Railway Track and Vehicle Onboard Monitoring: A Review

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Abstract. Railway condition monitoring is the compound of activities aimed at the detection and mitigation of faults in both tracks and vehicles. This minimizes damage and disruption, and increases the usability and benefits of railways. Trackside monitoring provides frequent data, but is costly and ineffective for large segments of track. Onboard monitoring using dedicated vehicles provides deep knowledge of the track, but is infrequent and requires allocated resources and track availability. The use of sensors onboard passenger trains overcomes these issues by acquiring signals more frequently and with relatively inexpensive devices, hence the increasing use of these devices. This review presents the current techniques applied for track and train condition monitoring techniques using onboard sensors, as well as the use of trackside sensors.

Keywords: Railways, Condition monitoring, Track, Train.

1 Introduction

Condition monitoring is a major component of predictive maintenance, aimed at developing and scheduling actions to be taken to prevent, identify and mitigate faults and failures on monitored systems. This compound of activities saves money, prevents delays and, ultimately, increases the life cycle of the monitored assets. Track and trains have specific operation conditions and onboard or trackside monitoring activities have different advantages in the quality of the condition monitoring systems outcome.

A distinction between monitoring and inspection is necessary prior to the review. In this regard, monitoring is considered as the set of actions aimed at observing railway assets for a period of time to observe their evolution and possible degradation, whilst inspection is a deep examination of the assets to evaluate their condition in a moment of time.

The main contribution of this paper is the review on the sensors and techniques applied for railways condition monitoring, separated into trackside and onboard monitoring. Onboard monitoring is separated as well into track condition monitoring and vehicle component.

The rest of the paper is organized as follows: Section 2 presents the current trends on trackside monitoring; Section 3 presents the state of the art on onboard railways monitoring, separated into track monitoring and inspection, and vehicle components; Section 4 discusses the findings; Section 5 summarizes the research carried out in this publication.

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2 Trackside Monitoring

Trackside monitoring is the set of monitoring activities carried out from the track aimed at monitoring the track, vehicles passing by or the interactions between them [1].

Track monitoring includes observing, track layers and their associated geometry, and their evolution over time. Trackside component inspection techniques depend on the component inspected: ultrasounds, magnetic field based and visual inspection are the most common for rail inspection [2]; sleepers are monitored using visual inspection, inertial sensors and geophones [1, 3]; ballast is inspected using particle analysis and studying its dynamic behaviour [4, 5]; the subgrade is inspected via ground penetrating radar [6, 7]. Other components, such as point machines and switches and crosses, are monitored using voltage and current signals [8, 9] or with inertial sensors [10], or ACFM sensors [11]. Signals are analysed using either mathematical or physical models [12], frequency analysis [13] or Artificial intelligence (AI) [14–16]. In summary, sensors such as visual, inertial, ultrasonic and magnetic are the most common for the upper layers, whilst ground penetrating radar and particle analysis is applied for the layers beneath sleepers. figure 1 shows the use of displacement sensors to measure deflection of the track.

Trackside vehicle monitoring and inspection equipment is mostly applied to the wheelset, usually wheels and bearings [18]. Common wheel defects are wheel-flats, fatigue, out of roundness and cracks [19, 20]; whereas common inspection techniques and sensors are thermal imaging, strain gauges, ultrasonic, inertial and visual sensors. Regarding bearings, thermography, acoustic and inertial sensors are most commonly used [18, 21]. Frequency and signal analysis are frequently applied for both components [22, 23]. Common sensors used for wheel inspection, are inertial and eddy current sensors [24], and optic sensors [25, 26].

In conclusion, trackside monitoring focuses on long-term track state measurement as well as vehicle wheelset inspection. Fibre optic sensors, accelerometers, magnetic and acoustic sensors are the most used ones as their technologies are well developed, providing valuable information.

![Figure 1. Displacement sensors installed to measure track deflection on the passage of a vehicle [17]](image-url)
3 Onboard Monitoring and Inspection

3.1 Track Monitoring and Inspection

Track inspection and monitoring are usually carried out by in-service vehicles or dedicated measurement fleets. Equipment used on dedicated vehicles is more advanced and allows more in-depth inspections, which is key for safety of the railways. However, these vehicles require dedicated scheduling and workers, which limit their use [27]. Current inspection vehicles are divided into self-propelled vehicles, towed coaches and hi-rail vehicles [28–30], shown in figure 2. These measurement units use technologies such as laser, image processing, ground penetrating radar, ultrasounds and electromagnetic sensors [28].

![Figure 2. Self-propelled vehicle (left), towed coach (centre) and hi-rail vehicle (right) [30].](image)

Because of technology advances, sensors can be small enough to be easily installed on in-service vehicles, so the measurements will be more frequent. Research on the use of in-service vehicles is oriented at both short- and long-term maintenance. Short term focuses on track inspection and fault detection, as well as maintenance and repair planning, whilst long-term monitoring focuses on detecting and preventing track degradation and faults developing over longer periods of time. Authors agree that the most used sensors for track monitoring are inertial (accelerometers and gyroscopes), optical (cameras and laser), acoustic (generally ultrasonic) and magnetic (eddy current sensors) [2, 31–33]. The following paragraphs discuss the most used sensors for track monitoring, as well as sensor fusion.

Inertial sensors, accelerometers and gyroscopes, measure acceleration or rotation rate, respectively, in the direction desired. Their use in railway track inspection is relatively recent [2, 32]. These sensors may be installed in the axlebox [34], bogie [35, 36] or cab [37], allowing a wide range of applications when their signals are processed; mainly track monitoring, fault detection and geometry extraction [38]. Track monitoring can be assessed through indices to evaluate its general state [39, 40] or by evaluating the received signal [41–44]. Track fault detection revolves around evaluating data to observe changes associated with faults and, if possible, identify them [45, 46] or detect changes before and after maintenance operations [47, 48]. Track geometry is extracted from measurements, generally evaluating its changes over time to observe track evolution and degradation [49, 50]. Inertial sensors are broadly used and merged with other sensors such as Global Navigation Satellite Systems (GNSS). Visual, acoustic and magnetic sensors are also used, but not as common [31, 51].

Optical sensors, among which LIDAR, laser and cameras are included, are mostly centred on obstacle detection and rail, sleeper and fastener inspection [52]. Faults observed are cracks [53], corrugation [54] or squats [55], and other rail conditions [56]. Image processing tools and machine learning are applied to evaluate tracks more effectively [52, 57]. Acoustic sensors are mostly used to detect wheelset faults, either wheels [58] or bearings [59, 60]. Magnetic sensors, mostly eddy current, focus on rail fault detection, identifying faults such
as contact fatigue [61] and cracks [62]. Since rails and fasteners are the only components possible to be monitored by these sensors, this NDT is very limited compared to others. Ground penetrating radar (GPR) is applied for evaluating the ballast and subgrade, identifying fouling and other faults related to these track layers [63, 64]. This NDT requires dedicated vehicles, and due to its sensitivity it must be carried out at low speeds.

In summary, onboard track monitoring and inspection is generally carried out using in-service vehicles, as their higher frequency allows to evaluate the evolution of the track. Amongst the most common used sensors, inertial sensors are identified as the most advantageous, due to their robustness and versatility.

3.2 Onboard Vehicle Component Monitoring

Railway vehicles are complex systems with a wide variety of components with different characteristics and requirements depending on the harshness of the environment. The different sensors and techniques applied for condition monitoring are discussed in this section.

Vibration sensors can help to identify any harmonics or unspecified resonances that indicate faults or changes in behaviour of certain components. Sensors applied for wheelset monitoring are commonly installed on the axlebox [59, 60, 65], and dedicated to bearing and wheel fault detection and monitoring. Their behaviour is generally analysed using frequency and statistical analyses tools, such as harmonic detection, cepstrum analysis and kurtosis analysis [59]. Common tasks for vibration sensors are fault detection, mostly related to the dampers [66].

Visual sensors applied for component monitoring are mostly cameras, laser sensors, and LIDAR. These are usually for inspecting wheelsets and detecting wheel faults. However, the lenses are likely to become useless due to dust and harsh conditions and require frequent cleaning and maintenance [67, 68]. Instead, their use is more extended for track component inspection, such as rails, ballast or fasteners, and for location and obstacle detection [64].

The use of thermal sensors is only to identify critical conditions, as they can only detect faults once in an advanced state [58] and provide information only of the presence or absence of a fault. Nevertheless, their applications are mostly centred on axlebox bearings [18, 69], and brake blocks [70], where temperature increases indicate faults, generally related to poor lubrication, friction or component breakage. Sensors measuring electric current or voltage are mostly applied for the power drive or traction-related components, as the signal output provides information on the related components [71]. Figure 3 shows an example of the use of vibration and acoustic sensors installed on a wheelset.

In short, most commonly used sensors and techniques for wheelset monitoring are magnetic, acoustic, thermal, visual and inertial; for the suspension, inertial and dynamic models; and for the cab, modelling. Onboard component monitoring is applied by instrumenting vehicles and evaluating their condition over time. Inertial sensors are the most versatile, as they can be used for many components. Other sensors, such as visual, acoustic or thermal, are applied only to certain components and conditions, thus limiting their usefulness. Due to the dynamic behaviour of the system, considering resonance frequencies may be useful to associate faults to certain components.

4 Analysis of Findings

This section presents a quantitative analysis of the articles presented, classifying them depending on the location of the sensors (trackside or onboard), the asset monitored (track, vehicle or both), the sensors used for acquiring data, the analysis technique applied, and the
fault or issue considered for monitoring. Most of the references here presented are journal papers, and the evolution of publications over time is presented in figure 4.

![Figure 3. Vibration and acoustic sensors installed on a wheelset [65].](image)

The amount of publications in the following years is expected to increase, as the use of railways keeps extending and the need for monitoring is increasing. Regarding the proportion of publications, figure 5 shows the distribution of articles based on the position of the sensors and the asset monitored (track, vehicle or both assets).

Most of research (62%) is carried out using data from the vehicle, either to monitor the track or the vehicle itself. As aforementioned, installing sensors on the track is ineffective for large sections of track, and vehicle inspection using trackside sensors can only be applied to the wheelsets. These two reasons explain the prevalence of onboard sensors, as their use in vehicles allows for the inspection and monitoring of longer track sections and vehicle.
components. Regarding the monitored asset, publications are centred on monitoring the track (64% of publications). This is because railway tracks require constant monitoring to assess their condition, and because most of faults and issues in railway industry occur in the track. This is also reflected in the issues considered, shown in figure 6.

Figure 5. Distribution of publications depending on the position and asset monitored.

Figure 6. Distribution of publications depending on the fault or issue studied.

Most of the issues considered for study are related to the track (geometry, condition and corrugation), whilst issues related to the vehicle are mostly vehicle location and passenger comfort. Faults and issues applicable to both are anomalous condition or behaviour, or deformation. Track geometry and condition is studied to evaluate the deviation from the design
and from the safety levels indicated in the standards and the models presented. Prevention and detection of track corrugation and rail cracks is extended, as these faults are common and severely affect the vehicles. Comfort is assessed based on standards and is more limiting than safety in passenger tracks. The sensors and signals applied for railways monitoring are presented in figure 7, whilst signal analysis and processing techniques are presented in figure 8.

![Figure 7. Distribution of publications separated by the type of sensor applied.](image)

Inertial sensors are the most used (30% of publications), followed by visual (16%) and acoustic (15%). This is due to the robustness and versatility of inertial sensors, as well as the relatively low amount of data to be used for analysis, compared to visual and other sensors. The variety of components and systems involved in railways explains the different sensors used, such as acoustic and magnetic for the track and bearings, Ground Penetrating Radar (GPR) for the track subgrade, and electrical signals (power or voltage) to assess faults in the point machines or vehicle power systems. These signals condition the analysis techniques to be applied; frequency analysis is the most common signal analysis technique (37% of publications), as it is applied for vibration, acoustic and GPR signals, amongst others. Physical and mathematical models are extended (31% of publications), as these models generally provide guidelines and thresholds for the condition of the vehicle and track.

5 Conclusions

In this work a review of the most common applications of sensors for railway condition monitoring; track inspection and vehicle inspection have been presented. Research trends and main gaps are discussed in this section.

Trackside monitoring techniques are usually applied for vehicle component inspection, mainly wheelsets. The proximity of the components to the tracks and their characteristics allow for quick inspections capable of evaluating their state and detecting faults. However, due to the train speed and availability of a short window for measurements, deep inspections are not feasible, so detected faults are mostly in an advanced state, sometimes forcing the vehicles to stop immediately and causing disruption. Thus, earlier fault detection will lead
to more efficient maintenance and reduced unexpected delays. Regarding track inspection, most activities focus on track parameter characterisation.

Onboard monitoring allows for both track and vehicle monitoring. Large sections of track can be monitored and analysed. Generally, only the upper track layers and components are inspected, as lower layers require dedicated measurement vehicles. Onboard vehicle component monitoring allows deeper inspection, as sensors of any kind can usually be located on the desired component and collect enough data to analyse with confidence. Amongst these, vibration and acoustic sensors are most common, as moving parts generate vibrations that can be analysed to identify their state of performance.

Regarding sensors used, inertial sensors have been proven to be the most extended. These sensors are used for all the applications mentioned in this review, due to their robustness, versatility and relative low volume of data generated, as compared to sensors such as visual, acoustic or thermal. Signals provided by the sensors are mostly analysed using mathematical or physical models, and frequency analysis. The use of Artificial Intelligence is not extended but is expected to increase in the following years.

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References


