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Determination of rail vehicle speed with acoustic signal processed using continuous wavelet transform

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Abstract The paper presents the course of research and analysis on the possibility of using time-frequency methods of acoustic signal processing to determine the speed of moving rail vehicles. An experiment was conducted in the form of a trackside pass-by test of the acoustic pressure emitted by passing trams representing the rolling stock of the Municipal Transport Company in Poznan. The recorded signal was then processed using the Continuous Wavelet Transform (CWT), resulting in a scalogram that is a variation of the time-frequency characteristics. This made it possible to identify in the signal the travel time of individual bogies and their wheelsets, as well as the most sensitive value of the scale parameter. The waveform of the scalogram fragment for the selected value of the scale parameter was processed using the RMS envelope, and then the peak values were identified. Juxtaposing the obtained results with the knowledge of the structural dimensions of the tested vehicle, it was possible to determine its moving speed. To validate the results of the experiment, photocells located on both sides of the measurement track were used, which generated voltage when the test vehicle passed between them, allowing the determination of its average moving speed. The result of the study was the formulation of a method that can be used to determine the speed of a vehicle based on the time elapsed between the identification in the signal of the components corresponding to the passage of successive sets of wheels.

Keywords: continuous wavelet transform, acoustics, rail vehicle, speed detection

1. Introduction

Monitoring and traffic control systems are being developed and put into use to ensure the appropriate level of safety and efficiency of modern rail transportation. These systems are designed to assess the speed of a rail vehicle, its environmental impact, and operational safety [1–5]. Great attention is paid especially to railway noise [6–8]. The methods for determining speed include algorithms that use wheel and axle speeds measured with dedicated sensors that are part of the vehicle's design, including odometry algorithms [9, 10], passing vibration [11], detection and counting of axles by sensors located on the track [12], or the use of positioning with GPS [13].

One of the goals of designing such systems is to optimize them as a function of cost and to automate them and make them fully intelligent [14]. One possibility of optimization is to reduce the number of parameters processed. This can be achieved by using them for multiple purposes, e.g. acoustic measurement for simultaneous assessment of environmental impact, as well as axle detection and determination of travel speed.

While the overall acoustic impact on a vehicle's environment can be assessed by averaging sound levels to single point measures using developed standards, precise speed determination is more difficult due to interference in the acoustic signal caused by, among other things, noise associated with, for example, acoustic components generated by rail vehicle drive elements or damage to the vehicle. This makes it necessary to develop methods of preliminary signal decomposition that allow extracting for further analysis only elements of the acoustic signal useful in determining the speed of movement. One category of such methods is time-frequency analysis, which makes it possible to transform the time course of a signal into a characteristic that reveals the distribution of signal energy simultaneously for different frequency bands and different time intervals. Among the time-frequency methods we can mention short-time Fourier transform, wavelet transform, Wigner-Ville distribution or Hilbert-Huang transform [15, 16].

This article presents the course of research and analysis of results in the possibility of applying time-frequency analysis to determine the speed of a selected rail vehicle using an acoustic signal. A continuous wavelet transform was used for preliminary analysis of the signal and extracting from it the components most sensitive to the passage of the vehicle's wheelsets. These were then de-noised using the RMS envelope and, based on them, the passing time of the test stand by successive bogie axles was indicated, which, with knowledge of the vehicle's structural dimensions, made it possible to determine its speed. The goal was to develop a method that would allow estimation of the passing speed with a relative error of less than 5%.

2. Research methodology

2.1. Research object

The object of the research was a low-floor Solaris Tramino S105p tram manufactured by Solaris Bus & Coach and operated by Municipal Transport Company in Poznań Sp. z. o. o. The design diagram of the Solaris Tramino S105p tram is shown in Fig 1.

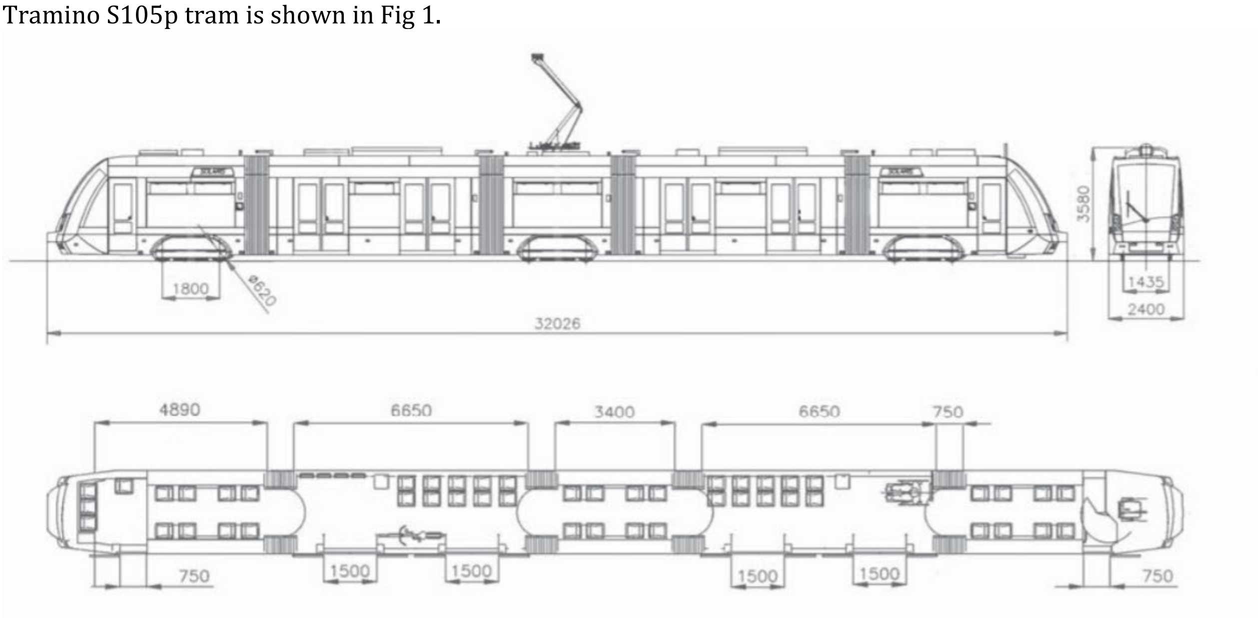

Figure 1. Design diagram of the Solaris Tramino S105p tram [17].

The technical parameters of the tested vehicle are presented in Table 1.

Table 1. Selected technical parameters of the Solaris Tramino S105p tram.

Total length	32026 mm	Number of bogies	3
Width of the wagon body	2400 mm	Wheel track	1435 mm
Width of the wagon body inside	2195 mm	Diameter of new wheels	620 mm
Height with pantograph lowered	3760 mm	Diameter of worn wheels	540 mm
Number of segments	5	Floor height above rail head	350 mm

It is a fully low-floor, articulated tram designed for one-way traffic. It is one of the main vehicles of the rolling stock operated by the city carrier.

2.2. Test stand and measurement conditions

The measurements were made under favorable weather conditions for acoustic measurements, without precipitation. The temperature was between 11 °C and 13 °C, the atmospheric pressure was 1020 hPa, and the wind speed did not exceed 5 m/s.

The research assumptions included conducting an experiment of a passive nature [18]. The measurements were carried out on the premises of the Poznań–Franowo Tram Depot. The parameters of the recorded acoustic signal were observed without prior knowledge of the technical condition of the object. The drivers of the vehicles were not instructed on detailed behavior when passing the test stand, which meant that the research team had no influence on the speed of passing objects. The test stand was located close to where the rails were joined together, which caused additional acoustic effects associated with the wheelsets driving over them despite the good quality of the thermite weld.

Measurements were made from the position of the track in a pass-by test. The object of the research was the physical phenomenon of sound pressure rather than environmental noise, therefore the unit of pressure - pascal [Pa], was recorded.

A microphone matrix of 9 microphones (M1-M9) was used to carry out the research. Ultimately, however, microphone M5 was selected to the further analysis. The use of matrix measurements was justified by the fact that the analyses carried out in this article are part of a broader study focusing, in addition to the development of new signal processing methods, on sensitivity analysis of the location of measurement points. The location of the microphones depended on the geometry of the trams' running system (the diagram shown in Figure 2). The horizontal distance from the track to the matrix resulted from kinematic gauge standards [19] to ensure that the running vehicle would not hit the microphones. The vertical position of the matrix and its total height resulted from the construction of the tram – the aim was to cover the area from the height of the rail head to the height of the bogie recess.

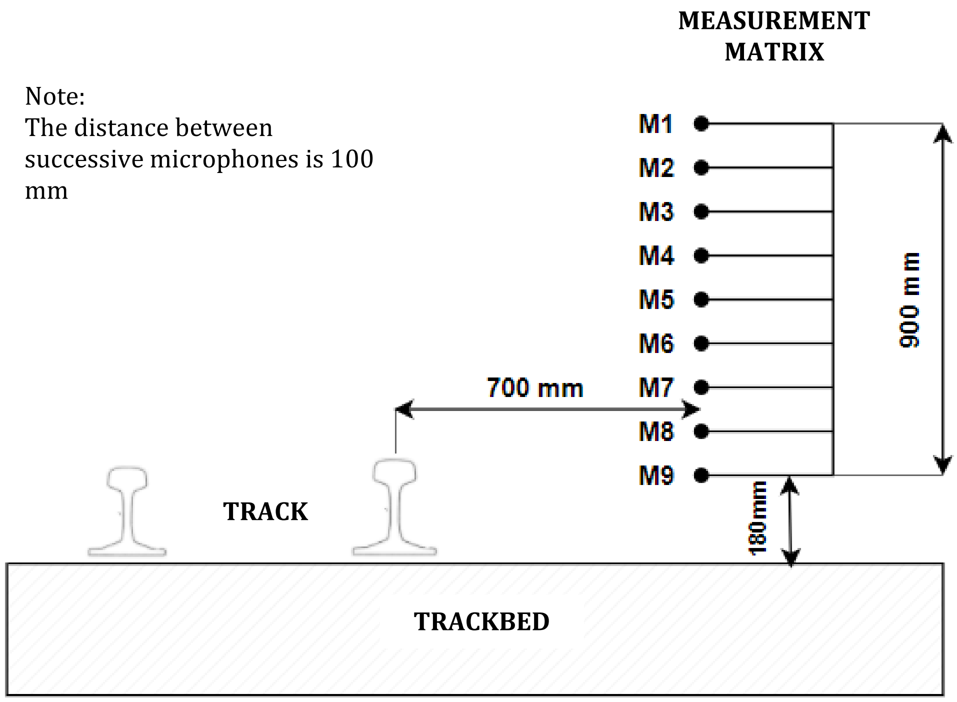

Figure 2. Diagram of the test stand [own elaboration].

Signal recording was started by the test stand operator about 3 seconds before the test tram entered the measurement cross-section, and ended 1-2 seconds after it left. To determine the exact time of passing the test stand by the front and rear of the vehicle, and thus to extract for further analysis the acoustic signal associated only with the movement of the vehicle, data from the photocell received by the measurement cassette synchronously with the acoustic signal was used. The sampling frequency was 65536 Hz. This allowed the signal to be acquired over the full frequency range recorded by the microphone. The actual location of the measurement matrix is shown in Fig. 3.

Modular measurement apparatus was used to carry out the test. In the measurements, a condenser matrix microphone of the B&K 4958 type was used, designed to measure also non-stationary signals, i.e. such signals as were planned for acquisition during the experiment. They allowed recording in the frequency band of 20-20000 Hz. A pair of BX15M-TDT photoelectric sensors was used to record the moment the trams passed the measurement stand. According to the product specification, a latency of 20 ms may be expected during the measurement with provided sensors. A PULSE 9727 system with a B&K 3560C data acquisition module enabling lossless, synchronous recording of signals in all channels in the band from 0 to 25600 Hz was used to record and archive signals. Control of the measurement apparatus and data recording were performed using a personal computer equipped with BK Connect 2018 software.

Figure 3. Measurement stand during the excution.

2.3. Processing of recorded signals

The recorded acoustic signal in the first step was compared with the synchronously recorded signal from the photocell. Then the acoustic signal from the microphones was trimmed so that only the measurements from the moment the vehicle passed the test stand were included in further analysis.

Such a signal was subjected to processing using the continuous wavelet transform described by Eq. 1 [20]:

$$\mathrm{CWT}_{\Psi}(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}x(t)\cdot\Psi^{*}\left(\frac{t-b}{a}\right)dt, \tag{1}$$

where: $\Psi(t\text{-}\tau)$ – mother function, $x(t)$ – continuous signal in the time domain, a – scale parameter, b – shift parameter (place), Ψ^{*} – function coupling $\Psi(t\text{-}\tau)$.

The use of CWT resulted in a distribution of wavelet coefficients in the time and scale domains. The scale parameter does not have a simple translation to the frequency of the signal. Higher scale parameters correspond to low-frequency components of the signal, while lower scale parameters correspond to high-frequency components. This made it possible to obtain a time-scalar representation of the signal (a scalogram), which is one variation of the time-frequency characteristics, which made it possible to determine the moments of occurrence of the largest increases in amplitude and which ranges of the scale parameter were characterized by the greatest sensitivity to changes in the signal caused by the passage of individual wheelsets.

For further analysis, a domain reduction of the scalogram was performed - the wavelet coefficients were left to run over time for a selected one value of the scale parameter from among the ranges most sensitive to changes in amplitude.

The signal in the obtained characteristics was too noisy to directly infer the moment of the wheelsets' passage from it. An envelope of RMS values was generated. The width of the moving envelope window was set to 750 samples. For the signal registration parameters of the experiment conducted, this was the optimal value. The signal was de-noised enough to indicate amplitude peaks corresponding to wheel overruns, while at the same time the envelope window was not too wide to cause two independent peaks to be averaged into one.

In the final step of signal processing, the identified amplitude peaks were assigned to individual wheelsets. Then, knowing their location in time and the structural dimensions of the test vehicle, the speed was determined (Eq. 2, 3) and compared with the average speed known from the measurements from the photocells:

$$V_{l_i}=\frac{l_{zk}}{t_{zk_{i+1}}-t_{zk_i}}, \tag{2}$$

$$V_{l_{avg}}=\frac{1}{n}\sum_{i}^{n=5}V_{l_i}, \tag{3}$$

where: V_{li} – local average speed between consecutive wheelsets [m/s], V_{lavg} – average speed of the whole set [m/s], l_{zk} – distance between individual wheelsets [m], t_{zki} – time to note the passage of the i-th wheelset in the acoustic signal [s].

In the case studied, the distance between wheelsets 1–2, 3–4, 5–6 was 1.8 m. For pairs 2–3, 4–5, the distance was equal to 9.65 m.

3. Analysis of results

The results described in the article are presented for a tram with the rolling stock number 519, hereafter referred to as tram 519. The analysis was carried out on the measurements of only one tram because the research has a case-study character – the aim was to show novel method on a representative vehicle. Due to the passive nature of the experiment, it was not possible to analyze the efficiency of the presented approach on trams with different technical conditions. According to the municipal transport operator's operating log, there were no damaged vehicles during the investigation. Figure 4 presents the time course of the acoustic pressure during the passage of the test object. The characteristics illustrate the signal after time selection using the signal from the photocell - so the first sample coincides with the front of the vehicle, and the last sample coincides with the end of the vehicle. Based on the length of the signal over time (4.487 s) and the knowledge of the length of the vehicle, the average speed of the entire set can be determined, which was 25.7 km/h. Considering the measurement latency of photoelectric sensors (20 ms) there may be ± 0.1 km/h error in the estimation of the average speed which corresponds to the relative error of 0.4%.

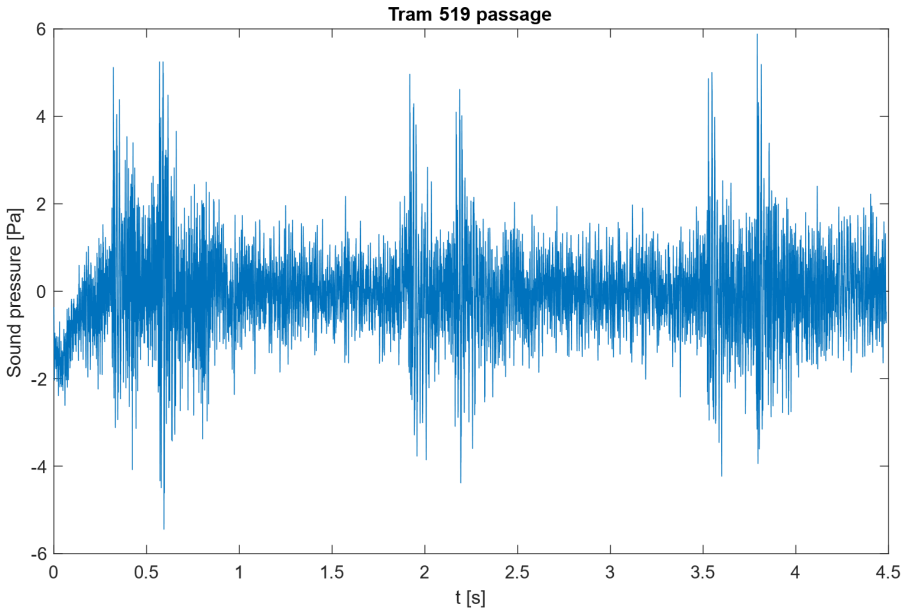

Figure 4. Time course of acoustic pressure magnitude during the passage.

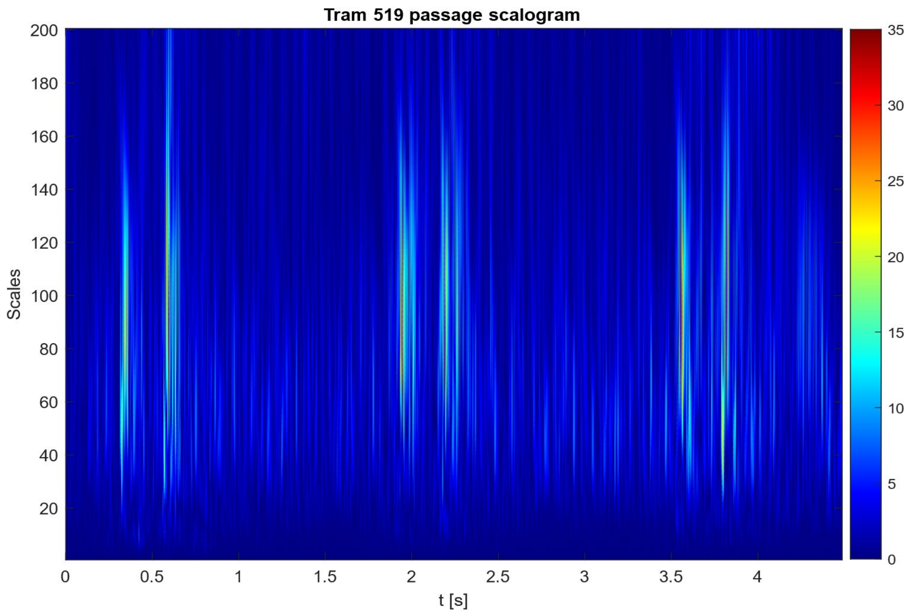

Figure 5. Scalogram of acoustic pressure waveform - sym7 wavelet - absolute value of wavelet coefficients.

The acoustic pressure signal over time was then processed using a continuous wavelet transform. A sym7 wavelet and a scale range from 1 to 200 were used. The resulting scalogram is shown in Figure 5. Values of wavelet coefficients are shown as absolute value.

Analyzing Figure 5 it can be seen that the selected wavelet shows sensitivity to changes in the signal caused by wheel overrun on the rail joints - it is possible to distinguish individual bogies and even wheelsets. The highest dynamics for all passages is observed for the range of scales 70-140. A fragment of the scalogram for scale 80 was selected for further analysis, since the effect of wheel overrun on the magnitude of the wavelet coefficients in this case was the largest - it reached the value of 29 (dimensionless magnitude). It is shown in Figure 6 and compared with the envelope of RMS values.

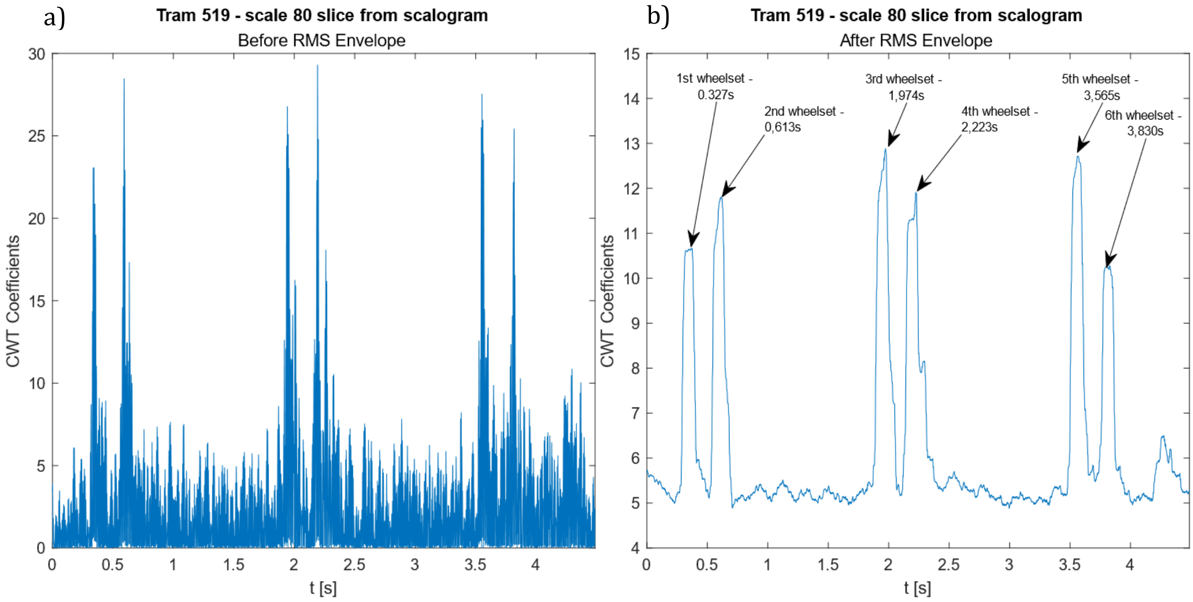

Figure 6. Scalogram for scale 80 acoustic pressure waveform (a) and its RMS envelope (b).

Analyzing the signal envelope shown in Figure 6 the time of passing the test stand by successive sets of wheels of the tested vehicle can be precisely indicated. The amplitude peaks of the wavelet coefficients can be identified manually. The signal is de-noised to such an extent that it is possible to algorithmize this process. In the presented case, an algorithm for finding peaks on the basis of minimal relative height difference (peak prominence) used in topography was applied [7]. A value of 4 was adopted for minimal peak prominence. Using equation (2), the average local velocities between successive wheelsets were determined to be 7.496 m/s, 7.090 m/s, 7.207 m/s, 7.195 m/s, 6.789 m/s, respectively. By substituting these values into equation (3), we obtain the average speed of the entire set (equation 4):

$$V_{l_{avg}} = \frac{7.496\frac{\mathrm{m}}{\mathrm{s}}+7.090\frac{\mathrm{m}}{\mathrm{s}}+7.207\frac{\mathrm{m}}{\mathrm{s}}+7.195\frac{\mathrm{m}}{\mathrm{s}}+6.789\frac{\mathrm{m}}{\mathrm{s}}}{5} = 7.156\frac{\mathrm{m}}{\mathrm{s}} = 25.762\frac{\mathrm{km}}{\mathrm{h}}. \tag{4}$$

The average speed using the photocell was 25.7 km/h. Thus, the relative error between this value and the average speed of the set determined using the acoustic signal was calculated (equation 5):

$$\delta = \frac{\left|25.7\frac{\mathrm{km}}{\mathrm{h}}-25.762\frac{\mathrm{km}}{\mathrm{h}}\right|}{25.7\frac{\mathrm{km}}{\mathrm{h}}} \cdot 100\% = 0.24\%. \tag{5}$$

The demonstrated relative error is favorable and its value is below the assumed 5%. However, the measurement error must be taken into account. In addition to the photocell error, one must consider possible shifts of peaks caused by RMS window averaging. With the window width of 750 samples and sampling frequency of 65536 Hz, a maximum peak dislocation of 11 ms may be expected which corresponds to 2.82% relative error in the worst scenario case where all peaks were maximally dislocated. The measurement error of the precision microphones was negligible in the case presented. Adding up the relative errors, one obtains a value of 3.46%, which is still considered favorable and below the 5% threshold.

This demonstrates the effectiveness of the presented method. Furthermore, by analyzing the results obtained, it is possible to assess the driving behavior of the driver. The lower average speed between wheelsets 5-6 compared to the others indicates that the driver started to slow down in the final phase of the test. This could not be determined from the average driving speed calculated from the photocell indications.

4. Conclusions

Based on the tests conducted and the acoustic signal processing performed using the continuous wavelet transform and the RMS envelope, it can be concluded that the method presented in the article can be effectively used to detect the local speed of passing rail vehicles. The relative error compared to the average speed determined using photocells was less than the assumed 5% and amounted to 0.24% or 3.46% taking a measurement error into account. It was also possible to determine the occurrence of acceleration and deceleration by the driver of the vehicle in the individual phase of the passage through the measuring section.

However, in evaluating the method, attention should be paid to its limitations related to the boundary conditions of the experiment. In the case analyzed, the test object was a vehicle without defects, and no background sound interference was identified. Attention should also be paid to the CWT assumptions themselves - the selection of a different waveform could significantly affect the results.

In further research, it will be necessary to analyze the effectiveness of the method for non-standard test scenarios, taking into account the occurrence of rolling stock and infrastructure defects that could affect the results of the experiment - primarily the occurrence of flat spots on the wheels. Further analysis on a statistically significant test sample and analysis of the impact of non-standard factors in the form of damage and interference on the effectiveness of the method would be reasonable. In addition, it should be verified whether it will be sufficient in such cases to change signal processing parameters, e.g. wavelet type, minimal peak prominence, or envelope window width.

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Additional information

The author(s) declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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