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In-Service Railway Infrastructure Monitoring: Multi-Sensor Instrumentation of a Norwegian Passenger Train

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Abstract

This paper presents a measurement system installed on a Norwegian Type 73 passenger train operating in regular traffic. The work is part of a nationally funded research project investigating the possibility of using trains in ordinary service to observe railway infrastructure condition. The instrumentation combines bogie-mounted accelerometers, pantograph force and acceleration sensors, strain gauges, internal inertial sensors, satellite positioning, and a cabin microphone. The paper describes the installation layout, coordinate convention, sensor roles, data acquisition architecture, and data handling workflow. Example measurements from 2025 show synchronised 30-minute time-series data from train speed, lateral and vertical bogie acceleration channels, and the microphone. The installation provides a research platform for developing methods, algorithms, and workflows for condition monitoring based on regular trains in traffic.

Keywords: railway condition monitoring, in-service monitoring, passenger trains, measurement instrumentation, track dynamics, pantograph and catenary interaction, data acquisition, predictive maintenance

1 Introduction

Safe and reliable railway operations depend on well-maintained track infrastructure. Track geometry parameters such as gauge, alignment, longitudinal level, cross-level, and twist deteriorate under repeated traffic loading and environmental exposure. If deviations are not detected and treated, they can lead to speed restrictions, operational disruption, increased vehicle-track forces, and, in severe cases, unsafe running conditions. A Bane NOR status report from 2022 stated that a significant share of the Norwegian railway network required renewal [1]. This motivates monitoring strategies that can detect degradation early enough to support condition-based and predictive maintenance.

Traditional railway infrastructure monitoring relies on dedicated inspection vehicles, such as track recording cars and measurement trains. These vehicles may be equipped with high-grade inertial, optical, and profile measurement systems and remain essential for regulatory inspection and reference-quality measurements. In Norway, the Roger 1000 measurement vehicle has been used to survey track geometry, rail profile, rail surface condition, and overhead line condition at operational speeds [2]. Dedicated vehicles provide high-quality measurements, but they also require special planning, trained crews, and track access. For many routes, this limits the frequency with which condition data can be collected.

In-service monitoring addresses this limitation by instrumenting trains that already operate in passenger or freight traffic. Each scheduled trip can then become a measurement opportunity. Network Rail and academic partners demonstrated the value of in-service measurement from the early 2000s onward, including systems using compact bogie-mounted sensors and unattended geometry measurement units [3–5]. Similar ideas have been explored in Germany through TrainLab, in Japan on Shinkansen vehicles, and in several research studies using inertial, acceleration, and vehicle-response measurements to infer track irregularities [6–8].

The main advantage of in-service monitoring is increased temporal and spatial coverage. A train running a daily timetable can observe the same route repeatedly, allowing degradation trends to be followed between dedicated inspection campaigns. This does not remove the need for reference measurement vehicles, because measurements made from regular rolling stock are affected by vehicle dynamics, suspension condition, operating speed, loading, and sensor placement. It does, however, create an opportunity to use frequent measurements as a screening layer that flags changes, prioritises maintenance planning, and guides the use of specialist inspection resources.

Several studies have shown that reduced sensor sets can provide useful information about track and vehicle condition. Weston et al. used gyroscopes and accelerometers on bogies to monitor track geometry and vehicle faults [4, 9]. Bocciolone et al. developed an accelerometer-based system for rapid rail inspection in urban railway maintenance [10]. Lee et al. compared axle-box and bogie accelerometers and proposed filtering approaches to estimate lateral and vertical track irregularities [11, 12]. Other work has considered low-cost inertial measurement units, position and trajectory estimation, and machine learning methods for estimating track irregularities from onboard response measurements [13–15]. Reviews of inertial sensor approaches emphasise the trade-off between sensor robustness, placement, bandwidth, and maintenance effort [16].

The research challenge is therefore not primarily to install sensors on a train, but to establish a measurement architecture that preserves enough information for later method development. A single acceleration channel can show repeated dynamic events, but it cannot by itself explain whether the event is caused by track geometry, rail surface condition, a switch or crossing, vehicle suspension behaviour, speed, loading, or environmental factors. A useful research installation must therefore combine response measurements with time, position, operating state, and reference data. It must also be robust enough for normal railway operation, because a system that requires frequent manual attention would not represent the practical conditions of regular traffic.

The objective of this paper is to present a multi-sensor measurement system installed on a Norwegian Type 73 passenger train in regular traffic. The paper focuses on the instrumentation, data acquisition architecture, and data handling workflow. The purpose of this architecture is to support future development of methods and algorithms for condition monitoring using measurements from regular trains in traffic.

2 Measurement System

The measurement system is installed on a Norwegian Type 73 electric multiple unit operating in regular passenger service. The train normally runs on the Oslo to Trondheim corridor, exposing the system to both urban and regional railway environments, different speed regimes, tunnels, bridges, open track, switches, and stations. The installation was carried out in 2022 at Mantena, Nyland, Oslo. Figure 1 shows a Type 73 train, and Figure 2 shows the instrumented bogie and pantograph locations.

2.1 Instrumentation overview

The system combines sensors mounted on the bogie, pantograph, passenger cabin, and onboard data collector units. Table 1 summarises the main instrumentation. The bogie-mounted accelerometers are intended to capture vehicle response to track irregularities and dynamic excitation. The pantograph sensors target pantograph-catenary interaction. Strain gauges add structural response measurements from the bogie frame, while inertial and positioning sensors support localisation and repeated pass comparison. The microphone provides an additional acoustic channel that can be correlated with physical measurements.

The sensors were distributed so that the installation could support several research questions from the same train. The bogie instrumentation is closest to the wheel-rail interface and is therefore expected to contain information about vertical and lateral

Figure 1: Norwegian Type 73 passenger train used as an in-service monitoring platform.

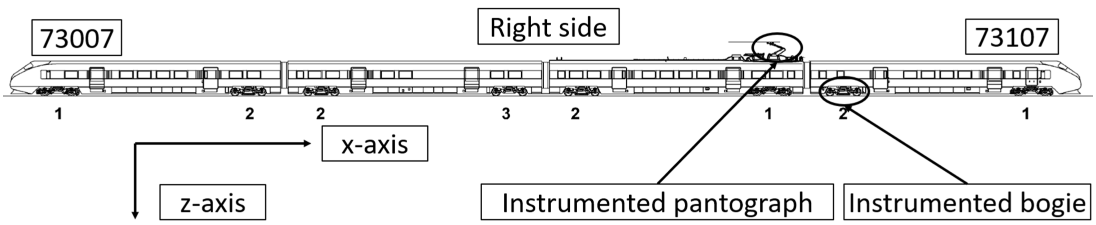

Figure 2: Overview of the instrumented pantograph and bogie locations on the Type 73 train.

excitation from the track. The pantograph instrumentation is physically separated from the bogie sensors and is intended for overhead-line studies. The internal inertial sensors and satellite positioning receivers do not replace the high-rate dynamic measurements, but they provide contextual streams that help identify train movement, stops, speed changes, and approximate location. The microphone was added as an exploratory channel because acoustic events in the passenger cabin may coincide with mechanical events, even though the acoustic data require additional privacy handling.

Instrumentation type	Quantity
Dual-axis bogie accelerometers	10 units
Pantograph acceleration sensors	4 units
Pantograph force sensors	4 units
Bogie strain gauges	6 units
Internal inertial measurement units in data collectors	3 units
Global navigation satellite receivers	2 units
Cabin microphone	1 unit

Table 1: Main instrumentation installed on the Type 73 train.

2.2 Coordinate convention

The installation follows a common project coordinate convention. The longitudinal axis is aligned with the track and train running direction, the lateral axis is transverse to the vehicle, and the vertical axis follows the installed sensor convention shown in the layout drawings. Sensor orientation is corrected in software so that the exported channels follow a consistent body-frame convention. Consistent axis definitions are essential because the data set combines direct physical measurements, internal inertial measurements, and position data from different onboard units.

The coordinate convention is particularly important for the dual-axis bogie accelerometers. Some sensors measure an axis pair that is not directly aligned with the final exported lateral and vertical directions, and some are mounted through brackets to obtain the required orientation. The processing workflow therefore treats the physical mounting location and the exported channel direction separately. This is why the channel names include both a sensor position and a direction suffix, for example `z` for the vertical component and `y` for the lateral component.

2.3 Bogie instrumentation

Ten dual-axis accelerometers are installed on the selected bogie. They are mounted on both sides of the bogie frame and close to the axle-box regions, as shown in Figures 3 and 4. The accelerometers measure lateral and vertical response components and are intended to capture vibration signatures associated with track irregularities, wheel-rail interaction, and vehicle dynamic response.

The instrumented bogie is the second bogie counted from one end of the train set, and is a trailer bogie without propulsion. This location was chosen within the practical constraints of installation access, cable routing, available space, and rolling-stock maintenance requirements. From a research perspective, a bogie-mounted installation is a compromise. It is closer to the excitation source than a car-body installation and can retain higher-frequency content, but it is also more exposed to vibration, water, temperature variation, ballast impact, and maintenance operations. These constraints are representative of the challenges that must be solved before regular train monitoring can be used routinely.

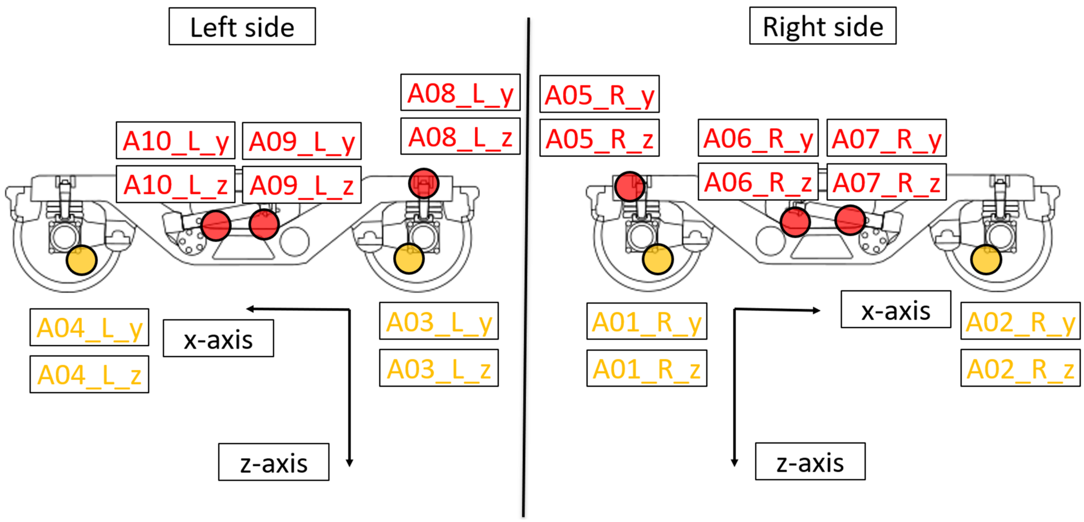

Figure 3: Side-view layout of bogie accelerometer locations and channel labels.

Because the dual-axis accelerometers do not all align directly with the required measurement axes, some sensors are mounted using right-angle brackets. Figures 5a and 5b show examples of direct and bracketed installations. After axis decomposition, the bogie instrumentation provides twenty acceleration channels named according to sensor position, train side, and response direction. Examples include `A08_L_z`, `A08_L_y`, `A05_R_z`, and `A05_R_y`. The channel naming is useful because it preserves both physical sensor location and transformed response direction in later data processing.

Six strain gauges are installed on the bogie frame and measured through a strain-gauge amplifier. These channels provide local structural response information that can be compared with acceleration-based indicators in later studies.

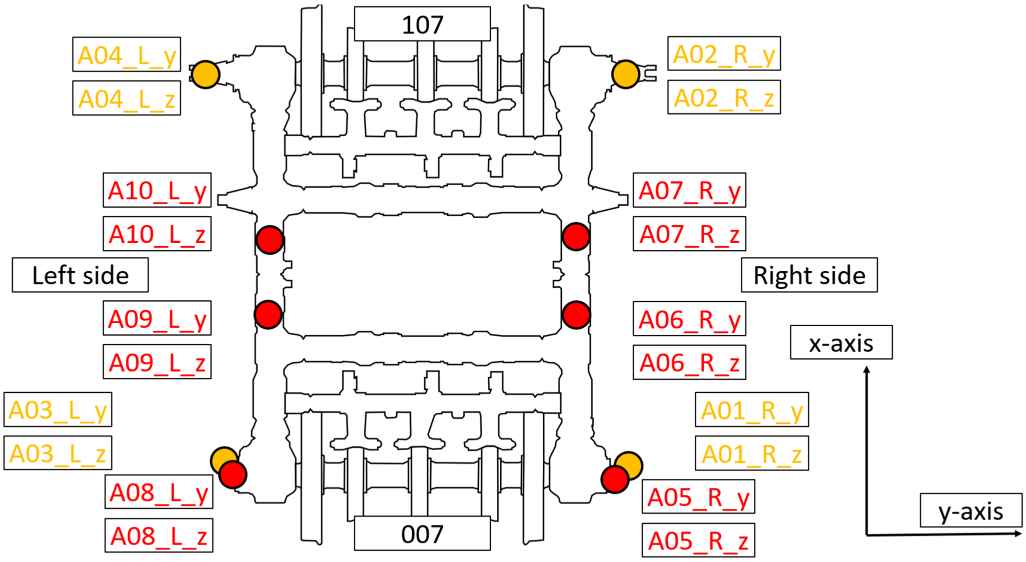

Figure 4: Plan-view layout of bogie accelerometer locations and channel labels.

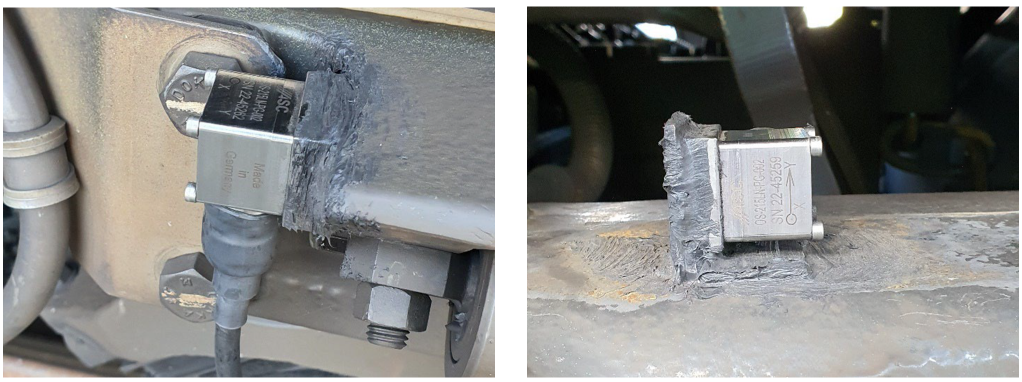

Figure 5: Examples of bogie accelerometer installation: (a) direct mounting and (b) bracketed mounting for axis alignment.

2.4 Pantograph instrumentation

The pantograph installation includes four force sensors and four acceleration sensors located near the pantograph head, as illustrated in Figure 6. These measurements are intended to support studies of pantograph-catenary interaction, including dynamic response caused by contact-wire irregularity, contact force variation, and operating conditions. Their inclusion also makes it possible to study whether track-related events and pantograph-related events can be separated in later multi-sensor analysis.

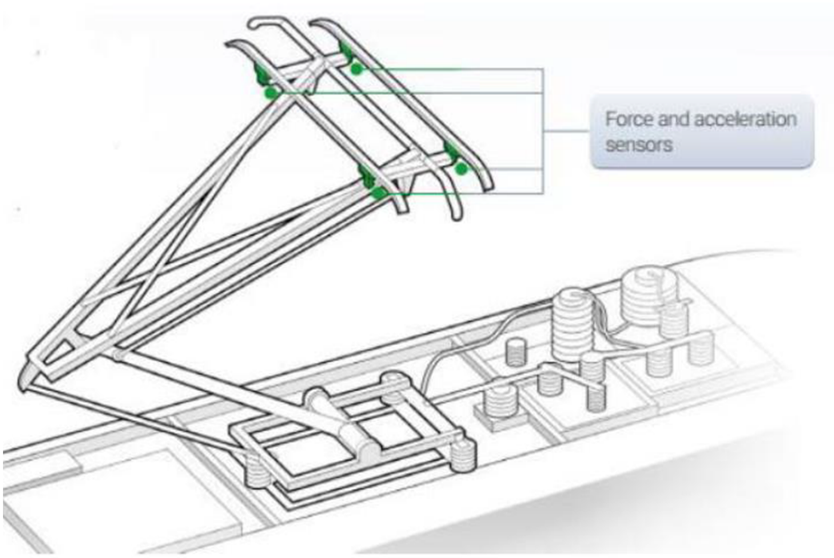

Figure 6: Pantograph force and acceleration sensor locations.

2.5 Data acquisition

The bogie accelerometer and microphone channels are connected to a data acquisition system. In the example data used in this paper, these high-rate dynamic channels are sampled at approximately 1.42 kHz. The strain gauges are conditioned through a strain-gauge amplifier. The pantograph force and acceleration channels are recorded through a separate measurement unit and have been used at 100–200 Hz in project measurements. Three data collectors are installed onboard. Each data collector includes an internal six-degree-of-freedom inertial measurement unit with a nominal 1 kHz measurement stream, and two of the collectors include satellite positioning receivers that provide lower-rate speed and position information, typically at approximately 5 Hz. The data collectors store records while the train is powered.

The data architecture can be viewed in three layers. The first layer is the sensor and signal-conditioning layer, where accelerations, forces, strains, microphone pressure, internal inertial measurements, and speed or position records are acquired. The second layer is the onboard collection layer, where data streams are buffered and time stamped. The third layer is the remote storage and analysis layer, where data from different trips can be organised, filtered, aligned, and compared. This layered architecture is important because the train operates without a researcher onboard, and because the data are generated under normal passenger-service constraints rather than in a controlled laboratory experiment.

The different data streams have complementary research roles. Bogie accelerations are used for vehicle-track dynamic response in lateral and vertical directions. Bogie strain adds local structural response. Pantograph force and acceleration support studies of pantograph-catenary interaction. Internal inertial measurements and speed records provide movement and operating context. The microphone is an exploratory acoustic channel that can be correlated with mechanical events after privacy-preserving processing.

A microphone is installed inside the passenger cabin. The microphone provides an acoustic channel that can be correlated with accelerations, strain, pantograph response, speed, and location. Figure 7 shows the cabin microphone installation. The long-term motivation is to investigate whether acoustic signatures can support low-cost condition screening or explain events detected in the physical response measurements.

Figure 7: Cabin microphone installation: (a) close-up and (b) location in the passenger cabin.

3 Primary Data and Preliminary Checks

The installed system produces complementary primary data streams. High-rate dynamic channels are stored in data acquisition files suitable for bogie vibration and microphone analysis. The data collector streams provide time-stamped inertial and speed records. Example data from 2025 include acceleration, microphone pressure, and train speed. These records give the basis for relating dynamic events to train operating state and for comparing repeated passes over the same route.

An example section from 2025 was selected to illustrate the primary data. The section covers 30 min of ordinary operation using three consecutive high-rate data acquisition files. Figure 8 shows train speed together with direct time-series samples from one vertical bogie acceleration channel, `A08_L_z`, one lateral bogie acceleration channel, `A08_L_y`, and the cabin microphone. The high-rate data were down-sampled only for plotting clarity, while the channels shown are direct time-series measurements. All four panels use the same time axis, so the figure illustrates that speed, acceleration, and acoustic measurements can be brought together as a coordinated time-series data set.

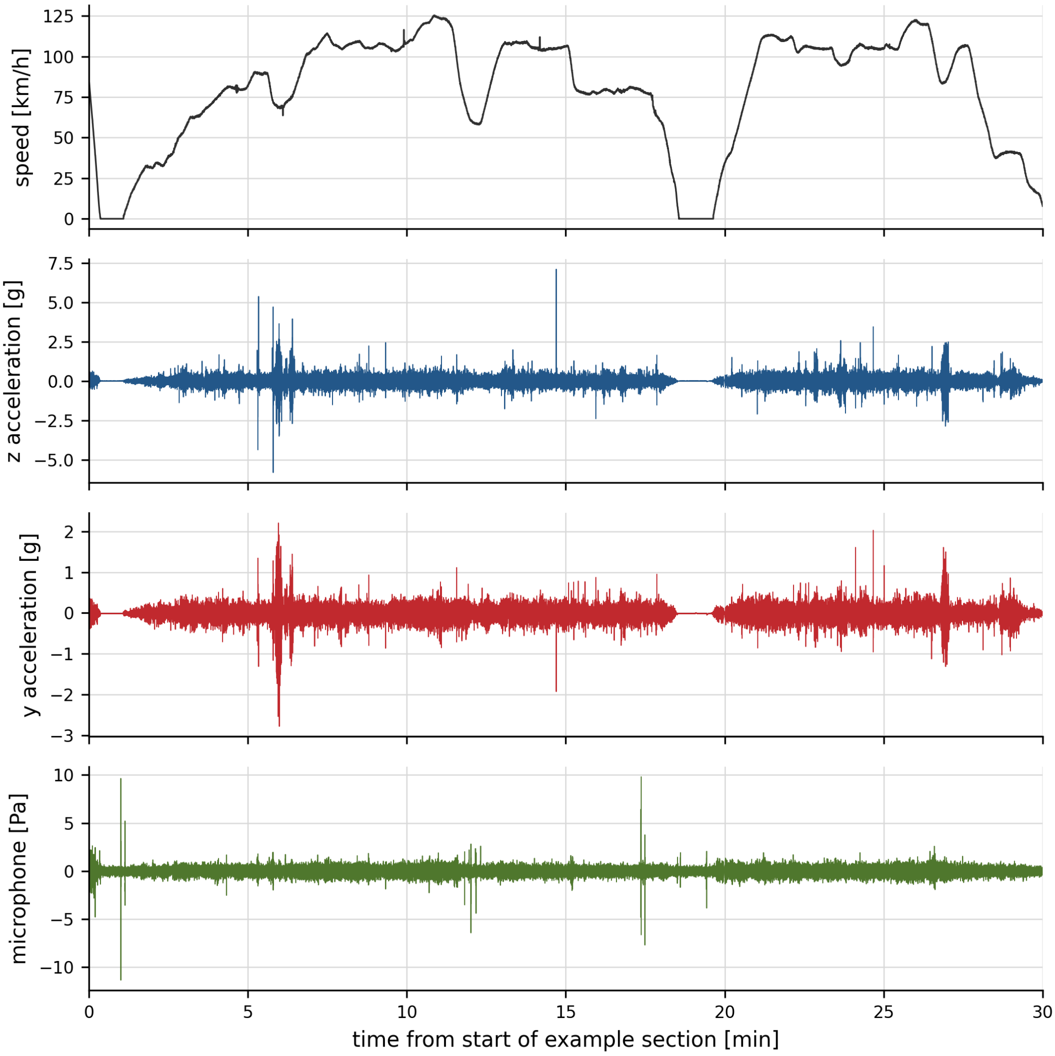

Figure 8: Example synchronised 30-minute time-series data from 2025. The panels show train speed, direct samples from the vertical bogie acceleration channel `A08_L_z`, direct samples from the lateral bogie acceleration channel `A08_L_y`, and the cabin microphone.

The acceleration and microphone traces are not interpreted here as infrastructure defects. They are examples of measurement events that can later be investigated using repeated passes, track geometry reference data, operating state, and other contextual information. For later condition-monitoring studies, these direct time-series measurements can be processed into indicators that are appropriate for the specific infrastructure component or degradation mechanism being studied.

The example also illustrates why primary data checks are needed before condition-monitoring analysis. A time-series segment may contain running periods, low-speed periods, stops, gaps between files, and different excitation levels. Peaks in the acceleration or acoustic channels must therefore be evaluated together with operating state and location. In later work, the same raw section can be reprocessed into frequency-band features, event indicators, route-referenced signatures, or repeated-pass statistics depending on the infrastructure question being studied.

4 Discussion

Multi-sensor architecture. The Type 73 installation provides a practical architecture for researching infrastructure monitoring with trains in regular traffic. The combination of bogie accelerometers, pantograph sensors, strain gauges, inertial sensors, speed records, satellite positioning, and microphone measurements gives a richer picture than a single-sensor monitoring approach. This breadth is important because infrastructure condition is not observed directly from a regular train. It must be inferred through the coupled response of track, vehicle, pantograph, and operating environment.

Synchronisation between data streams. A central challenge has been synchronisation between independent data collectors, positioning receivers, and high-rate acceleration acquisition. These systems do not naturally share a single time base. In the project workflow, this has been addressed by aligning streams using timestamps, train speed, and positioning information before the data are interpreted together. Figure 8 illustrates this workflow by placing speed, bogie acceleration, and microphone measurements on a common time axis. Further work will use repeated passes and reference data to quantify the remaining synchronisation and positioning uncertainty.

Bogie instrumentation and maintenance. The bogie accelerometers are expected to be useful for studying repeated dynamic signatures associated with local track irregularities, switches, crossings, joints, rail surface defects, and vehicle-track interaction changes. However, the installation on a train in regular traffic also creates practical maintenance challenges. Sensors and cables mounted on or near the bogie are exposed to vibration, water, temperature variation, and normal rolling-stock maintenance activities. When the bogie is sent for maintenance, parts of the instrumentation may have to be removed and mounted again afterwards. This makes sensor documentation, reinstallation control, and post-maintenance data checks important parts of the measurement workflow.

Microphone data and privacy. The microphone gives a complementary acoustic channel, but acoustic measurements in a passenger train require careful handling. Because the sensor is installed in a passenger environment, privacy requirements under the General Data Protection Regulation (GDPR) must be considered. The research workflow must therefore anonymise or otherwise process the sound data so that passenger conversations or other personal information are not identifiable. In this project, the microphone is considered as a potential source of acoustic condition indicators, not as a source of passenger information.

Data volume and idle periods. The amount of data is another practical challenge. The train can generate data both when it is running and when it is powered while standing still or stored in idle mode. If all such data are transferred directly, the remote storage and analysis pipeline are filled with large amounts of data that are not useful for infrastructure monitoring. The data handling workflow therefore needs filtering routines that separate running data from idle or non-informative periods, using information such as speed, position change, and operating state.

Ground truth and reference data. Ground truth is essential. Measurements from a regular train can show repeatable response patterns, but those patterns cannot automatically be interpreted as specific track or overhead-line conditions. The project therefore relies on collaboration with measurement-train operators and infrastructure owners to compare the onboard measurements with track geometry and other reference measurements. Open source InSAR and other geospatial information may also provide useful context for studying infrastructure condition. These reference data sources are needed to develop and validate algorithms that can turn the instrumentation data into meaningful condition indicators.

Repeatability versus interpretation. If an event appears at approximately the same route position on several passages, this suggests that the event is connected to the infrastructure or to a recurring operating condition. It does not by itself identify the physical cause. The analysis workflow must therefore combine repeated-pass statistics, train speed, route location, maintenance records, reference measurements, and engineering judgement. This is one reason why the present paper focuses on the measurement system and primary data architecture rather than presenting a final condition classification.

5 Conclusions

This paper has presented a multi-sensor measurement system installed on a Norwegian Type 73 passenger train operating in regular service. The system includes bogie accelerometers, bogie strain gauges, pantograph force and acceleration sensors, onboard inertial and satellite positioning sensors, and a cabin microphone. The installation was developed for research into the possibility of using regular trains in traffic to observe railway infrastructure condition.

Example primary data from 2025 show how train speed, bogie acceleration, and acoustic measurements can be organised on a common time axis. The example illustrates how the instrumentation and data acquisition architecture can support coordinated multi-sensor analysis during ordinary train operation, provided that data stream synchronisation, privacy handling, maintenance of bogie-mounted instrumentation, and filtering of idle data are properly managed within the research workflow.

With the sensor architecture established, the focus shifts to applying the onboard multi-sensor data to the actual railway being monitored. The recorded data will be correlated to known features and components, identifying baseline dynamic signatures, and validated against ground-truth data collected by measurement trains and manual reference measurements. The long-term aim is to use this instrumentation to develop and validate methods for monitoring railway infrastructure degradation using trains in regular traffic.

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