Indirect Analysis of Railway Infrastructure Anomalies Using Passenger Comfort Criteria

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Abstract. Railways are one of the most efficient and widely used public transport systems for medium distances. To improve the attractiveness of this type of transport, it is necessary to improve comfort, which is greatly affected by vibrations caused by the train motion and wheel-track interaction, making railway track infrastructure condition and maintenance a main concern. Based on the passenger's discomfort level, a new methodology capable of detecting railway track infrastructure maintenance requirements is proposed. While performing regular passenger service, acceleration and GPS measurements were performed on Alfa Pendular and Intercity trains between Porto (Campanhã) and Lisbon (Oriente) stations. Following ISO 2631 methodology, instantaneous floor discomfort levels were calculated. Matching the results for both trains, twelve track section locations were identified as requiring preventive maintenance actions. The developed methodology was validated by comparing these results with those obtained by the EM 120 track inspection vehicle for which similar locations were found. The developed system can identify critical maintenance sections but does not distinguish the type of defect.

Keywords: ISO 2631, passenger comfort, preventive maintenance, railways, vibration.

1 Introduction

Railways are among the most widely used public transportation systems, mainly because of their high transportation capacity, reduced boarding time, and low environmental impact. Furthermore, due to climate changes, governments are promoting their use as the reference mass transportation system, leading to a 10% increase in train passengers in Europe in the last decade [1].

Increasing train attractiveness and journey comfort is crucial to maintain this rising trend. Considering a railway journey, passengers prioritise safety, comfort, and user conditions [2]. High safety levels are achieved through proper maintenance actions based on corrective or preventive strategies, aiming to recover normal working conditions, anticipate problems and minimise potential faults [3,4].

Preventive maintenance aims to preserve railway functions and prevent system to fail, while condition-based maintenance (CBM) is a standard railway track infrastructure condition monitoring system. Both methods can be performed manually or automatically, depending on the type and extension of work required. The human inspection involves well-trained inspectors walking along railway track infrastructure to detect defects. As it involves stopping or restricting the traffic, this traduces an expensive and potentially hazardous maintenance technique [3]. Following technological advances, automatic inspection methods, like inspection vehicles, have been developed to detect and evaluate infrastructure performance. Usually, these vehicles use optical and inertial sensors linked to a GPS, increasing efficiency and reducing the time required [4,5]. However, as with human inspection, these vehicles can introduce traffic disruptions, affecting regular service operations. Different inspection vehicles are used worldwide. In Portugal, the EM 120 inspection vehicle, identifies maintenance needs and railway track infrastructure failures. Recently, freight vehicles were also used as instrumented inspection vehicles, particularly in the axle box, but their experimental setup implementation needs to be revised, limiting their use [6].

As passenger trains continuously run over the network tracks, the ideal solution would be to use instrumentation on these trains that can provide a basic level of inspection, thus providing information on a regular base, at a reduced cost and without disrupt the normal train schedule. It is known that there is a significant difference in the vibration level and spectrum when comparing a healthy with a defective railway track infrastructure. Thus, besides affecting safety, isolated and continuous infrastructure defects lead to poor passenger comfort due to increased vibration levels [4]. In fact, vibration caused by train motion and tracks irregularities, significantly affect passenger comfort, transmitting whole-body vibration (WBV) through contact surfaces, causing discomfort and fatigue. For this purpose, ISO 2631 standard can be used to accurately quantify WBV comfort, human health, and motion sickness [7].

Based on the close connection between railway track infrastructure condition-induced vibration, and passengers' discomfort levels, it was possible to develop the proof of concept of a new CBM methodology to identify critical railway track infrastructure locations, providing a low-cost solution with increased infrastructure availability, overcoming the limitations of the traditional methods. This work aims to contribute to the existing literature by developing a methodology capable of detecting rail track infrastructure abnormalities or damages based on measurements on in-service trains, ensuring regular operation without disruption or interference. Therefore, it defined the need for maintenance actions when multiple in-service trains with different dynamic characteristics presented floor discomfort at the same GPS location. The methodology's accuracy and precision are not dependent on the vehicle type, making it applicable to passenger trains with different characteristics.

2 Ballasted track

The ballasted is the most common railway infrastructure system used worldwide. This ballasted system has lower construction costs and adequate resistance to static and dynamic forces. It is assembled into superstructure and substructure, with the former consisting of rails, sleepers, ballasts, and components. At the same time, the latter is associated with the geotechnical system, including sub-ballast, embankments, and subgrade layers, Fig. 1 [8].

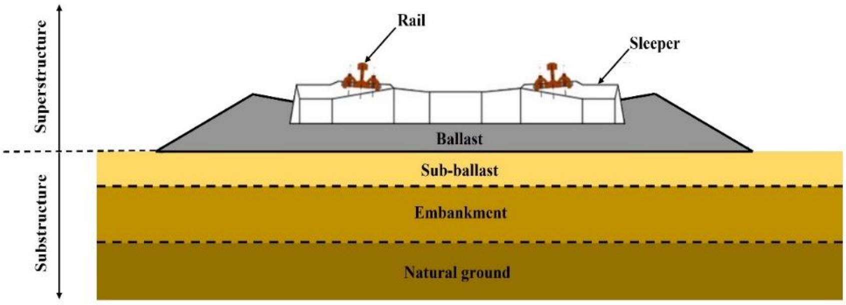

Figure 1. Schematic illustration of the railway ballasted infrastructure.

Track integrity problems are influenced by superstructure and substructure deformation, affecting structural performance [8]. Substructure issues, such as sub-ballast and subgrade deterioration, can induce poor drainage and track settlements, reducing the track stability, capacity, and safety, leading to misalignments and increased wear. Superstructure track faults can be grouped into geometry-related conditions (cross-level, alignment, longitudinal levelling, twist and gauge), rail surface faults (surface, corrugation, fatigue cracking, squat and creep), and ballast conditions (fouled ballast, ballast pockets and poor ballast drainage) [9]. Track defects and irregularities negatively affect track performance and safety, with wavelengths between 10-120 m mainly affecting passenger comfort.

Rail defects and increased speed amplify dynamic interaction forces between vehicles and tracks. Low-frequency forces are exerted when the track does not present defects or abnormalities, but faults increase frequency, leading to dynamic impact forces. Dynamic loads, connected to track irregularities, amplify rail deterioration rates. Vehicle vibration magnitudes are strongly linked with track irregularities; thus, they can be used to assess the general track condition, as acceleration analysis can identify defects based on peak values [8,10].

3 Train suspension system

The interaction between the wheels and railway track infrastructure, healthy or with defects, generates vibration with varying amplitude and frequency. This vibration can cause damage to both, trains and railway track infrastructure; thus, it must be controlled. The train suspension system, constituted by a primary and a secondary suspension, fulfils this function by enabling the filtering of the vibrations derived from the vehicle-track dynamic interaction, thus promoting ride comfort and controlling the kinematic modes of the bogie (therefore promoting stability) [11].

Although with the same goal, different trains present different suspension systems, which interfere with the filtered ranges of frequencies. The present research conducted tests on Alfa Pendular (AP) and Intercity (IC) trains with different suspension systems (tilting mechanisms for the first and model series for the latter). Therefore, characterising those trains' suspension systems is essential.

The AP train has an active tilting system capable of reducing the lateral acceleration perceived by the passengers and, consequently, allows the performance of curves at higher speeds than the balanced one while maintaining high passengers comfort levels. The AP primary suspension is composed of helicoidal springs (sets of two plus two) and a vertical damper. In contrast, the secondary suspension comprises flexi-coil springs (grouped within units of three) and vertical, transversal and anti-yaw hydraulic dampers [12].

On the other hand, the IC train suspension system comprises helicoidal springs and vertical dampers as primary suspension and helicoidal springs, vertical and transversal dampers acting as secondary suspension [13].

4 Indirect Method for Infrastructure Condition Assessment Based on Comfort Criteria

Railway track infrastructure maintenance interventions are often based on inspection vehicle measurements rather than dynamic responses of in-service railway vehicles. As aforementioned, passenger comfort is affected by vibrations derived from its motion and railway track irregularities that can be assessed through acceleration measurements. Thus, there is a strong link between railway track irregularities and passenger comfort level, which is the base of the present method. Based on the natural excitation created by the passage of railway vehicles over the track and the fact that a defective railway track system induces higher vibration, it is expected that high discomfort levels will be proficient when in the presence of an abnormality on the railway track infrastructure. In this way, it was hypothesised that a critical section of the railway track infrastructure is identified if several trains with different suspension systems reported instantaneous floor discomfort levels at the same geographic location.

A CBM identification methodology was developed to investigate the aforementioned hypothesis. The procedure includes experimental acceleration and location measurements, performed using a 3-axial accelerometer and GPS. ISO 2631 standard provided a reference for assessing passenger comfort. A MATLAB algorithm was developed to match multiple vehicles' discomfort locations and identify possible maintenance requirements. The methodology was applied to ballasted tracks, but no assessment differences are expected if applied to ballastless tracks.

4.1 Whole-body vibration evaluation – ISO 2631

ISO 2631 standard quantifies WBV regarding comfort, health, and motion sickness. This defines the frequencies comprehended between 0.5 and 80 Hz as the interesting range, as this vibration frequency affects the body as a whole. The standard states the measurement of 3-axial acceleration at the interface surfaces between the user and the transmitting surface. Considering the present application, those measurements were taken on the railway floor. Discomfort is calculated in four steps; initially, the root-mean-square acceleration is calculated for each axis, and then those accelerations are weighted based on the human dynamic response. This weighting process is calculated according to Eq. (1):

$$a_w = [\sum W_i a_i]^{\frac{1}{2}} \tag{1}$$

where W_i represents the weighting frequencies and a_i the RMS accelerations. Then, the total vibration (a_v)

is obtained by the following Eq. (2):

$$a_v = \left(k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right)^{1/2} \tag{2}$$

where the a_w are the weighted accelerations for each axis, and k represents the multiplying factor. Considering floor measurements, that factor is equal to 0.25 for both x and y axes and 0.40 regarding the z-axis. Lastly, based on a_v discomfort is evaluated by a defined scale, Table 1 [14].

Table 1. ISO 2631 comfort evaluation scale. Adapted from [14].

$a_v (m/s^2)$	Ride comfort
≤ 0.315	Not uncomfortable
0.5 – 0.63	Little uncomfortable
0.63 – 0.8	Little uncomfortable to fairly uncomfortable
0.8 – 1.0	Fairly uncomfortable to uncomfortable
1.0 – 1.25	Uncomfortable
1.25 – 1.6	Uncomfortable to very uncomfortable
1.6 – 2.0	Very uncomfortable
2.0 – 2.5	Very uncomfortable to extremely uncomfortable
≥ 2.5	Extremely uncomfortable

The present research applies the calculation of instantaneous floor discomfort by performing the standard analysis per second and using its recommendations.

4.2 Methodology and data analysis

As aforementioned, floor vibration measurements were performed by a 3-axial accelerometer (PCE-VDL-24I) located at multiple positions inside the train, corresponding to the train's beginning, middle and end points. An Arduino was programmed to acquire the GPS geographic location during the tests. Experiments run under multiple AP and IC trains while performing regular passenger service at the Portuguese Railways Northern Line.

Data analysis was performed using an algorithm developed for this purpose. The algorithm starts by calculating the instantaneous floor discomfort (discomfort level at each second) according to ISO 2631 recommendations for each rail journey. Based on the discomfort levels reported in Table 1, a slight adaptation of the standard was conducted, and only two levels were defined. Those a_v values equal to or under 0.315 m/s^2 were ranked as “Not uncomfortable”, whereas those above 0.315 m/s^2 were rated as “Uncomfortable”. The uncomfortable locations were identified and mapped in all journeys. It was assumed that only common discomfort sections required maintenance, i.e., segments identified by multiple trains.

5 Case study: Portuguese Northern Line condition assessment

As aforementioned, to conduct the proof of concept and verify the accuracy of the developed methodology, vibration records took place at multiple AP and IC trains while performing regular passenger service at the Portuguese Railways Northern Line, downward direction, connecting Porto (Campanhã) to Lisbon (Oriente). Then, its results were compared with those reported by the EM 120-track inspection vehicle.

Fifteen records were conducted, nine on AP and six on IC, corresponding in equal numbers to the position of the start, mid and end points of the train. Moreover, those measurements were specifically taken near the carriage's rear bogies.

5.1 Maintenance requirements identified by the indirect methodology

The more recent report on the Portuguese Railway Northern Line infrastructure evaluation and maintenance needs detection demonstrated multiple track sections in poor conditions and, consequently, with maintenance needs [15]. The interesting segments can be found in Table 2.

Table 2. Track segments' maintenance needs identified by IP through the passage of EM 120 inspection vehicle (adapted from [15]).

Track Section		Kilometre interval		Track segment
Start station	End station	Start	End	
Alhandra	Castanheira do Ribatejo	26	27	A
Albergaria dos Doze	Alfarelos	147	199	B
Pampilhosa	Válega	232	297	C
Válega	Espinho	297	316	D

According to Karoumi et al. [10] and Norris [16], a railway track infrastructure with isolated irregularities has higher vibration levels at those locations than a healthy one. Hereby, those higher vibrations will lead to increased discomfort levels. The proposed methodology categorises floor discomfort levels into “Not uncomfortable” or “Uncomfortable”, depending on the instantaneous acceleration evaluation. Matching the defined categories with those of ISO 2631, the first level is characterised by under 0.315 m/s^2 accelerations, whereas those above that discomfort threshold are grouped in the second category. Therefore, an abnormality in the railway track infrastructure was expected to present higher than 0.315 m/s^2 discomfort peaks at that location. In contrast, a healthy infrastructure should have instantaneous floor discomfort at the first level, meaning lower than that threshold floor discomfort. Ideally, those discomfort levels should present consistent behaviour. The reported trend was observed in the acceleration records and analysis. Figure 2 illustrates AP and IC trains' behaviour regarding the same locations (latitude).

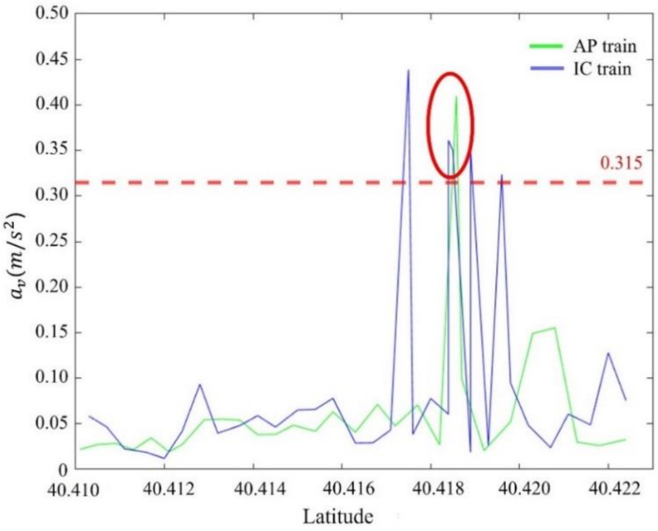

Figure 2. Instantaneous floor discomfort levels for AP and IC trains (where the red mark identifies a railway track infrastructure abnormality).

Vibration peaks capable of going through primary and secondary suspension systems cause passenger’s discomfort. Once, AP and IC trains have dissimilar suspension systems composed of different elements, it can be concluded that when the discomfort sections of both trains agree, the railway track infrastructure requires maintenance. Figure 2 illustrates an example of that matching between both trains, the overlapping is represented by the red marks. In this way, it can be established that an abnormality is presented at that specific location, and thus, the railway track infrastructure needs maintenance. Figure 3 presents all maintenance sections identified on the Northern Line by applying the present methodology.

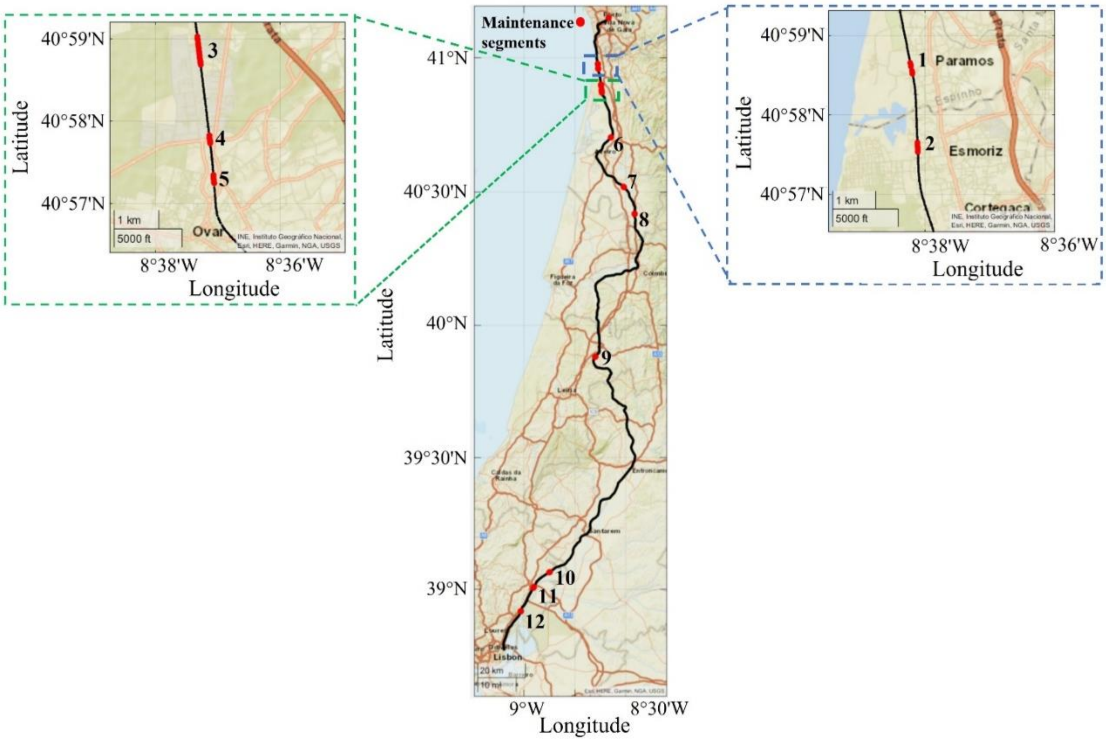

Figure 3. Sections of the Northern Line railway track infrastructure identified by the proceeding as requiring maintenance; detailed zones (left side and right side) are at the laterals.

Twelve maintenance zones were identified; for those, the start and end coordinates and their associated line kilometre were registered in Tab. 3.

Table 3. Segments identified as needing maintenance and comparison with EM 120 inspection vehicle results.

Zone number	Initial coordinates		Final coordinates		Line km	Track segment IP
	Latitude (º)	Longitude (º)	Latitude (º)	Longitude (º)		
1	40.9776	-8.6374	40.9753	-8.6368	315	D
2	40.9609	-8.6354	40.9589	-8.6353	313	D
3	40.9005	-8.6221	40.8948	-8.6212	306	D
4	40.8805	-8.6189	40.8789	-8.6187	304	D
5	40.8725	-8.6178	40.8708	-8.6176	303	D
6	40.7044	-8.5727	40.7038	-8.5735	283	C
7	40.5196	-8.5108	40.5180	-8.5087	255	C
8	40.4198	-8.4564	40.4172	-8.4566	242	C
9	39.8820	-8.6489	39.8807	-8.6507	166	B
10	39.0651	-8.8734	39.0639	-8.8758	46	-
11	39.0081	-8.9518	39.0047	-8.9542	37	-
12	38.9159	-9.0155	38.9149	-9.0160	26	A

Ten listed locations match those identified by the EM 120 inspection vehicle, confirming that the obtained locations are critical points of the railway track infrastructure and validating the methodology. Nevertheless, it should be noted that the proposed methodology cannot identify the abnormality type present in the infrastructure but is focused on detecting the critical track sections. In the future, more work is intended to be developed regarding abnormality identification using more advanced methodologies, such as supervised machine learning procedures.

6 Conclusions

Railways are a widely used mass transportation system that is being expanded in capacity, velocity, and load demanded, accelerating the railway track infrastructure degradation. Additionally, the interaction between the rail infrastructure, wheels and vehicle motion creates a complex vibration environment, leading to a need for continuous maintenance.

The proof of concept of a new methodology to identify railway track infrastructure maintenance requirements based on comfort measurements without timetable disruptions was developed. The developed system was validated against the gold standard and provides a complementary, low-cost CBM railway track infrastructure analysis capable of detecting abnormalities using in-service passenger trains, thus avoiding service disruptions. Moreover, applying comfort levels to assess maintenance requirements is a novelty compared to previous studies. A future goal is to identify the type of abnormality using machine learning procedures.

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