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Development of an index for quantification of structural dynamic response in a railway catenary section

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ABSTRACT

In an attempt to quantify the amount of the dynamic reaction in a railway catenary system due to the dynamic action created by the interaction with the pantograph of the train, a catenary dynamic index (CDI) is developed. The index is intended for comparing structural dynamic responses in different situations. Comparisons between positions in a catenary to evaluate the design or comparisons between passages to evaluate train passages and automatically tell if a pantograph is faulty. This index can be a helpful tool for infrastructure managers, designers and academics to evaluate both measured and simulated data as well as controlling trains in the rail network. The CDI is computed for a given position on the catenary using the response before and after train passage. This involves both the pre-passage interaction dominated phase and the catenary free vibration phase of the catenary response. This approach is significantly different from using the pantograph contact forces since the contact forces only gives one value per contact point, while the index describes a single point over a period of time, both along the wire. More important, this method can assess a great variety of train passages, in stark contrast to the contact force measurements, which describes the behaviour often from one single control train with very limited number of passages a year (in Norway no more than two times). Therefore, the CDI quantitatively describes the energy content in a railway catenary for a whole train passage. This paper presents the method and results when using the CDI on field measurements. The results show that the catenary dynamic index can describe important variations the dynamic response of a catenary system and that it changes with changing boundary conditions. During a short monitoring period the method identified successfully two real outliers, important for the infrastructure owner, and showing a suitability for structural health monitoring.

1. Introduction

The quantification of the amount of vibration in civil engineering structures makes it possible to compare the dynamic response in structures of the same type with different outlines. Railway catenary systems exist in many different configurations depending on country, designer and train speed. However, these systems are all cable systems with the same types of components exposed by the same type of action, namely, the pantograph of the train. The ability to compare the dynamic response of these catenary systems is important for researchers and infrastructure owners so that decisions regarding design, renewal and research can have values that they can relate to.

The cable system supplying electric energy to a train, i.e., the railway catenary system, is a structure whose main task ensures a stable electric power transfer to the train. The cable system is in direct contact with the pantograph on the train, and its response is of utmost importance as the train travels along a catenary section. The whole system consists of two nonlinear dynamic systems in contact: the in-space stationary catenary system and the moving pantograph. A catenary section, a cable system with a length up to 1.5 km, consists of approximately 25 pole spans. This system length means that a train entering a section initiates a dynamic response that is propagated along the 1.5 km long cable system. The design of the spans is generally not equal, so the behaviour of the catenary sections is expected to be different depending on the direction of the train and location within a section, especially for single track railway lines.

Analyses of time series sampled on in-use structures are very important for understanding the true nature of the dynamic response. Measurements directly sampled on catenaries under train operation have been increasingly used in the literature to assess the behaviour of railway catenary systems. Both analyses from accelerations [1–8] and displacements [9–11] have been used to assess the structural behaviour.

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The validation of numerical results is another important usage, as shown in [6,8,9]. An alternative approach is to estimate the frequency and damping properties [1–5,7,12] among others, showing that these systems are lightly damped. Rønnquist and Nåvik [3] studied the differences in the vertical and lateral responses, and demonstrated that both the lateral and the vertical movement are substantial under train loading and can be utilized when interpreting the structural behaviour. Nåvik and Rønnquist [4] also investigated catenary renewal with measurements before and after the upgrade and found that the dynamic response changed considerably to a more distinct response around some frequencies for a higher tension force. Vo Van et al. [7] also used measurements to study the waves in the cable system. Line measurements can also be highly relevant for continuous monitoring and condition-based maintenance, as highlighted by a recent review paper [13].

Currently, an evaluation of the quality of the pantograph-catenary interaction is mainly based on contact force and acceleration measurements on the pantograph [14–19], both in field and in computational analyses [20–22].

A large number of studies are published regarding fault detection, structural health monitoring and diagnosis of railway catenary systems. Collina et al. [23] studied the impact of overhead line irregularities on current collection and diagnosis. A simple image acquisition system was used in [24] for developing real-time fault diagnosis of contact lines and pantograph. A more detailed study by Shen et al. [25] on using camera tracking for real-time inspection of the contact point evaluates different methods for tracking the contact point and is used for developing a contact state surveillance method. Acceleration data from pantographs were used in [26] for condition-based monitoring of overhead lines using RMS values to identify local and distributed defects. Wang et al. [27] used the quadratic time–frequency representation on contact force data to detect contact wire irregularities, and detecting the irregularities faster than power spectral densities could. Fault detection has been performed by 3D-scanning for detecting major defects of the collector strips [28] and by pantograph mounted monitoring system by force sensors and FBG strain sensors to identify defects of the pantograph and the catenary [29]. For more references on condition monitoring and fault detection see Bruni et al. [30] and Brahimi et al. [31]. Measurements from the pantograph are natural to use since they evaluate the direct pantograph-catenary interaction, which is important for the interaction quality, the dynamic response, the contact strip wear and the power supply. However, these studies are limited to the contact point moving along the catenary. After an extensive study of field measurements of both contact forces from the pantograph and accelerations from the catenary, it is identified a need to quantify the pointwise dynamic response in the catenary itself.

This paper is introducing an index with the intention that quantifies the dynamic response in the catenary system under and after a train has passed. This index will be able to assess the dynamic response of the cable system in itself, not only the interaction. The catenary dynamic index (CDI) makes it possible to compare the response of any catenary system regardless whether the time series comes from either field measurements or numerical analyses. As an example, for infrastructure owners, a CDI basis can be made for a particular catenary system, and then it will be easy to determine if a train passage is operating outside of normal operating behaviour or if a structural monitoring system is up and running.

2. Railway catenary systems

The main structural parts of the cable system are the contact wire, messenger wire and dropper and stitch wires. This system is mounted on a cantilever installed on a steel, concrete or wood mast in intervals of up to approximately 75 m span. Moreover, one catenary section is a continuous cable system of up to approximately 1500 m. The main components are presented in Fig. 1.

3. Field measurements

The used measurements in this paper were collected along the Dovre railway line in Norway at a location called Fokstua during November and December 2015. All measurements are sampled during normal scheduled train operation. The maximum speed for passenger trains was 130 km/h, whereas freight trains travelled with between 80 and 100 km/h, rendering a speed range between 80 and 130 km/h. There were mainly two different pantographs mounted on the passing trains, Schunk WBL85 and WBL88, which have similar configurations. The recorded measurements are acceleration time series sampled using a self-developed wireless monitoring system including 10 sensors and one master unit, described in detail in [1], all synchronized in time. The time series are all 8 min long, and sampled at 200 Hz, and lowpass filtered at 0.8 times the Nyquist frequency, 80 Hz [32]. Only the time series sampled on the contact wire are used in this study. The currently used sensors were placed according to Fig. 2. The positions of the sensors were chosen for investigating several research ideas, not solely for this paper. However, to show the use of the CDI estimation the following positions are considered important. A sensor close to the support is important since it is likely to be the position with the least disturbance from environmental effects (wind). Sensors placed in the mid-span are important because they have the largest response in terms of displacements, and amount of dynamic response. Finally, the first dropper after the stitch wire is also included since this point often have high point wear.

The Fokstua railway catenary section is a Norwegian "System 20" catenary system design with a pre-tension of 13 kN in both the contact and messenger wires. The contact wire is a RiS120CuAg type, and the messenger wire is Bz II 70/19. This system gives a wave propagation speed in the contact wire of 397 km/h, calculated according to [33] where the wave propagation equals the square root of the tension in the contact wire divided by the mass per unit length. The geometry is shown in Fig. 2 and Table 1. The highlighted parts in Table 1 is for the spans where sensros are located. The first natural frequency is 1.2 Hz and corresponds to the half sine mode shape of the longest span. However, it is maybe more appropriate to talk about groups of frequencies for these type of structures. For the half sine mode response the frequency ranges between 1.2 Hz and 2.0 Hz in this particular catenary section.

4. Development – The catenary dynamic index

Developing an index that can properly describe the desired effects is challenging. The CDI is meant to capture the dynamic response of the catenary as the train passes. The index should be able to 1) describe difference in responses on the same railway line and point for different traffic loads, 2) describe differences for different points along the section for the same line i.e. same traffic different position, and 3) describe the difference in dynamic reaction levels between different catenary systems which have different configurations and different traffic loads.

There are many ways to describe the dynamic content of a passage based on the acceleration of the contact wire. However, these methods more or less try to capture the energy content for a finite time duration. Thus, the first step in the methods is how to define the time duration of analyses.

4.1. *Time duration*

The nature of an acceleration time series from a contact wire under train passage can be divided into four parts. The duration of every part is mainly dependent on the train speed for one catenary section. A typical acceleration time series from the contact wire is divided into five parts as shown in Fig. 3.Fig. 4.

- The first part is prior to the passage of the train, giving only the

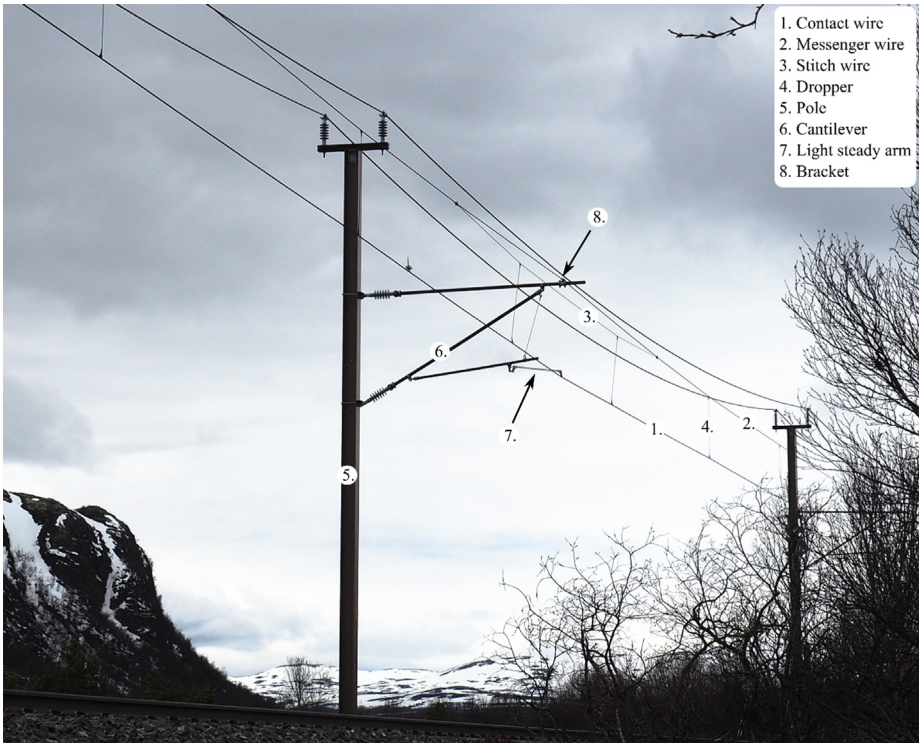


Fig. 1. The main components of a typical railway catenary section for this study [2].

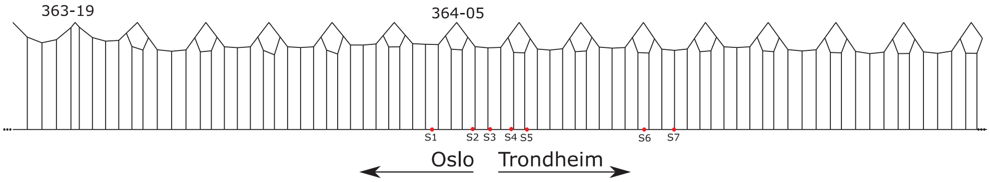


Fig. 2. Geometry of the monitored catenary section and the sensor positions at the measurement site, Fokstua.

response from environmental loading. Often high signal to noise ratios

- The second part is the response at which the accelerometer measures the response of travelling waves initiated by the train, but arrives before the train.
- The third is the actual train passing the location of the measurement.
- The fourth is the part after the train has passed the accelerometer, referred to as post-passage.

For completeness, there also exists a fifth part that comes after all responses because the train loading has damped out, and then we are back to the first part. However, this process takes a long time due to low damping in railway catenary systems. Understanding the nature of the different parts is vital for designing the criteria for which time duration is to be included in the analysis. It is important to have our index more or less independent of environmental loading while still capturing the entire train passage.

The time period will be defined by time before a passage and time after a passage. The time before the passage cannot be a fixed value because the duration of this part is largely dependent on the train speed. On the other hand, the time after passage can be fixed because the response is mostly dependent on the short duration of the train passing and the low damped dynamic response.

It is easy to see the transitions between the duration parts in the moving mean, preferably with a decibel scale on the y-axis. The time before can be set by evaluating when the obtained signal is sufficiently different from the first part. The procedure to decide the time before from the moving mean is as follows:

1. Find the max dB of the first part (10 s in this paper)
2. Choose a level lower than this value to give you the time before

Table 1
Span lengths of the Fokstua railway catenary section.

Span	1	2	3	4	5	6	7	8	9	10
Length	44.27	44.98	45	49.45	45.51	45.65	44.88	**45.03**	**45.1**	44.54
Start pole	363–17	363–18	363–19	363–20	364–01	364–02	364–03	**364–04**	**364–05**	364–06
Span	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Length	45.28	**44.76**	45.34	48.87	49.02	48.77	50.8	52.23	51.95	52.1
Start pole	364–07	**364–08**	364–09	364–10	364–11	364–12	364–13	364–14	364–15	364–16
Span	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**		
Length	51.87	52	52.06	42.48	39.95	30.99	39.54	42.55		
Start pole	364–17	364–18	364–19	364–20	364–21	364–22	364–23	364–24		

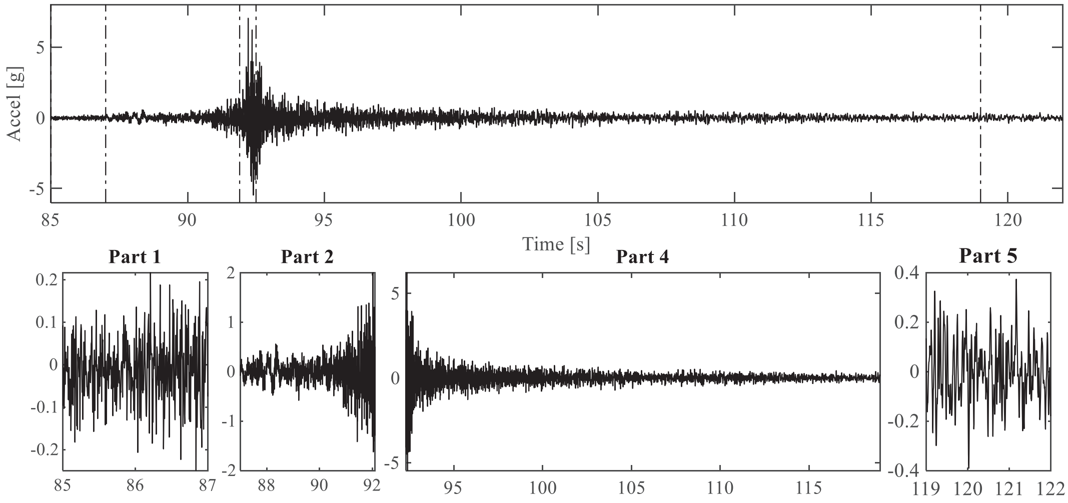
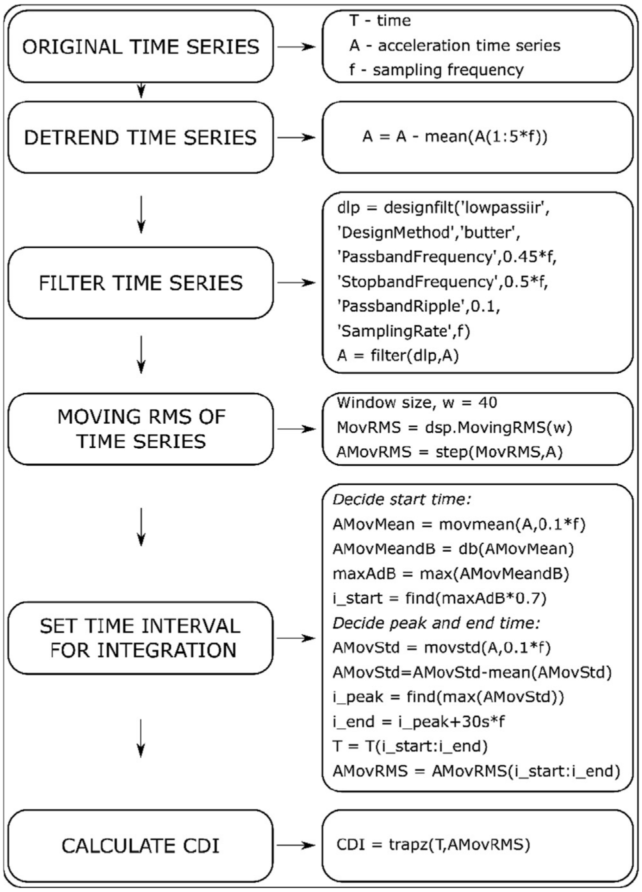


Fig. 3. A typical acceleration time series from the contact wire divided into the five parts.



```
T - time
A - acceleration time series
f - sampling frequency
```

```
A = A - mean(A(1:5*f))
```

```
dlp = designfilt('lowpassiir',
'DesignMethod','butter',
'PassbandFrequency',0.45*f,
'StopbandFrequency',0.5*f,
'PassbandRipple',0.1,
'SamplingRate',f)
A = filter(dlp,A)
```

```
Window size, w = 40
MovRMS = dsp.MovingRMS(w)
AMovRMS = step(MovRMS,A)
```

```
Decide start time:
AMovMean = movmean(A,0.1*f)
AMovMeandB = db(AMovMean)
maxAdB = max(AMovMeandB)
i_start = find(maxAdB*0.7)
Decide peak and end time:
AMovStd = movstd(A,0.1*f)
AMovStd=AMovStd-mean(AMovStd)
i_peak = find(max(AMovStd))
i_end = i_peak+30s*f
T = T(i_start:i_end)
AMovRMS = AMovRMS(i_start:i_end)
```

```
CDI = trapz(T,AMovRMS)
```

Fig. 4. Block diagram of the method for estimating the CDI of an acceleration time series including Matlab-code.

(0.7*max dB in this paper)

3. Identify at what time this value exceeds the first time

In this paper, the after time has been set to 30 s because it sufficiently describes the response in our experience.

4.2. Train speed estimation

The speed of the train is estimated by introducing one known distance between two sensors and that the response at the two locations are similar in nature separated by a time lag. The distance divided by the time lag renders the train speed. Two different methods have been used to estimate the train speed in this way, time difference between peaks in the response and the time lag found using cross-correlation.

The filtered raw data was found to be noisy to be used as a basis for train speed estimation, thus both suggested methods were performed on the moving standard deviation of the time series. This was done for all combinations of two sensors to get the best estimate. It is important to recognize that this is estimates, and that the estimates of the speed are generally best for sensors the longest apart in distance. The procedure is described in 6 steps below. And, this is the procedure that gave us the best and most stable estimates of the train speed using this measurement setup.

The procedure in steps:

Raw data @200 Hz
Filter @80 Hz
Moving standard deviation with a 10-sample window
For all combinations of two sensors
4.1. Find the speed by identifying the time lag between the maximum response in the moving standard deviation time series of two sensors
4.2. Find the speed by finding the lag from the cross-correlation of the moving standard deviation time series of two sensors
5. Find the median speed from both methods (the mean is too influenced by estimates that misses the true value too much) and the standard deviation
6. Which median speed to use, peak or correlation, is chosen to be the one that has the smallest standard deviation

4.3. The catenary dynamic index, CDI

There are several possibilities that can fulfil the purpose of setting one value to the dynamic response of a railway catenary section. Five different methods were tested in the process of deciding on the CDI method. These methods are as follows:

- The cumulative value of the moving standard deviation of the acceleration time series, using MATLAB's movstd function and a window length of 0.1 s.
- The cumulative value of the moving variation in the acceleration time series, using MATLAB's movvar function and a window length of 0.1 s.
- The cumulative value of the moving root mean square (RMS) of the acceleration time series, using MATLAB's dsp.MovingRMS and the

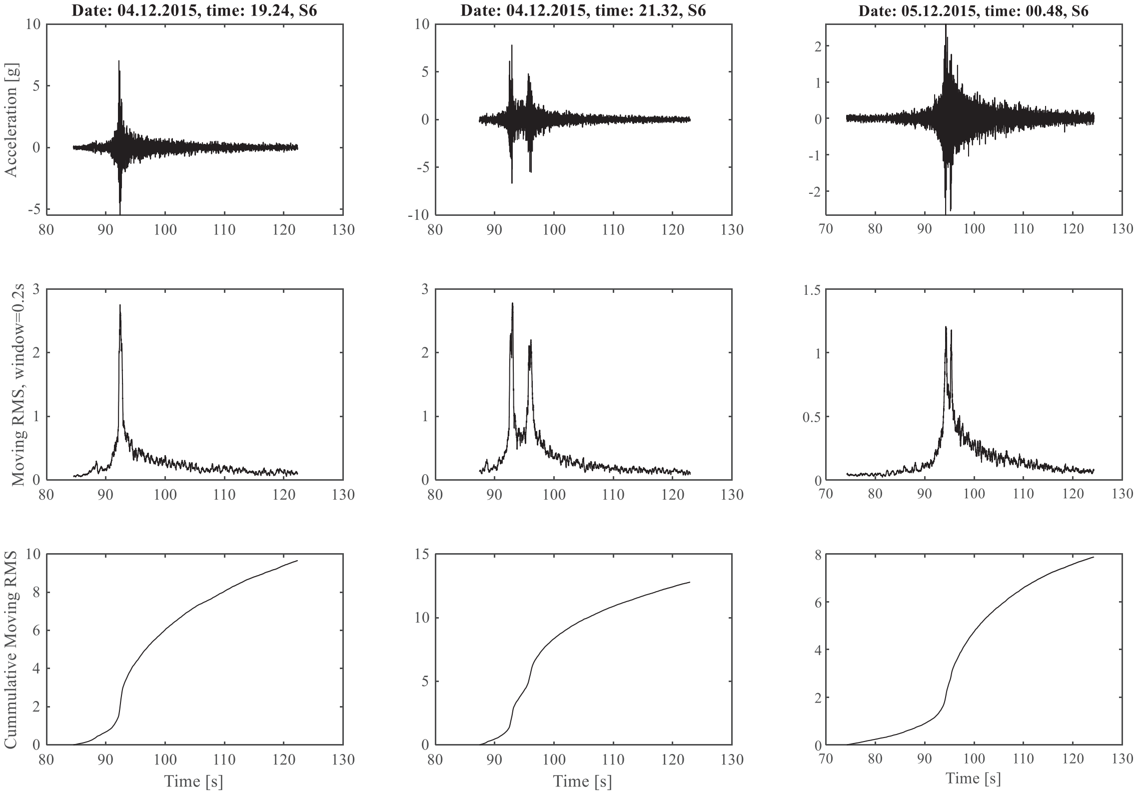


Fig. 5. Example time series from sensor S4 shown from the left: a single pantograph passenger train passage, a double pantograph passenger train passage and a double pantograph freight train passage.

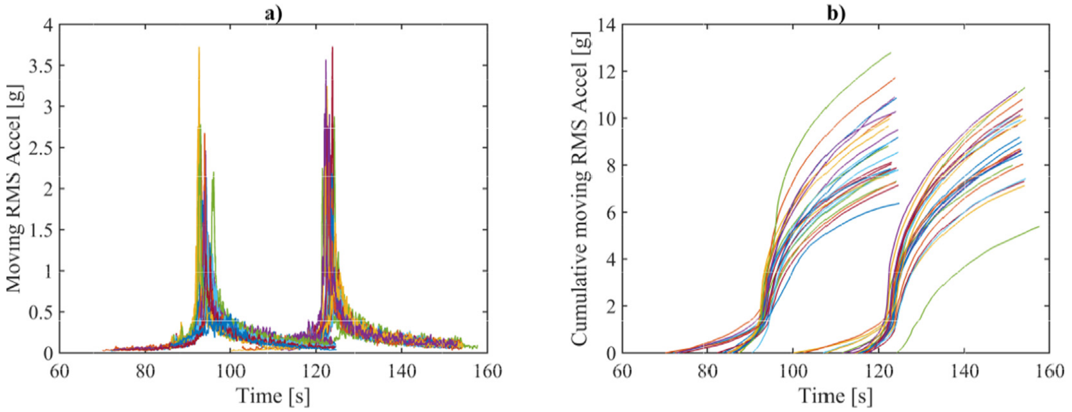


Fig. 6. The moving RMS, a), and the cumulative moving RMS, b), for plots of the acceleration time series of all passages at sensor S4.

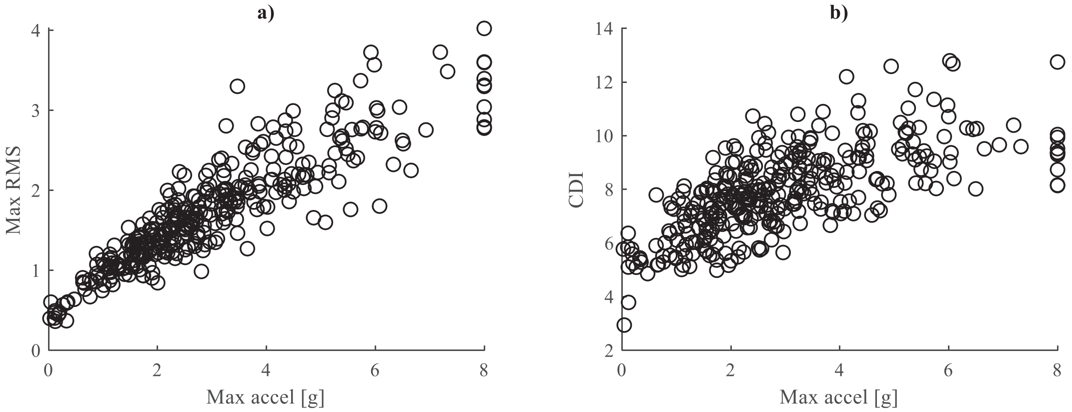


Fig. 7. Maximum RMS, a), and CDI, b), values plotted against the maximum acceleration for all sensors and all passages.

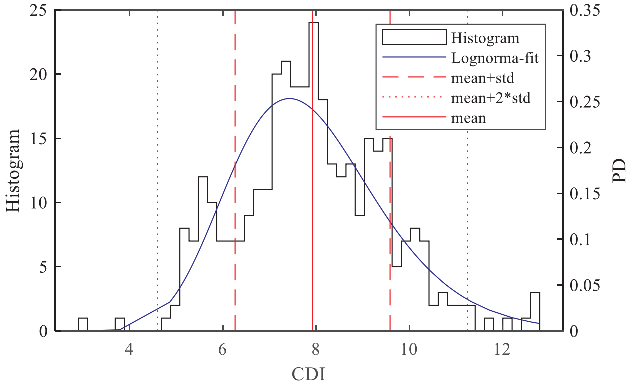


Fig. 8. The calculated lognormal distribution of the CDI values from all sensors and passages.

step function and a window size of 40.

- The energy of the acceleration time series, by computing the square of the norm of the signal.
- The power of the acceleration time series, by computing the sum of the FFT times the conjugate of the FFT.

All these methods gave good results and could constitute the abovementioned purpose. However, the moving standard deviation and RMS are in the same unit as the original signal and are easier to relate to and analyse. The simplicity and ease of relating to the numbers is especially important because they provide a great benefit to infrastructure owners and consultants in addition to academics.

The procedure described in the formulas is given below and is performed separately for every passage and sensor:

$$a_{RMS,i} = \sqrt{\frac{1}{N}\sum_{l=i}^{i+N-1} |a_l|^2}$$

$$CDI = \sum_i a_{RMS,i}, \ -timebefore \le t_i^{'} \le 30s \rightarrow 1 < i < f\,(hz) * (timebefore + 30s)$$

where N is the window length of the RMS, a_l is the acceleration at point *l*, and $a_{RMS,i}$ is the moving RMS of the acceleration at point *i*. N was chosen to be 40 by trial and error giving the best and most stable result.

5. Results and discussion

The results are all based on the field measurements taken during regular traffic on the Fokstua railway catenary section. Great variations between the recorded time series are expected and are mainly due to the train type, pantograph, speed, wear of both the pantograph and catenary, and environmental loading. It is important to be aware of the nature of these time series and the differences expected between them. To illustrate this acceleration time series, the corresponding moving RMS and cumulative RMS for three different train passages are presented in Fig. 5. It is clear that these three time series represent three different scenarios, and they are, from left to right, a passenger train with a single pantograph, a passenger train with two pantographs and a freight train with two pantographs. The acceleration time series can be used to distinguish between single or double pantograph uses, but only if the pantographs are a sufficient distance apart. These series also show the peak acceleration and can indicate if wind was present. The moving RMS makes it easier to distinguish single or multiple pantograph use and clarifies environmental loading. The cumulative moving RMS provides a clearer picture of the relative energy content during the passage. The inclination of the curve indicates how much energy is actually introduced by the pantograph and if the response is smooth or impact like.

The moving RMS and the cumulative moving RMS for all passages for the response at sensor S4 are shown in Fig. 6 left, a) and right, b), respectively. The results are divided into two areas because the line has traffic in both directions, and S4 is therefore further away from the triggering sensor for southbound trains. The moving RMS, a), is included to show that it is easier to look for other differences than the peak value in the plots showing the cumulative moving RMS, b). In b), notably, the shape of the lines follow the same trend even though both freight and passenger trains are included, with one gradient before the train passes, an exponential increase as the train passes and a decreasing gradient afterwards towards zero. The response from the passenger trains have in average the steepest gradients which results in that the CDI, which is the last value in the cumulative moving RMS, has a very large spread. This spread proves that the response of the catenary is affected by the type of train passage long after the train has left. Research into multiple pantograph operation should consider this behaviour. It is also of interest to see that the response from southbound trains is less spread, left plots in b), than the response from northbound trains, right plots in b).

The cumulative moving RMS has already shown that it is important to assess more than the peak values from both the moving RMS and the acceleration time series. For a further illustration, the maximum RMS values are plotted against the maximum acceleration in Fig. 7 left, a), and the CDI values are plotted against the maximum acceleration in Fig. 7 right, b). Fig. 7 a) shows a linear relation, while b) is more complex. Very large differences in the CDI value can be seen in b) for the same maximum acceleration. This result shows that the CDI captures the differences in response during a larger time frame and that the response is dependent on more than the peak value.

The distribution of CDI values is expected to be different between sensor positions. However, the distribution parameters show if the monitored position has a small or large response and the dependency of

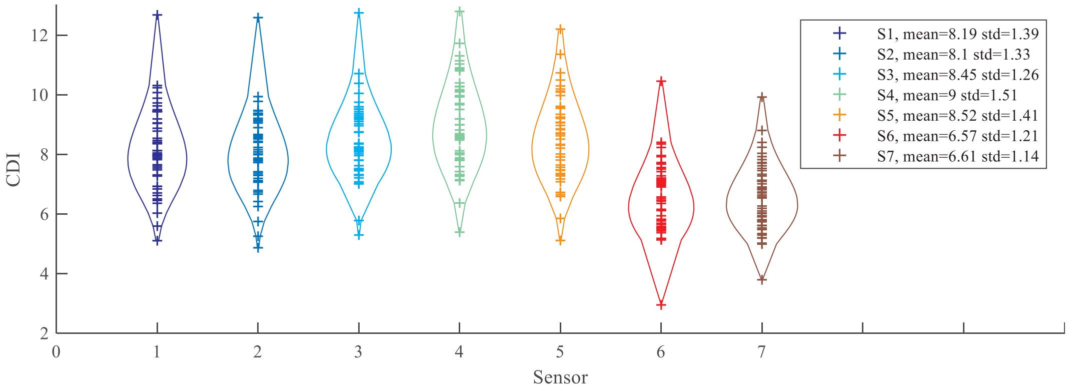


Fig. 9. All CDI values calculated from all passages divided into sensor groups. The lognormal distribution for each is plotted around the results.

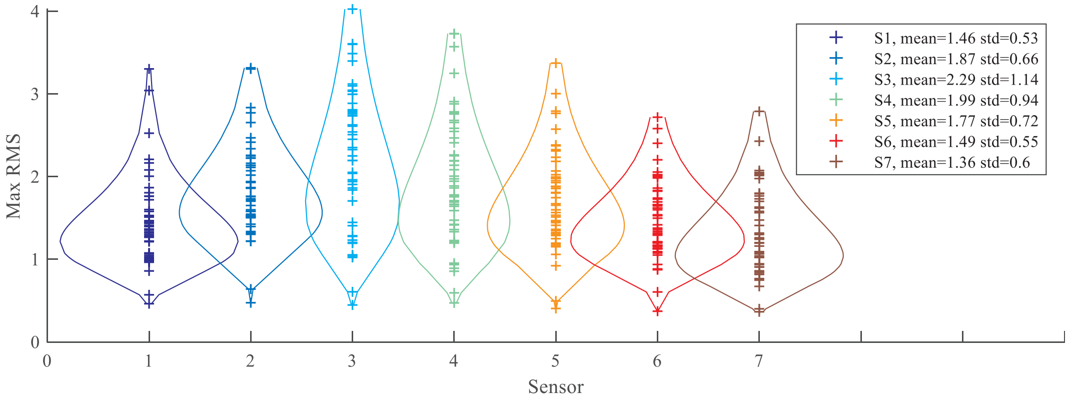


Fig. 10. All maximum RMS values calculated from all passages divided into sensor groups. The lognormal distribution for each is plotted around the results.

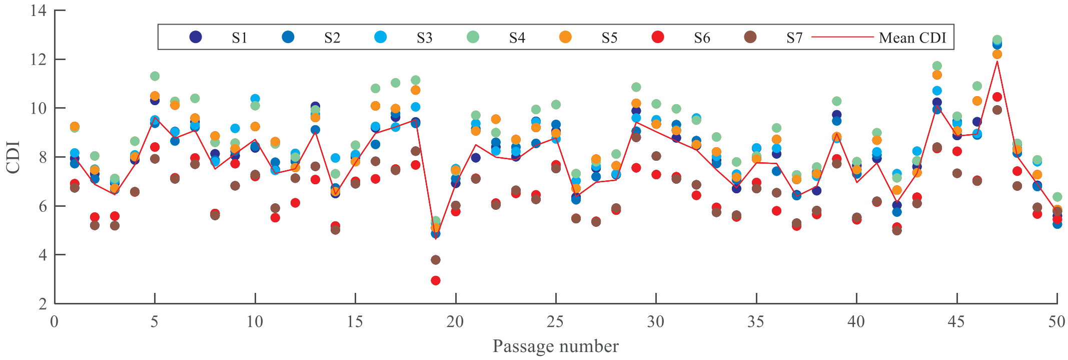


Fig. 11. All CDI values presented separately and shown for each passage.

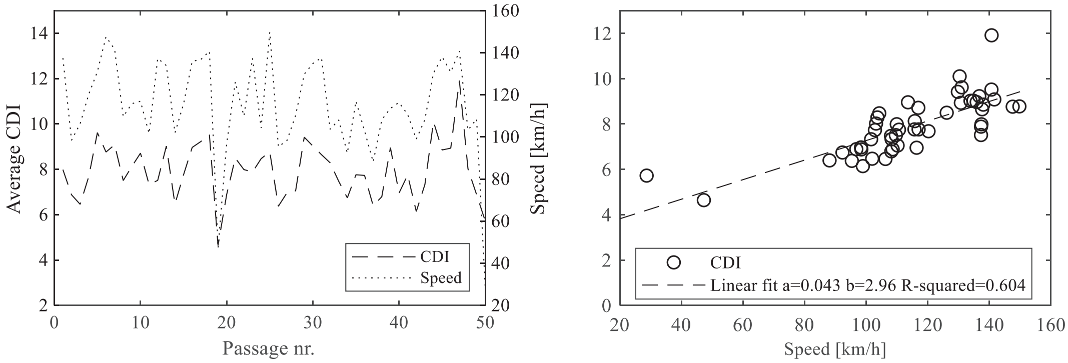


Fig. 12. The speed per passage and the CDI per passage (average for all sensors).

the response on the train passage. The histogram in Fig. 8 shows the distribution of derived CDI values from measurements. As this is a skewed distribution, the CDI values are typically low with a sizeable variance where the CDI values cannot become negative. That is, the values are bounded to at least always positive values and with a substantial upper tail. This also corresponds well to the expected distribution of the power terms represented in the derived CDI values. Thus, a lognormal distribution is used to represent the CDI distribution. The lognormal distribution for the CDI values at S6 together with a histogram shown in Fig. 8 includes lines representing the mean value, and the mean plus one and two times the standard deviation.

This paper only includes sensors mounted on the contact wire, and the results for all 7 sensors are presented in Fig. 9. The results show all CDI values with crosses and the distribution as a surrounding envelope. The legend gives the mean and standard deviation as well.

Note that the differences between the positions are very evident and large. The first finding is that sensors S6 and S7 have similar values as have sensors S1, S2, S3, S4 and S5. These groups of sensors in Fig. 2 are closer to each other and show that the differences in the CDI values are dependent on the catenary design. Sensors mounted within the same pole span have clearly similarities, whereas there are differences in the response compared to sensors mounted in another pole span. The same counts for sensors placed close to each other and far from each other. This is a very interesting and useful result for the infrastructure owners.

The final comparison between the maximum and cumulative values can be seen by comparing Figs. 9 and 10. The maximum RMS values and their distributions are shown in Fig. 10. For the sensor positions used in this investigation, it seems that the distribution of RMS values begins at approximately the same value, while the CDI distributions have different starting points. A very interesting result is that if the comparative value for the dynamic response was the maximum RMS values, then the results would indicate that the largest value was at S3. However, if the CDI values were used as comparative values for the dynamic response, then the results would indicate that the largest value was at S4, which is a more accurate interpretation.

The CDI plots show a more concentrated result than the RMS plots, which are so wide that it is difficult to see what mirrors the dynamic effects. Additionally, the uncertainty is greater, as shown by the standard deviation envelope. In summary, compared with Fig. 10, Fig. 9 has a much more unambiguous variation regarding the minimum, maximum and mean values.

The mean of the CDI for all sensors for one passage can to a certain extent be informative regarding the general response of the catenary for one train passage. This is valuable information for the infrastructure owner such that trains with either damaged pantographs or pantographs with the wrong pressure can be stopped. The mean CDI for every passage is shown together with individual sensor values in Fig. 11. The variation in the mean CDI is expected to be quite small at the instrumented location because it is far from a station and on a straight section, so it is expected that the trains run at maximum speed. It is assumed that the deviations are mainly due to if it is a freight or passenger train and if it is a single or double pantograph. However, the values for passage 19 were very low, and it can be assumed that something was not as normal. In Fig. 12 it can clearly be seen that the train had a very low speed, 47 km/h, which is a good explanation for the low CDI value. The high response was observed in the detailed analysis due to a double pantograph operation on a passenger train, which is not normal on this line, in addition to quite high speed, 140 km/h.

Finally, the CDI - speed relation is important to address. For all the 50 passages the speed has been estimated as described in the Methods section. The speed per passage and the CDI per passage, average for the sensors, has been plotted on the left in Fig. 12. On the right in the same figure the CDI has been plotted against speed with a linear fit using the Matlab function fitlm. There is an evident relation between the CDI and the speed. This is natural since the loading increases with the speed, but the relation does not explain all variability between passages.

6. Conclusions

This paper has presented an index that describes the amount of dynamic behaviour for a point on a railway catenary section under train passage. This study shows that the CDI index works well for the given situation with field measurements. Even for this short measurement period it identified two outliers, that later could be explained by train speed and double pantograph operation. The too high train speed and double pantograph operation could have been reported to the infrastructure owner in real time if this was part of a structural health monitoring system, and the train could have been told to lower one of the pantographs, and slow down.

The method can be used on both field and numerical data, and for both academics, infrastructure owners and consultants. The index is intended for comparing the response of different train passages and different catenary sections. Particular applications for the CDI are parametric studies and for structural health monitoring. The index can be used to evaluate differences between different catenary systems in the world, both numerically and in the field. The CDI can be used to assess all passing trains in real time. Thus, the CDI index could be used by infrastructure owners to control the pantographs passing through their network or on borders with other countries making sure that trains with faulty pantographs are stopped. The larger database of CDI values, the better the evaluation of the nest passing train.

For structural health monitoring the authors suggest placing sensors at support and in mid span if possible. The index value should be a living value that uses every passage to update and improve it. It is up to the user how to use this index, but with regard to the results presented, the comparison should be carefully selected. The CDI values are dependent on the speed, train speed, single or multiple pantograph operation, travel direction and position. This dependence means that when the CDI value can be used for structural health monitoring where the baseline values should be divided into suitable groups so that normal operation does not show as an extreme value.

CRediT authorship contribution statement

Petter Nåvik: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Stefano Derosa:** Methodology, Software, Investigation, Writing - review & editing. **Anders Rønnquist:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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