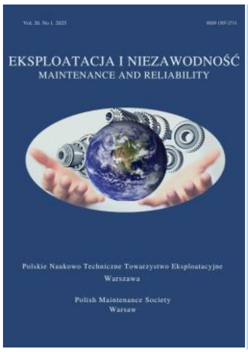

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Application of vibration signals as independent and alternative information channels to support the reliability of positioning and prediction systems for transport means movement

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Highlights

- Prediction of transport means movement.
- Vibration methods as a source of information.
- Operational reliability of the transport system.
- Safety in transport.

Abstract

One of the most important aspects affecting both the safety and reliability of transport systems is the issue of proper positioning of moving transport means in the context of tracking their location while moving within the transport network. Therefore, this article presents the issue of the importance of information for the operational reliability of a selected subsystem related to the detection of a rail vehicle before a railway-road crossing, which is a critical infrastructure element and a particularly dangerous element in the transport network. The article presents an original and own vibration method for predicting the movement of a transport means, using the example of early identification of approaching rail vehicles. Redundant information can be significant for the operational reliability of safety systems in transport. In this aspect, reliable and continuous, and above all, independent information flow is crucial, even at the cost of system redundancy.

Keywords
Transport, operational reliability, vehicle prediction, vibration

1. Introduction

The key parameters that determine the correct operation of transport systems, regardless of their purpose, are safety and reliability. Despite clear trends in the development of transport systems towards increasing their autonomy, both in terms of suprastructure elements (means of transport) and infrastructure, humans will continue to actively participate in transport processes as passengers or operators [1]. Therefore, the safety of transport systems, mainly related to vehicle movement, has been, is, and will remain a key research aspect. Expectations for transport systems, both in passenger and freight transport, are also constantly growing. These expectations primarily concern timeliness, compliance, and quality of transport services. Each of these expectations is strongly dependent on the reliability of the transport system, understood as a set of interconnected means of transport, infrastructure, and computer support systems.

One of the most important aspects affecting both the safety and reliability of transport systems is the issue of proper positioning of moving means of transport in the context of tracking their location while moving within the transport network. Information about the current location of the means of transport allows for tracking transport processes, assessing implementation, and estimating timeliness using dedicated fleet management systems or other logistics systems. In passenger transport, it enables the assessment of schedule compliance and the introduction of necessary corrections in passenger information systems [2]. This is particularly visible in the case of passenger rail transport or public urban transport. Positioning of means of transport requires the use of appropriate vehicle tracking systems (e.g., GPS) or detection systems (e.g., motion sensors) located at specific points in the transport network [3]. The importance of vehicle detection for traffic safety becomes

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crucial at critical points in transport networks, such as level crossings, railway crossings (especially unguarded ones), where drivers or transport operators expect information to support their decision to cross. In such situations, systems responsible for traffic control or warning systems determine transport safety. Therefore, they are required to be fully reliable.

There are many methods and devices for positioning and detecting means of transport. The most widespread system is the one using GPS satellite navigation [4]. Its advantages are range and scope, as well as independence from transport infrastructure. However, its disadvantages include strong dependence on GPS infrastructure, positioning accuracy, and limited cooperation with other traffic control system devices (e.g., traffic lights). Therefore, it is still recommended to use additional vehicle detection devices integrated with traffic control systems. In road transport, examples of such devices are cameras, radars, or inductive loops. In rail transport, SRK (Rail Traffic Control) devices include track occupancy control sensors and wheel counters (e.g., EON, ELS, EOC, CTI). In air transport, advanced GPS systems are used, e.g., GBAS with the use of GNSS reference stations equipped with special antennas [5, 6], as well as distance measuring equipment (DME) as transponder-based radio navigation technology to measure slant range distance by timing the propagation delay of VHF or UHF radio signals and Primary surveillance radar (PSR) works on the principle of signal reflection for distance and position calculation. It consists of a primary rotating radar, which radiates a high power directional frequency beam on a low GHz band and secondary surveillance radar (SSR) works on the principle of interrogation [7]. In water transport, radar stations are used as the basic element of ship traffic monitoring and regulation systems to monitor and direct ship traffic in port waters, as well as marine radar and ECDIS which are now mandatory equipment for safe navigation [8]. Research is also being conducted on the use of image analysis methods as independent and onboard ship detection systems and collision risk detection [9,10]. Nowadays challenges for the monitoring of worldwide ship traffic is related with such issues like piracy, ocean dumping, and refugee transportation. A separate issue is the detection and navigation of unmanned aerial vehicles (UAVs), which is gaining particular importance in the current situation of threats from armed conflicts and experiences from the ongoing war in Ukraine. The main UAVs (drone) detection technologies are radar-based detection, radio frequency (RF)-based detection, acoustic-based detection and vision-based detection or multiple sensor fusion detection systems [11].

It can be concluded that the effectiveness and reliability of positioning systems for moving means of transport are strongly conditioned by the effectiveness and reliability of detecting the means of transport. The very fact of detection depends on the method and device used. The current state of technology in the field of detection devices and sensors indicates the dominance of solutions using GPS systems or radar or image technologies, which are susceptible to external disturbances, including weather conditions. Additionally, experiences from recent years indicate another very significant risk factor, significantly affecting the reliability of these systems, which is unauthorized external interference, e.g., cyber terrorism. Therefore, reliability and cybersecurity should be considered as determinants of the correct operation of these systems. For example, as the aviation sector becomes digitized and increasingly reliant on wireless technology, so has its attractiveness to cyber attackers including nation-state actors and terrorists [7]. In recent years, several cyber-terrorist attacks on rail traffic control systems have also been recorded. Already in 2015, during the CeBIT trade fair in Hanover (Germany), simulations were presented in which a typical railway infrastructure was recreated to estimate the type and intensity of malicious actions that could be taken against such systems. During the 6 weeks of simulations, 2,745,267 attacks were recorded, of which 10% managed to gain partial control over the rail traffic control system and infrastructure.

Therefore, the investigations on new and alternative methods of detecting and locating means of transport, which can support existing systems as an additional information channel, is justified in terms of improving the overall reliability of the system.

Additionally, the methods and devices for detecting means of transport described above enable the detection of a moving means of transport at a specific location in the transport network, resulting from the location of the device (sensor) and the detection range. The use of a method that allows for the prediction of such an event, i.e., provides additional time before the arrival of the means of transport, will increase the range of the system's operation and provide early information about the approaching means of transport. Prediction compared to detection also has significant importance for improving the safety of transport systems through early warning about vehicles.

The article presents an original and own vibration method for predicting the means of transport, using the example of early identification of approaching rail vehicles.

2. The Importance of Information for the Operational Reliability of Safety Systems in Transport

Dependability, as the ability of an object or system to perform its intended functions under specified conditions for a given period of time, is one of the key quality characteristics. To describe it, quantitative values called reliability indicators are often used. This allows for the development of reliability models determined by measures and mathematical dependencies based on probability theory [12]. The features describing such a model refer to measures representing:

- availability: as the ability to remain in a state that allows the performance of specified tasks.
- reliability: as the resistance to damage or the ability to function correctly without interruption.
- maintainability: as the serviceability or the ability to maintain or restore a state in which it can perform required functions under given operating conditions, assuming that maintenance is carried out under established conditions with established procedures and means [13].

Additionally, according to the IEC 61069-2:2016 standard [14], the components of dependability include credibility, determined by measures of integrity and security, as indicators of compatibility and integrity of components and their ability to secure. Dependability defines the system's ability to recognize and signal the system's state and prevent the occurrence of incorrect enforcement or unauthorized access. In this aspect, a reliable and continuous, and above all independent, flow of information is crucial, even at the cost of system redundancy.

When analyzing the issue of transport system reliability, it is necessary to distinguish between technical reliability, as the probability of not experiencing damage or failure state, and operational reliability, as the probability of correctly performing transport processes [15]. Technical reliability is strongly determined by the technical condition and operating parameters of the elements and components of the transport suprastructure and infrastructure [16,17]. By using dedicated diagnostic and monitoring systems and appropriate exploitation and maintenance systems, both for means of transport [18], infrastructure (e.g., engineering structures such as bridges, viaducts, roads, terminals, transport hubs), as well as elements of traffic management and control systems (e.g., ITS, SRK), the probability of damage and failure state is minimized, increasing the technical reliability of transport systems. The operational reliability of transport systems is obviously dependent on the aforementioned systems and their connection to technical reliability. However, the probability of correctly performing transport processes is also strongly dependent on the integration and configuration of transport system elements and proper information flow procedures, data processing, and decision models [19]. It goes beyond technical and operational issues, considering the dependencies and mutual relationships of system elements and a process-system approach. In this context, the operational reliability of transport systems defines the system's ability to function and perform transport tasks. When designing transport systems and estimating operational reliability, it is necessary to ensure the integrity and coherence of the system and the compatibility of its components. They determine the operational functionality of the transport system under nominal and extreme (including extreme) internal and external conditions of the system's operation, even in the event of sudden disturbances, unauthorized external interference (including cyberattacks), accidents and transport incidents, and extreme weather conditions (e.g., snowstorms, floods) and even disasters and natural events (e.g., floods, earthquakes, hurricanes).

In the case of simple systems or technical objects, as well as older solutions of more advanced systems, there is often a conditional dependence that reduces the estimation of operational reliability to technical reliability. Since almost every state of failure state (damage) of technical elements of the system or object causes the inability to perform the intended function, i.e., operational unreliability. With technical development, especially in transport systems, the principle of redundancy has been applied, as a result of which the states of failure state of system components (damage) did not directly affect operational functionality. This results from multi-stream functional dependencies and alternative solutions that multiply the results of selected system elements' actions to ensure continuity of operation. This increases the independence of operational reliability from technical reliability, improves operational continuity, and often safety, which are particularly important in transport systems [20]. At the same time, it significantly affects the production and operational costs of systems and the increasing dependence on decision modules, i.e., electronic control systems. This simultaneously increases vulnerability to the risk of cyberattacks. System redundancy includes structural, functional, parametric, informational, temporal, and durability redundancy [21]. When considering the mutual dependencies of technical and operational reliability of transport systems, the following states should be considered:

- the probability of task completion by a well operational system (absence of damage, unauthorized external interference, accidents and transport incidents, extreme weather conditions, or disasters and natural events). - K_r;
- the probability of task non-completion (execution of the transport process or accompanying tasks) by an operational state system - $\overline{K_r}$;
- the probability of task completion by a failure state system – K_q;
- the probability of task non-completion by a failure state system - $\overline{K_q}$.

Therefore the operational reliability of a transport system can be defined as an equation.:

$$K = RK_r + K_q Q = K_r R + (1 - R)K_q = K_q + R\left(K_r - K_q\right) = = K_q + R\left(\overline{K_r} - K_q\right) = K_q + R(\overline{K_q} - K_r)$$

, where:

R – technical reliability,

Q – technical unreliability (failure).

A transport system is not an autonomous and independent system. It includes various operators and owners of system elements, such as infrastructure, ITS systems, means of transport, etc. Additionally, it is exposed to external influences, including weather conditions and infrastructure repairs. Furthermore, as recent incidents have shown, it is vulnerable to cyberattacks and even destruction due to military actions, for example, the destruction of transport infrastructure as a result of the war in Ukraine. There is also a risk of other random events, such as accidents and even transport disasters, which affect operational reliability. Due to human involvement in transport processes, the human factor is also significant, especially in the context of transport safety. Considering the interdependencies of all these events and the mutual relationships of transport system elements, estimating the overall reliability of transport systems is a very challenging issue. Therefore, this article addresses only the issue of the importance of information for the operational reliability of one subsystem related to the detection of rail vehicles before a railway-road crossing, which is a critical infrastructure element and a particularly dangerous element in the transport network. The proposed solution introduces a new and independent information channel in the system, which increases technical and operational reliability by using a redundant reliability structure of the system.

In the case of a comprehensive system analysis considering technical and operational reliability, studies presented in [21] indicate that operational unreliability is only slightly dependent on the unreliability of the technical object. Operational reliability is largely determined by the operator and the environment. The actions of operators in transport systems are strongly dependent on the information provided to them or their perception of the environment. Therefore, this article focuses on the importance of information for the operational reliability of transport systems, especially in the context of safety related to the early detection (prediction) of moving vehicles. To this end, an original method for predicting rail vehicles based on vibration signals is presented as an example of information redundancy in the transport system and increasing the independence of information channels in railway traffic control systems.

In rail transport, it has been introduced that an accredited institution must issue documentation called a "safety case" at the stage of approving new elements of railway traffic control systems. The safety case of a new application is a document confirming compliance with harmonized standards regarding the specification and demonstration of reliability, availability, maintainability, and safety, which in Poland are described in the standard PN-EN 50126-1:2018 "Railway applications - the specification and demonstration of reliability, availability, maintainability, and safety (RAMS)" [22]. The RAMS method involves analyzing four parameters related to technical means: R for Reliability, A for Availability, M for Maintainability, and S for Safety. The goals of implementing RAMS are to increase the reliability, availability, maintainability, and safety of products in rail transport. Safety in the case of trackside elements and traffic control systems is understood as the technical level of the system free from unacceptable risk of damage [23]. For example, for signaling at railway-road crossings, the term safety refers to the Safety Integrity Level (SIL), in accordance with EN 50129 [24]. This standard is applicable to safety-related electronic systems (including sub-systems and equipment) for railway signaling applications [25].

3. Method for Predicting the Movement of Means of Transport

Considering the importance of information for the operational reliability of transport systems and its direct impact on safety, it is justified to conduct research to seek additional and independent sources of information and to develop the concept of a redundant reliability structure for such transport systems. To ensure the substitutability and complementarity of additional system elements, it is worth exploring the possibilities of identifying moving means of transport using various alternative phenomena. Currently used detection systems primarily utilize phenomena related to the appearance of an image (vehicle pattern recognition), disturbances in the field generated by radar systems or photocells, and even observations of electromagnetic field disturbances generated by inductive loops. A phenomenon that invariably accompanies moving wheeled means of transport is the wheel-surface (wheel-rail) contact, which generates vibrations [26] and wave propagation (Fig. 1). The natural medium transmitting the information contained in the vibration wave is the surface of the track. In the case of rail transport, it is the rail, which additionally significantly improves the quality and range of vibration wave transmission, enabling not only vehicle detection but even its prediction. The assumptions I developed regarding the use of information carried in vibration signals generated by the movement of wheeled vehicles for early detection (prediction) of the vehicle approaching the observation point allowed for the development of an original method for measuring and processing vibration signals on the recorded track (road, rails) to extract information about the approaching means of transport. Due to the critical importance of information, as the prediction of rail vehicles approaching unguarded railway-road crossings, validation studies of the developed method were conducted precisely at these points in the transport system. Unguarded railway-road crossings do not have any traffic separators (barriers) or light signals informing drivers of the need to stop before the crossing. For such crossings, the decision to enter depends solely on the driver, who makes it based on the visibility of the approaching rail vehicle. Unfortunately, there are often significant visibility limitations or other factors influencing drivers' incorrect decisions, resulting in tragic accidents. Therefore, the developed method is of great importance not only for the operational reliability of railway-road crossings but above all for transport safety at these crossings.

Considering the phenomenon of vibration generation due to wheel-rail contact in the informational aspect, it is necessary to distinguish the direction of vibration propagation and the place of signal registration. When the measurement system is located ahead and the rail vehicle is approaching it, we talk about leading propagation, which enables vehicle detection and, with the appropriate mathematical apparatus, even its prediction by extracting early symptoms in the signal. In the case of signal analysis after the rail vehicle has passed over the measurement point, it is possible to analyze the signal with the entire vehicle passage recorded. This allows for the analysis of the so-called vibration signature of the vehicle, which enables the identification of additional vehicle parameters, such as speed, type of train, number of bogies, length, and even damage detection. This signal can therefore be used in transport or infrastructure control systems.

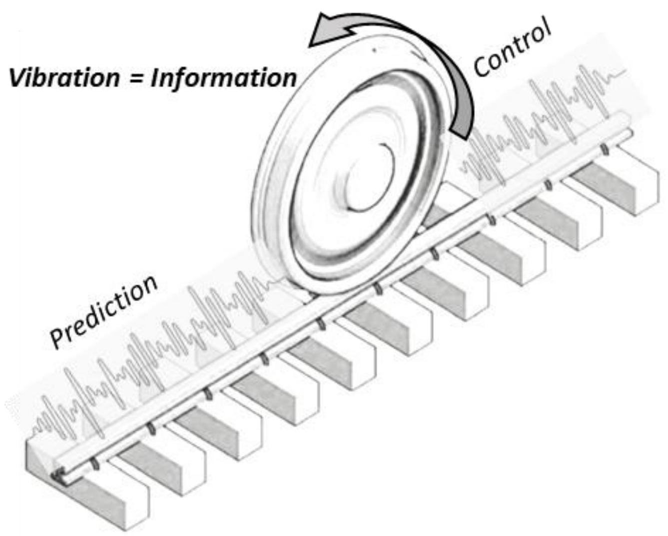

Fig. 1. Rail vibration as source of information.

Thus, it can be used to improve the technical reliability of the transport system by diagnosing early stages of potential damage. The idea of dividing and the importance of information contained in the signals generated by the vehicle passage (wheel-rail contact) in the reliability and safety of the transport system is presented in Figure 1. Therefore, it can be hypothesized that the information contained in the vibration signals generated by the passage of wheeled means of transport constitutes an additional and alternative source of information and can be used to improve the technical and operational reliability of transport systems.

The general concept of the method for predicting the movement of wheeled means of transport using vibration signals is presented in Figure 2. In the first stage, vibrations of the track are recorded at designated locations. Then, at specified time intervals, e.g., every 1 second, a preliminary signal processing algorithm is implemented to estimate the correlation of the time and frequency functions of the current signal window (in a specified time unit) with the previous signal window. In the case of low correlation of these functions (according to a predetermined correlation coefficient value, e.g., below 0.7), the next step involves proper processing of continuous vibration signals and their FFT spectra (Fast Fourier Transform) representations. As a result of signal processing, point estimators of time and frequency functions are determined as representative measures of signals in subsequent time windows. The next step is iteratively repeated, and simultaneously, a trend analysis of the changes in the values of the calculated point estimators representing subsequent time windows of vibration signals is performed. If the trend analysis shows a consistent upward trend, a prediction symptom of an approaching wheeled vehicle is signaled.

The proposed approach based on trend analysis, instead of a simpler method based on established threshold values, after exceeding which the approaching vehicle is identified, has many advantages. The most important of these are the effectiveness of prediction regardless of the location of the measurement sensors and the type and speed of the vehicle, as well as the reduction of the impact of measurement noise levels and natural vibration activity at the measurement site. This is very important for the reliability of this system and allows for its application to various wheeled transport systems.

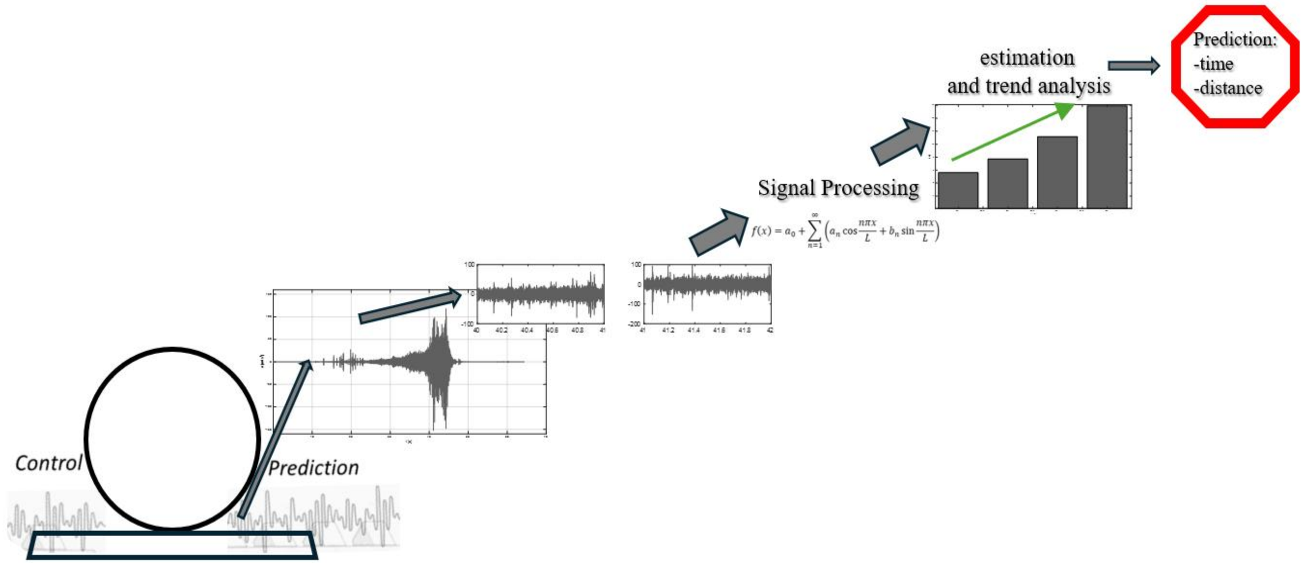

Fig. 2. Concept of the method for predicting the movement of wheeled means of transport by using vibration signals

An additional advantage of the developed method is that it utilizes the natural phenomenon generated by the movement of the vehicle and does not require the use of other symptoms based on synthetic intermediate mechanisms, which require the use of additional detection systems. In such cases, complex digital systems are often used, which are susceptible to interference and unauthorized external interference, significantly affecting the cybersecurity of such solutions. Therefore, the use of vibration signals as additional information channels supporting the reliability of positioning and prediction systems for means of transport is characterized by independence from other synthetic phenomena and resistance to interference.

4. Results and discussion

To validate the developed method, large-scale in situ studies were conducted under real-world railway transport conditions. These studies were preceded by experiments conducted on a test track, during which the information capacity of vibration signals was identified as a response to various dynamic excitations occurring under railway traffic conditions. The results of these studies confirmed the high information capacity and the possibility of separating and identifying signal components correlated with the passage of a rail vehicle. The results of these studies were presented at thematic conferences and published in publications [27]. During the in situ validation studies, vibration acceleration signals were recorded in three orthogonal axes using sensors mounted on the railway track. The scope of the studies included continuous vibration measurement and selection of signals recorded before and during the passage of various rail vehicles at different speeds. To identify the frequency components of the signals, the Fast Fourier Transform (FFT) was calculated. This approach enabled the analysis of windowed signals in both the time and frequency domains. Example signals and their spectra recorded before and during the passage of a maintenance train are presented in Figure 3.

To visualize the operation of the prediction method, the entire recorded signal of the passage was divided into consecutive 1-second time windows, reflecting the sequential processing of the signal accompanying the vehicle passage. For each signal in the windows, the frequency spectrum was determined using the FFT transform. Example consecutive signal windows are presented in Figure 4.

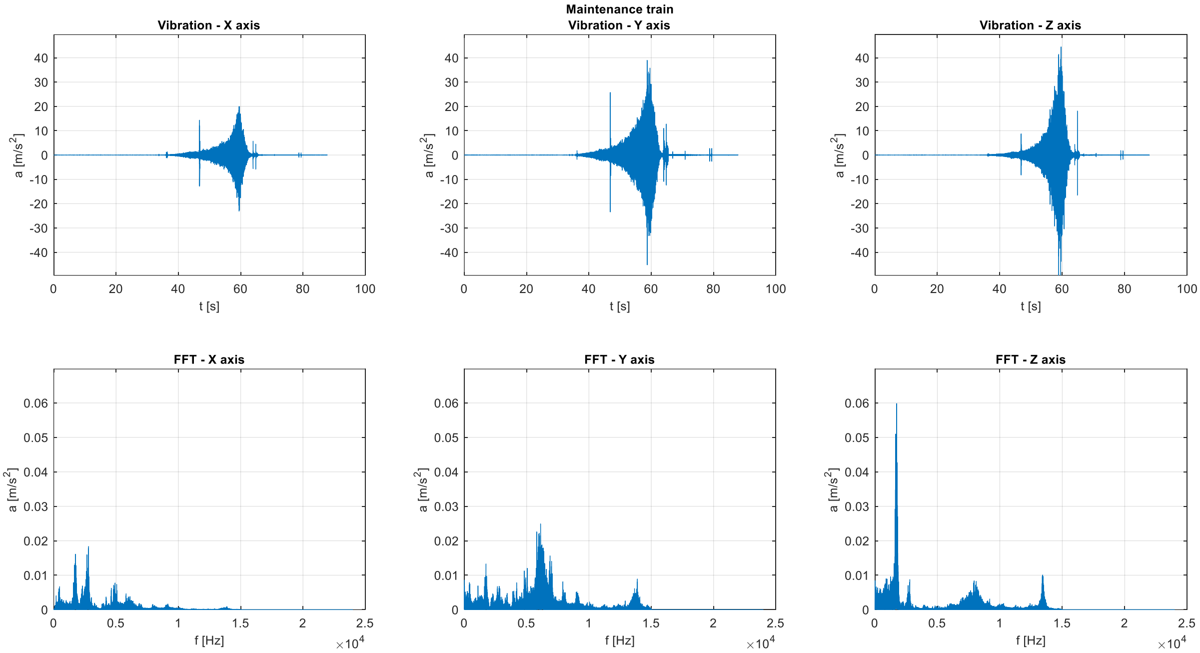

Fig. 3. Vibrations and FFT spectra recorded before and during the passage of a maintenance train, divided into 3 orthogonal axes.

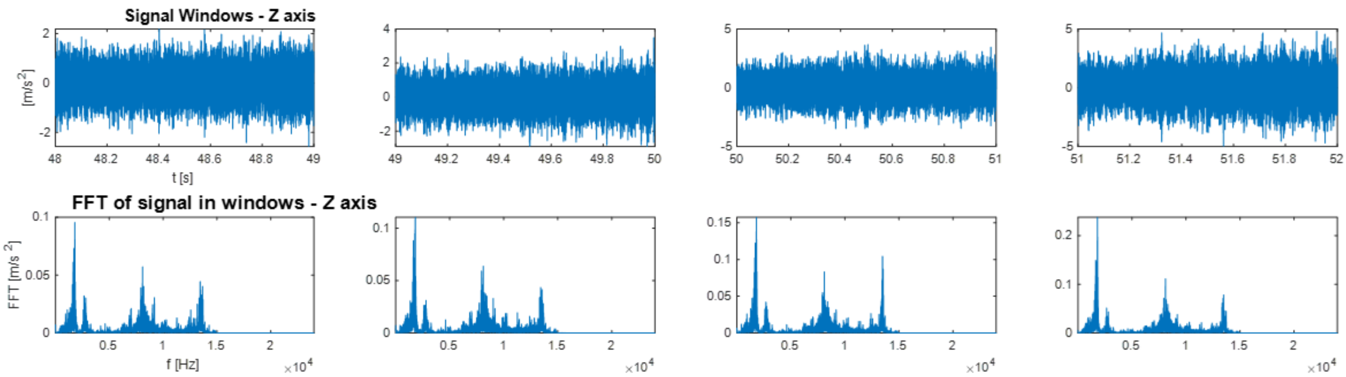

Fig. 4. Subsequent signal windows and FFT spectra recorded for the vertical Z-axis.

As the next step, estimators of signals in windows were determined, both for time courses and frequency distributions, to analyze the trends of their values (Fig. 5).

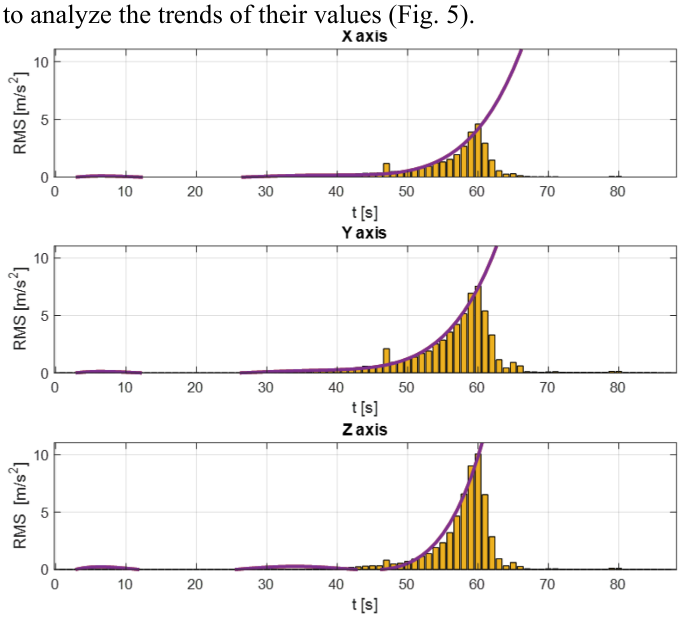

Fig. 5. Distribution of subsequent signal estimator values with trend analysis.

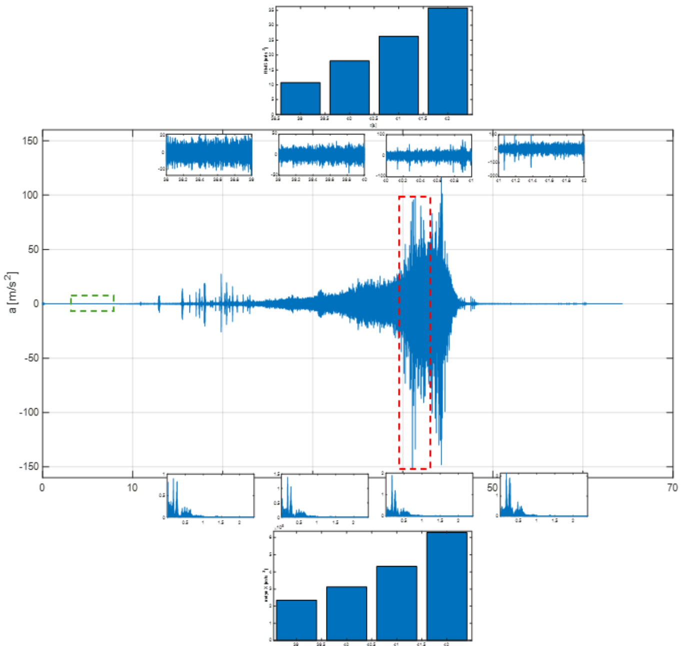

Fig. 6. Visualization of the operation of the vibration prediction method for approaching vehicles with detection windows (red) and prediction windows (green).

Detection of a vehicle passing over or just before the measurement sensor is not a challenge, as shown in Figures 6 and 7 and the signal window marked with a red rectangle. Subsequent signal windows and their spectra, as well as the estimators calculated based on them, clearly indicate an upward trend, which should be interpreted as the passage of a vehicle. However, the challenge posed to the developed method was to predict the vehicle as early as possible to inform users or operators of the transport system about the approaching vehicle. This allows for making the right decision and taking appropriate actions, which determines the momentary operational reliability of the user warning system, e.g., at an unguarded railway-road crossing. Therefore, to visualize the effectiveness of the developed method, the result for a much earlier observation window, marked in green in Figures 6 and 8, is presented.

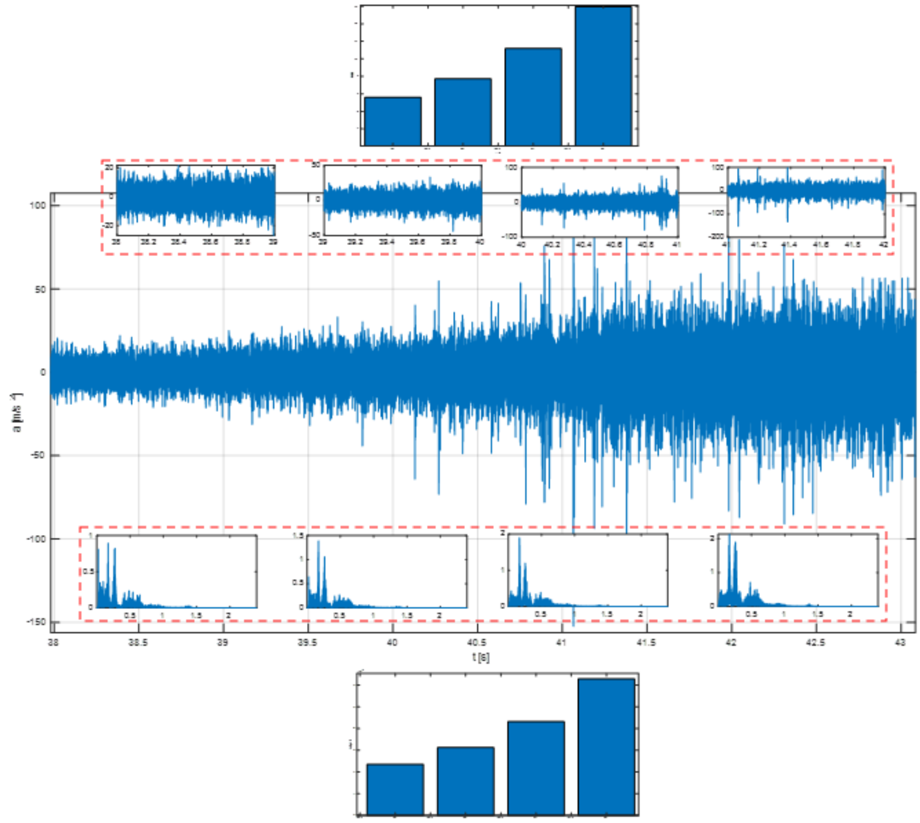

Fig. 7. Detection of a vehicle over or just before the sensor, time windows, and FFT at the time of passage (around the 40th second)

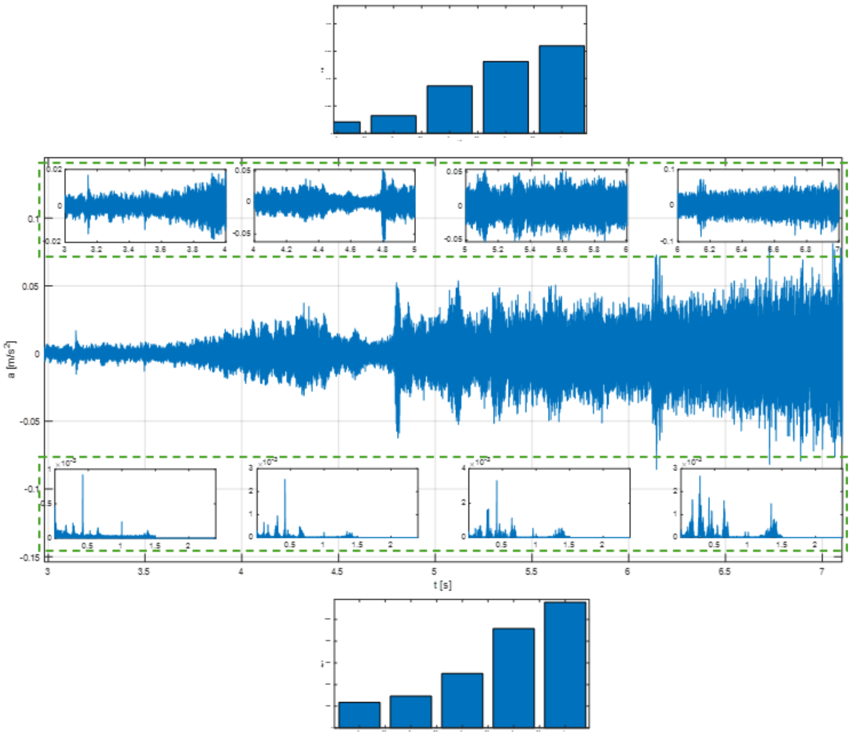

Fig. 8. Prediction of a vehicle located at a significant distance before the sensor, time windows, and FFT (around the 4th second).

As confirmed by the results of the conducted studies, the developed method for predicting the approach of a wheeled vehicle based on vibration signals is effective and allows for early detection of symptoms of an approaching vehicle. This provides additional and independent information from other vehicle detection systems, and most importantly, it has a predictive nature, meaning early detection of the vehicle, even if it is much further away than the field of vision or if weather conditions hinder visibility.

5. Conclusion

The article presents the importance of redundant information for the operational reliability of a selected safety system in transport. The research object chosen was the driver warning system at unguarded railway-road crossings, which are critical safety points in the infrastructure and transport network [28]. The assumptions and concepts of using vibration signals generated by wheel-surface contact during the movement of transport means as carriers of information about an approaching vehicle were presented. The procedure for the vibration prediction method was described, and example in situ research results were presented. The developed method is based on trend analysis of estimators of subsequent windows (realizations) of vibration signals in the time and frequency domains. The full validation of the developed method was carried out as part of a doctoral dissertation [29]. The results obtained and presented in it showed a high potential for early prediction of rail vehicles even at a distance of over 2000 meters and with more than 100 seconds' advance notice of the train's arrival. The developed method and the results of the conducted research were repeatedly presented at scientific conferences and industry meetings. As a result, a prototype rail vehicle prediction system was created, which has been installed at a category D railway-road crossing for over 3 years. The developed method has a very high development potential, as evidenced by international cooperation with a team of mathematicians and mechanics from Lithuania and the USA, within which analytical experiments are conducted using advanced mathematical methods for even earlier and more reliable prediction of transport means. The result of this cooperation is the article [30], which presents new possibilities for the prediction of approaching trains based on H-ranks of track vibration signals.

The developed method is dedicated to the early prediction of the approach of wheeled transport means (automobiles and rail vehicles). However, the best results are obtained for rail transport due to the possibility of using the railway track as a carrier of vibration signals. The rail has homogeneous material properties and is partially isolated from other transport infrastructure elements that may introduce disturbances [31]. The limitations of this method should be considered for all road infrastructure elements that affect the propagation of the vibration wave (dilations, changes in construction materials, etc.). These limitations may reduce the prediction range, but the effect of symptom anticipation in time relative to detection systems still occurs.

Due to the fundamental assumption of the developed method, which involves the use of vibrations generated during the movement of transport means and wave propagation, it can be assumed that the primary limitation of this method is its applicability to wheeled transport means, where vibrations are generated as a result of the contact between the wheels of a moving vehicle and the surface. However, one can take a broader view of the idea of the developed method as a prediction of a moving transport means based on the analysis of vibroacoustic emissions. In this context, we expand the set of signals to include acoustic emissions accompanying flying transport means (including unmanned drones). The author has also conducted such studies. In the case of floating transport means, wave phenomena propagating in the water medium also accompany them. Therefore, it can be assumed that their analysis can also provide information about approaching ships. These more general assumptions, however, require many additional analyses, studies, and validations and may determine the future research directions of the Author.

Due to the current geopolitical situation and threats to critical infrastructure, including transport (railway), the developed method has an additional very important advantage. The use of vibration signals as independent and alternative information channels supporting the reliability of positioning and prediction systems for transport means improves resistance to cyberattacks or destruction of ITS system elements. Vibrations as a natural effect of wheel rolling will always remain available and generated during the movement of wheeled transport means.

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