samples were 6 seconds long and were presented to the assessors over headphones (Sennheiser HD 449) at calibrated levels. The SenseLabOnline listening test software [6] was used for presenting the stimuli (with one repetition) in a randomized order for each assessor and for collecting their assessments. As the software is an online tool with full audio quality over the Internet [7], 14 of the assessors performed the test in their homes. The rest of the tests were performed in a listening booth.

The home tests were calibrated by a speech sample which the assessors adjusted to normal speech level. From a former investigation [8] it is known that the speech will be adjusted to an average of 64 dB with a standard deviation of 4.5 dB. The calibration of the headphones in the booth was made with ordinary technical means and will be accurate within 1 dB.

The assessments were made on the scale shown in figure 8.

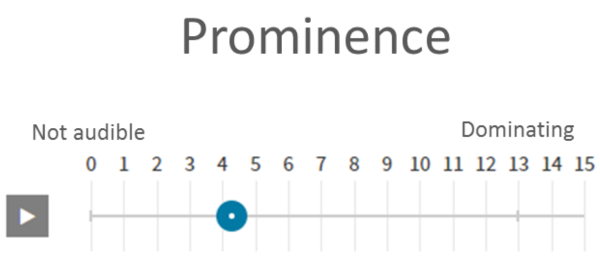

Figure 8. Scale used for the assessments in the listening test. "Indicate how prominent you perceive the impulses relative to the other noise".

The samples were presented one by one with no direct way of comparing samples during the assessments.

The assessors were asked to imagine the following scenarios:

Position P1 and P8: "You are standing near the road on the bridge. Assess the prominence of the impulses. If there are more impulses in the example, the assessment is given for the most prominent"

Position P5: "You should imagine being outdoors on a bench in a park or in your garden in a relatively peaceful suburb. You constantly hear the traffic from the road and the background noise, which originates mainly from distant traffic. Assess the prominence of the impulses. If there are more impulses in the example, the assessment is given for the most prominent"

8. Listening test results

The assessor's performance on discrimination and reliability was tested with the eGauge method [9]. All assessors showed satisfactory performance although the scale usage of some of the assessors trained in audio was rather extreme compared to the acoustic experts. Three assessors with high assessments of impulse prominence in position P8 (no joints) were excluded from positions P1 and P8. The results on the perceived impulse prominence are shown in figure 9.

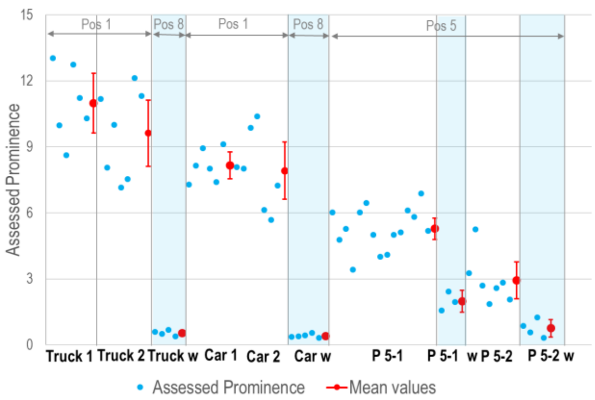

Figure 9. Results of the impulse prominence assessment for the 64 pass-bys in the listening test. Blue points: Average assessments of assessors. Red points: Average values and 95% confidence intervals. Truck 1 and 2, Car 1 and Car 2: Trucks/passenger cars in P1 before and after the improvement. Truck w/Car w: Trucks/passenger cars in P8 without impulses. P5-1 and P5-2: Impulses in P5 before and after. P5-1 w and P5-2 w: Samples with no or barely audible impulses.

By comparing the perceptual assessments in figure 9 with the physical measurements of the prominence in figure 4 it is concluded that the general pattern is very alike.

From the perceptual assessments it is conluded that for the before and after situation there is an improvement for trucks at the bridge but only a small tendency for improvement for the passenger cars. In the remote position P5 there is also a clear improvement in the after situation.

9. Combined results

Figure 10 compares the physical measurement of the prominence metric with the perceptual assessments of prominence from the listening test for each of the 64 samples. Generally, there is a high correlation although some of the vehicles are positioned far from the linear regression line.

Figure 11 shows a high correlation (R^2=0.95) between the physical metric P and the perceptual assessments. All confidence intervals except for point P5-2 overlap the trendline.

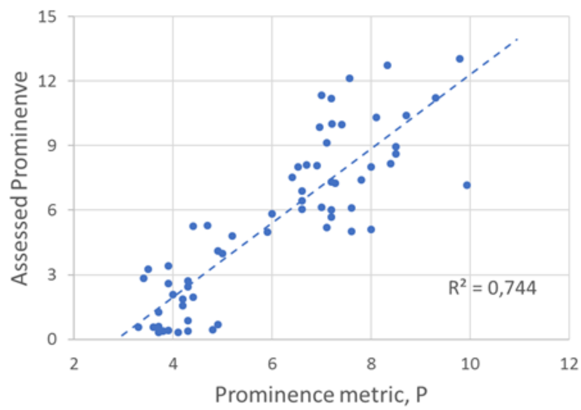

Figure 10. The physical measurement of the prominence metric, P) versus the average perceptual assessments of prominence from the assessors in the listening test. Each point represents one pass-by sample.

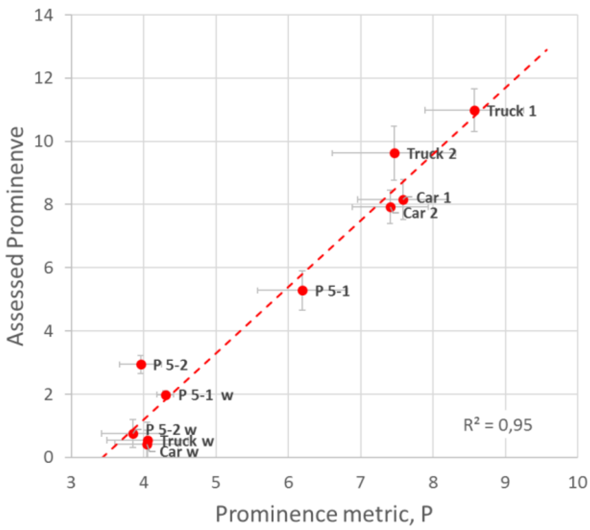

Figure 11. Average values and confidence intervals of the physical measurements of the prominence metric, P versus the average perceptual assessments of prominence. Truck 1 and 2, Car 1 and Car 2: Trucks/passenger cars in P1 before and after the improvement. Truck w/Car w: Trucks/passenger cars in P8 without impulses. P5-1 and P5-2: Impulses in P5 before and after. P5-1 w and P5-2 w: Samples with no or barely audible impulses.

Consequently, a decrease in the prominence of the impulses can be heard and the correlation with the physical metric is satisfactory. This method can be used for a quantification of the perceived impulse prominence.

10. Conclusions

The following conclusion can be drawn:

- The impulse prominence method is applicable for measurements on bridge expansion joints.
- The pass-by onset slope will trigger the impulse procedure unless the measuring distances is larger than 15-30 m (dependent on vehicle speed).
- The procedure is sensitive enough to detect the improvement of the expansion joint.
- There is a good correlation between the physical metric P and the assessments in the listening test ($R^2 = 0.95$ for average values).
- There was a measurable and audible improvement of the bridge expansion joint.

The overall conclusion: The impulse prominence method can be used to quantify the impact of the impulses from the bridge expansion joints on the environment.

Acknowledgement

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