# Evaluation of Detection Approaches for Road Anomalies Based on Accelerometer Data

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Abstract: Current container security systems record vibrations and shocks, but their potential for creating smart transportation systems remains underutilized. This study analyzes data collected from a truck and discusses a concept for generating road condition maps from accelerometer data. An experiment was conducted by mounting an accelerometer on a container door to gather acceleration data in various transport conditions. The study focuses on analyzing vertical (Z-axis) accelerations as a primary indicator of road anomalies. The developed concept can be integrated into logistics platforms, enabling vehicle drivers and infrastructure managers to respond to road defects in a timely manner.



## 1 INTRODUCTION

Transport infrastructure is a fundamental element of the economy and societal well-being; however, monitoring and maintaining its condition is a complex and resource-intensive process (Yarmukhamedov et al., 2020). Flaws such as potholes, sunken manhole covers, or uneven railway crossings can cause vehicle breakdowns, cargo damage, and an increased risk of accidents. Therefore, it is crucial to develop innovative, cost-effective solutions that enable real-time monitoring and assessment of road conditions. In this context, next-generation IoT (Internet of Things) technologies offer significant potential, enabling data collection and analysis using existing infrastructure (Ye et al., 2024).

Most modern containers designed for cargo transportation are equipped with integrated IoT systems that collect information about the container's location, vibrations, and impacts. These systems, based on low-power accelerometers, are primarily used for ensuring security; however, their potential for secondary data utilization remains underexplored (Barlogis et al., 2025). The simplified process illustrated in Figure 1 demonstrates how integrated IoT systems in containers can be adapted to monitor secondary events, such as detecting and recording road anomalies. These systems, utilizing existing accelerometer data, could identify events exceeding threshold values, such as impacts caused by potholes, railway crossings, or other uneven surfaces.


Figure 1: Concept of secondary event.

When such an event is detected, the recording device can analyze the nature of the event and, along with geolocation data, transmit this information not only to the owners of the recording devices but also to centralized data processing systems. Third-party systems (platforms), using algorithms and artificial intelligence, could identify recurring events and determine road anomalies in specific locations. The

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conclusions obtained, integrated into GIS (Geographic Information Systems) platforms, could be forwarded to the responsible authorities tasked with road maintenance and repair. The figure below illustrates how accelerometer data can be used for secondary events (see Figure 2).

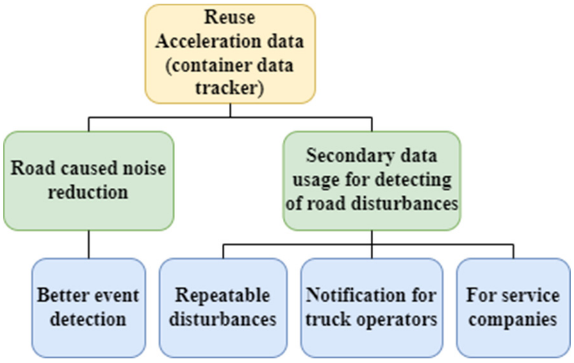


Figure 2: Secondary data usage model.

This process would ensure not only accurate and timely detection of road defects but also more efficient resource utilization for road maintenance. Additionally, this data could be used to create real-time road condition maps accessible not only to institutions but also to the transport sector and the public. Such a solution would allow logistics companies and drivers to plan their routes in advance, avoiding hazardous or poorly maintained road sections. Based on edge computing methodologies, these systems could be deployed on a larger scale, for example, for road condition monitoring [citation needed]. This approach would not only contribute to improving infrastructure maintenance but also support the development of green transportation infrastructure by reducing the costs and environmental impact of traditional solutions.

Road condition monitoring typically requires specialized equipment, such as LiDAR technology or cameras which are expensive and demand significant computational power. In this paper, we discuss alternatives—using accelerometers installed in containers as an additional data source. Accelerometers, which detect changes in acceleration during transport, enable the identification of road irregularities based on the vibration patterns of the vehicle. By integrating this data with GPS information, real-time road condition maps can be generated, which could be beneficial for both drivers and infrastructure managers.

# 2 RELATED WORKS

## 2.1 Road Damage

Various methodologies have been proposed in recent studies to assess and predict road damage, each employing diverse approaches.

For instance, Yang, X. et al. (Yang et al., 2024) in a recent study, sought to review and analyze advancements in automated systems for road maintenance, focusing on detecting road distress. The study explores the integration of computer vision, artificial intelligence, and robotics in the context of road infrastructure, emphasizing developments in detecting both surface and internal road damages. For surface distress detection, sensor technology, image processing, machine learning, and deep learning techniques like convolutional neural networks (CNNs) were integrated to enhance accuracy in identifying cracks and other damages.

Similarly, Deepa, D. (Deepa & Sivasangari, 2023) aimed to create an efficient method for detecting and classifying road damages using a hybrid deep learning framework. Their approach utilized a combination of techniques: pre-processing images with adaptive histogram equalization, segmenting damage using fuzzy c-means clustering, and extracting features with Laplacian edge detection and wavelet-Walsh transforms. These optimized features were classified using a hybrid DeepCapsule Autoencoder-based Convolutional Neural Network (DCACN) enhanced by Whale Optimization. The study concluded that "The proposed work attains 98.815% accuracy, and the obtained results outperform the existing approaches."

Furthermore, a study by Mattes, P. (Mattes et al., 2023) introduced Competitive Reconstruction Networks (CRNs) for detecting road damage in mobile mapping data, specifically focusing on anomaly detection within 3D LiDAR-derived point clouds. The authors set out to develop a semi-supervised machine learning approach capable of identifying road anomalies with minimal reliance on manually labeled data, addressing a major challenge in road quality evaluation. The study concludes that CRNs can effectively enhance road quality assessments by providing accurate, automated anomaly detection in road imagery derived from LiDAR point clouds.

Lastly, in a recent study, Boyarchikov Y., & Martinec T. (Boyarchikov & Martinec, 2024) aimed to develop a cost-effective, sensor-based solution for real-time road pavement monitoring, seeking an alternative to costly methods like LiDAR and laborintensive manual inspections. Using accelerometers and gyroscopes mounted on vehicles, the system captures vibration data, which is then processed through neural networks to classify road sections as "damaged" or "undamaged." Showing the potential of replacing LiDAR based technologies with accelerometer based devices.

### 2.2 Accelerometers for Road Anomaly Detection

Other studies also underlined the affordability and accuracy of using accelerometer based technologies to monitor and detect road and bridge damage.

For instance, a recent study by Gupta J. et al. (Gupta et al., 2024) set out to explore the integration of IoT-based sensor technology for sustainable road safety. It examined the role of sensors such as accelerometers, gyroscopes, and ultrasonic sensors in enhancing vehicle safety through applications like driver drowsiness detection, airbag deployment, and hazard identification on the road. The accelerometer relies on a MEMS (Micro-Electro-Mechanical Systems) framework, utilizing piezo resistive materials to register minute changes in resistance under strain. The study demonstrated that these accelerometer-based systems provide high accuracy and rapid response times, which are critical for reducing accidents and improving overall road safety.

Another example of such systems was presented by Kuladeep Chilamkuri et al. (Chilamkuri & Kone, 2020), who set out to develop a system for real-time structural health by monitoring vibrations and displacement of the Varadhi Bridge in India. The study used the ADXL335 accelerometer integrated with an Arduino UNO microcontroller to measure vibrations and displacement on one of the bridge spans. This setup provided a low-cost, efficient system for real-time structural health monitoring, enabling early detection of potential structural issues on the bridge. Through continuous data collection, the system identified critical vibration levels, enabling proactive maintenance alerts when vibrations exceeded safe thresholds. This study showed that using such accelerometer based systems can allow reliable condition monitoring of structures experiencing high traffic.

Similarly, Fujino Y. et al. (Fujino et al., 2019) in the study on Japan's infrastructure monitoring, accelerometers played a crucial role, especially in assessing the dynamic responses of structures like long-span bridges and high-rise buildings. Accelerometers measure vibrations and accelerations resulting from natural forces such as wind and seismic activity, providing critical data on structural behavior under stress. The authors concluded that Japan's approach to structural monitoring provides valuable insights, helping maintain resilience and operational safety in infrastructure. In a further study Fujino Y. et al. (Fujino & Siringoringo, 2020) outlined Japan's efforts to improve infrastructure management through a government-sponsored research program. In the methodology, accelerometers were installed at various structural points to capture real-time data. This setup allowed researchers to measure natural frequencies, damping ratios, and vibration patterns, helping to detect anomalies that could indicate structural weaknesses or damage. The data was then analyzed to confirm theoretical models, often aligning well with design assumptions, thus validating the structures' resilience. The results underscored the accelerometers' effectiveness in providing a non-invasive, continuous monitoring solution.

Furthermore accelerometer based systems were used by David Krier et al.(Krier et al., 2014), who aimed to improve the accuracy of vehicle control systems by directly estimating road-tire forces using in-tire accelerometers. Typically, these forces are estimated indirectly, but this study utilized accelerometers affixed to the tire's inner tread, capturing detailed tire-road interaction data through a Principal Component Analysis (PCA) model. The study concluded that the PCA model provided a feasible and effective method for capturing the vertical and longitudinal forces acting on the tire. The research suggests that this innovative approach could enhance vehicle safety and performance in real-world applications, though further work is needed to assess robustness across varying road conditions. A continuation of this type of methodology could allow for more accurate road condition estimation in further studies.

## 3 METHODS

### 3.1 Concept of Accelerometer Usage for Secondary Event Detection

As we know, perfect roads don't exist, at least not in our area. Road defects could be monitored using the vehicles traveling on them.

Smart systems installed in vehicles will generate timestamps and values of impact events caused by road defects and detected by sensors (see Figure 3).

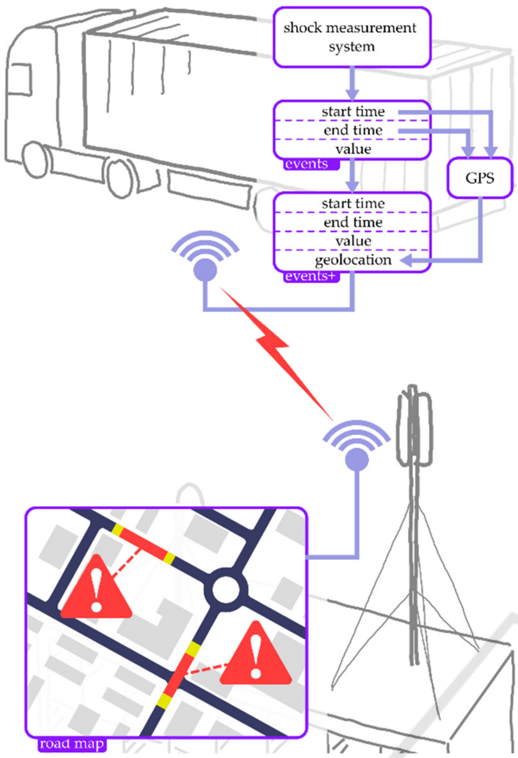


Figure 3: The concept of road monitoring system.

These data, synchronized with global positioning system (GPS) data, should be forwarded for analysis to the relevant authorities, who will assess road conditions in each section, provide this information to traffic participants, carry out preventive maintenance, and plan road repair work. Further we focus on detecting road defects using a sensor mounted on a container. The study was conducted blindly, meaning that conclusions about road defects were drawn solely based on data obtained from the sensor without knowing the actual physical condition of the road.

## 3.2 Measurement Method

When a vehicle's wheel enters a road defect zone, the trajectory of the wheel's axis usually changes abruptly, resulting in an impact. This generates vibrations that propagate throughout the entire vehicle. These impact-induced vibrations can be recorded by a sensor installed in the vehicle. The sensor could be installed either in the vehicle itself or on the transported cargo. For cargo, marine containers are particularly suitable because of their large mass—the amplitude of vibrations caused by impacts will be greater than with smaller masses, increasing the likelihood of detecting road defects. Additionally, it is currently a trend to install smart sensors on containers, and road defect detection could serve as an additional feature. For our experiment, it was decided to mount the sensor on the door of a container transported by a truck (Figure 4), as smart sensors are most commonly installed in this location.

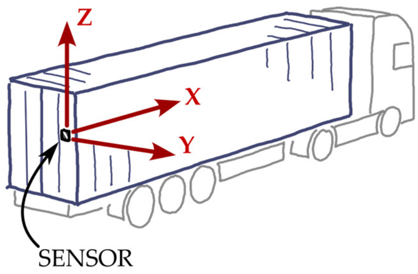


Figure 4: Sensor mounting position.

The sensor, using an accelerometer, recorded accelerations along three axes: X – longitudinally in the direction of the truck's movement, Y – transversely to the truck, and Z – vertically relative to the road surface. The sensor processes this accelerometer data using a special algorithm that determines whether an impact event occurred. In this study, accelerometer data with a 100 Hz sampling rate was used. The data was collected while the truck transported an empty container in the city of Klaipėda. The total duration of the collected data (the truck's journey) was 31 minutes. Two specific operational periods of the truck were selected for analysis: the first from the engine being off to the start of acceleration, and the second during road travel without active speed changes.

Approaching the resolution of this hypothesis, further research was focused on detecting road irregularities using edge computing-based algorithms. The sensors used in container security and data recording systems are low-power devices, which also means that their edge computing capabilities are very limited. Usually, these limitations are tied to device-level functionality. For example, in the case of FSM (Finite State Machine) algorithms, only predefined features can be used to implement the algorithm. All of this contributes to the complexity of solving this hypothesis. Classical detection methods, as mentioned earlier, cannot essentially be applied, making it necessary to seek simpler approaches and methods. To find these solutions, it is first necessary to understand the data (acceleration data), its nature and characteristics, identify its distinctive features, and find a method to extract them using predefined features. Considering this, a field experimental study was conducted, using classical data collection equipment to gather acceleration data.

The equipment was mounted on the door of the container (transported by the truck), simulating the typical installation position of data recorders. This is essential for detecting the characteristic properties of the data from a specific position. Changing the position is likely to alter the nature of the data (for example, mounting it at the front of the truck may affect the suspension impact, resulting in different patterns for the same anomaly). Therefore, during the field experiment, the classical device position was chosen.

# 4 EXPERIMENTAL RESULTS

## 4.1 Accelerations at the Start of Movement

In the vertical acceleration (Z-axis) graph (see Figure 5), during the period from 92.0 s to 96.2 s, the truck's engine was turned off. In this interval, the acceleration amplitude was very low, registering only minor mechanical vibrations (e.g., the driver closing the door) and the internal noise of the accelerometer.

The constant component of the vertical acceleration is not exactly 1 g as expected because the accelerometer is not perfectly oriented; that is, the X-axis is not perfectly aligned with the zenith, and the X and Y axes are not perfectly aligned with the horizontal plane.

At the time point of 96.2 s, the driver started the truck's internal combustion engine, and during the period from 96.8 s to 97.2 s, the engine's idle speed was increased several times. An increase in the recorded acceleration amplitudes is visible in all graphs, with the Z-axis showing the highest amplitude at 0.051 g. While the engine continued to idle during the period from 97.2 s to 106.7 s, lower acceleration amplitudes were recorded, with the Z-axis reaching a maximum of 0.008 g. It can be observed that, while the truck engine is running, the sensor registers the strongest vibrations caused by the engine on the Z-axis. This is likely due to the structural characteristics of the truck.

In the acceleration spectrum (Figure 6), the green color represents the Z acceleration spectrum when the engine was off (period from 92.0 s to 96.2 s), while the blue color represents the spectrum when the engine was idling and revved several times (period from 96.8 s to 97.2 s). It can be observed that the strongest influence of engine vibrations on the road defect detection algorithm occurs in the high-frequency range starting from 10 Hz, with amplitudes not exceeding 0.002 g.

In the case of Z-axis accelerations, an increase in acceleration amplitudes is also observed across the entire frequency range. A peak can be identified at approximately 1 Hz. When examining higher frequencies, it can be noted that, similar to the engine on/off case (Figure 6), the slope of the acceleration amplitudes differs from those observed in the X and Y axes. This can likely be attributed to the structural characteristics of the truck and the operating conditions of the engine.

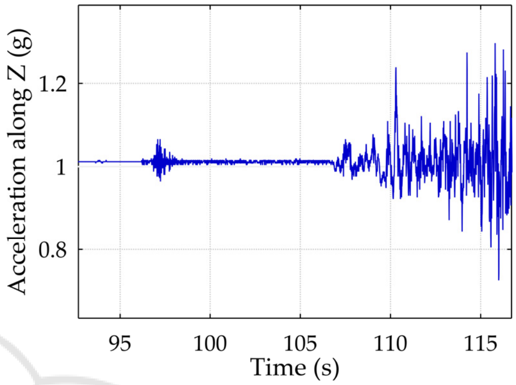


Figure 5: Start of movement: acceleration Z.

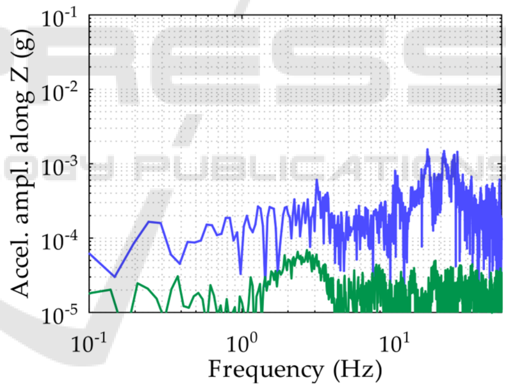


Figure 6: Z acceleration spectrum of the engine off and on.

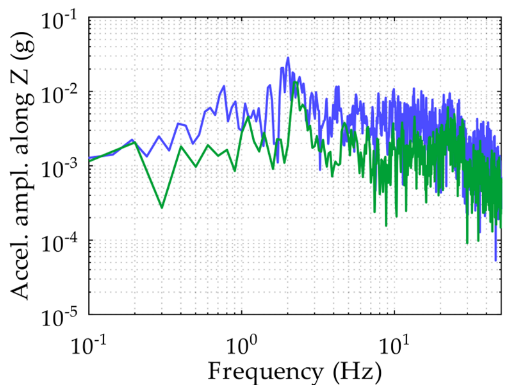


Figure 7: Z acceleration spectrum without acceleration and with acceleration.

Comparing the Z acceleration patterns presented in Figures 6 and 7 in the high-frequency range, it can be observed that the envelope characteristics of the patterns are not identical. Therefore, the influence of vibrations caused by road irregularities cannot be ruled out, as the vertical displacement of the truck's wheel when traveling over road irregularities is expected to be significantly greater than in the horizontal direction. This is further confirmed by the observation that, in the high-frequency range (from ~2 Hz), the acceleration amplitudes recorded on the Z-axis are significantly higher than those on the X or Y axes. Thus, it can be concluded that, for a road defect detection algorithm, it is sufficient to analyze only the Z-axis accelerations.

## 4.2 Accelerations While Driving

In the vertical acceleration graph (Figure 8), the green curve represents the accelerations when the truck was driving on a road without significant defects, while the blue curve represents the accelerations when the truck encountered three road defects. The graph clearly shows vibrations caused by impacts at the timestamps 1459.6 s, 1462.3 s, and 1465.2 s. It can be observed that the bursts of vibrations caused by the impacts occur in two stages, with the first likely originating from the front axle of the truck.

Looking at the acceleration patterns (Figure 9), where the green curve represents the truck driving on a road without significant defects and the blue curve represents the truck encountering three defects, the oscillations in acceleration caused by the road defects clearly stand out in the frequency range from 9 Hz to 17 Hz.

## 4.3 Results and Analysis of Road Irregularities

The data is collected at a low frequency of only 100 Hz, which is typical for such systems. This also presents a significant challenge, especially from the perspective of classical event detection methods.

During the experiment, a dataset was collected from a single container journey. The entire experiment was filmed to more accurately identify road sections where anomalies were detected. A more detailed analysis of the recorded impacts is presented below.

A manhole cover that has sunk into the asphalt was detected (see Figure 10). This is one of the most common road defects that can affect cargo. In this case, the defect is minor and has no significant impact. However, such road defects, where the manhole has sunk more than 5 cm, can not only damage the vehicle's wheels but also affect the cargo.

There have been known cases where similar defects caused pallets with cargo to topple inside a container (which could also result from improperly secured cargo).

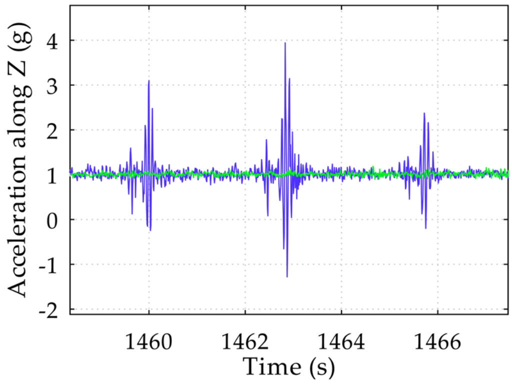


Figure 8: Z acceleration graph without impacts and with impacts.

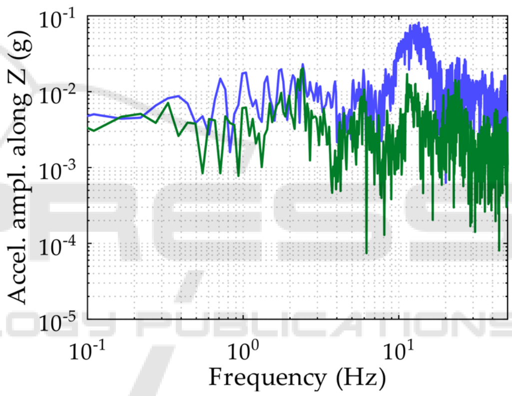


Figure 9: Z acceleration graph without impacts and with impacts.

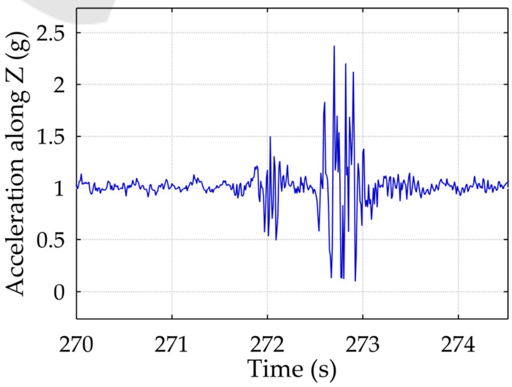


Figure 10: Shock detection - manhole cover.

Another commonly encountered impact-causing infrastructure element is a railway crossing(see Figure 11). Although this is not a critical element, such a reverse road condition assessment system could help identify crossings that will require maintenance in the near future. This would enable the creation of maps of road sections in need of repair and prioritize them based on the frequency and intensity of impacts.

Road wear, one of the more common defects, is observed in this case as recurring road depressions and potholes. These defects cause the container with cargo to sway. In this instance (see Figure 12), the damage is not critical; however, the frequency and severity of such defects along the road segment may indicate the need for road reconstruction.

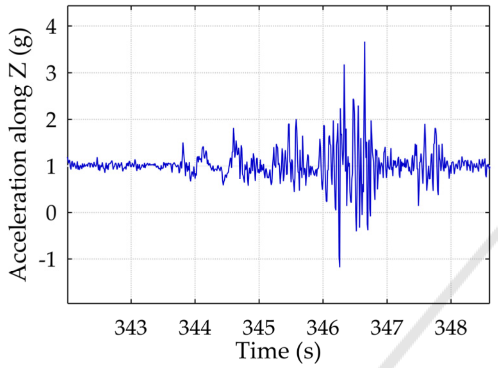


Figure 11: Shock detection – railway crossing.

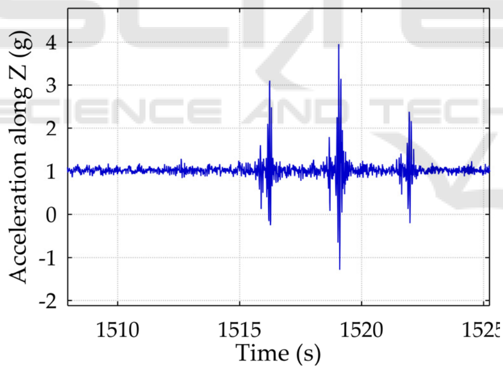


Figure 12: Shock detection – Pothole/uneven road.

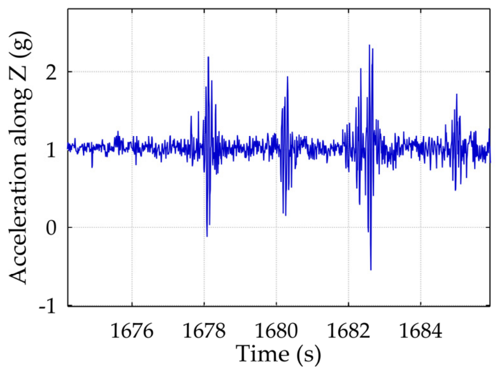


Figure 13: Shock detection – Overpass joints.

Another infrastructure element is overpass joints (see Figure 13). Damage and potholes often develop in the joints of older overpasses. Similar to railway crossings, these areas can be monitored, and as the risk of accidents increases, they can be identified as problematic locations.

## 5 CONCLUSIONS

Since many heavy vehicles transporting containers as cargo travel on the roads, most modern containers are equipped with data loggers and tracking systems for security purposes. This equipment is based on edge computing, focusing on safety and damage detection issues, such as critical impacts, deviations from the route, door openings, or lock damages. A significant portion of modern detection systems uses low-power edge computing solutions. One such solution is low-power accelerometers, which can process data locally and generate interrupts to data transmission subsystems when predefined thresholds are exceeded. These subsystems operate in sleep mode due to higher energy consumption, so they do not perform complex computations and rely on interrupts generated by sensors. Such algorithms are usually based on FSM (Finite State Machine) models. Limited rules and capabilities drive the need to develop algorithms based on logic and data analysis. The currently recorded events, such as impacts, are no exception. These are typically recorded when the sensor's value exceeds predefined g-force thresholds. This area provides significant flexibility and opportunities to refine event-based system algorithms. Additionally, there is potential to collect secondary information.

Imagine transforming the vast amounts of containers on the road into a road anomaly detection system. This would enable the creation of road condition maps based not on a single measurement but on collective events. Currently, road conditions are primarily assessed using specialized equipment in targeted evaluations. This approach produces accurate road models and assesses their condition, but it only addresses issues with specific roads and does not contribute to the broader monitoring of road conditions, which is essential for advancing green transportation initiatives.

However, this could change if modern IoT technologies and existing recorders, supplemented with new algorithms, enable data collection from these devices. This data would consist of events that exceed predefined thresholds on the road, allowing the identification of road issues such as potholes, uneven surfaces, inclines, and other irregularities. By combining this data with geolocation information, we can create a map of such anomalies. This map would not rely on isolated events but on recurring ones. For example, if a certain number of recurring events are detected at the same coordinates, it can be confirmed that an anomaly exists. By marking and classifying anomalies in this way, it becomes possible to create large-scale road maps. Based on the type of anomaly, road maintenance services can respond accordingly.

As a secondary use, this data would also benefit truck drivers and logistics companies. The latter could use this information to prevent transportation disruptions. It would work similarly to Waze or Google alerts. When integrated into appropriate GIS solutions, this information could warn container truck drivers about upcoming obstacles (such as road irregularities) on their route. Unlike Waze or Google, this information would not only rely on user input but also on data provided by recorders. This approach would be not only more accurate but also more reliable. For evaluating event classification, such as the size of a pothole or the potential risk of damaging vehicle wheels or suspension, artificial intelligence (AI) methods could also be employed. Here's how they could work:

The recorder's MCU can save accelerometer data stored in its buffer after an event and transmit it along with a notification to a data center. Subsequently, the data about the recurring event and the accelerometer readings can be sent to mathematical models (systems/algorithms) that can determine and evaluate the impact on the vehicle, the type of impact, and similar aspects (in the context of road irregularities). This contextual accelerometer information would thus serve as material for analyzing and processing specific events.

Integrating all of this would contribute globally to green transportation by reducing the number of incidents caused by road defects.

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