

## Research Article

# Smartphone's Sensing Capabilities for On-Board Railway Track Monitoring: Structural Performance and Geometrical Degradation Assessment

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Railway infrastructure managers run dedicated inspection vehicles to monitor the geometric quality of the track (among other aspects) to detect irregularities and ensure safe running conditions of railway lines, in accordance with specific regulations. Unfortunately, these inspections disturb the normal traffic operation, especially in networks with intense traffic; are generally carried out only a few times per year; and, consequently, do not provide prompt identification of critical situations. Considering the recent developments and cost reduction in sensing capabilities of smartphones, the authors present an approach to use these technologies to perform constant acceleration measurements inside in-service trains to complement the assessment of the structural performance and geometrical degradation of the tracks. Cross-correlation values above 0.85 were obtained between the standard deviations of the longitudinal level and the experimental vertical accelerations measured on-board a passenger train on an 11-km railway stretch. The results showed that the approach can be used to identify critical situations that affect the performance of the track, regarding passenger comfort, degradation rates, and risk of derailment. It may comprise a low-cost and crowdsourced complement to the general current practice of track geometric inspection by dedicated vehicles and contribute to an earlier detection of track malfunctions, consequently, to a more efficient maintenance planning and infrastructure management.

## 1. Introduction

In ballasted railway tracks, the position of the rails changes with time, mostly caused by the development of differential settlements in the structure and by the accumulated railway traffic, which induces wear of components and plastic deformations in the supporting layers [1–3]. With time, this unwanted behaviour amplifies irregularities or faults in the position of the rails, causing the degradation of the geometric quality of the track. Eventually, this negatively affects the performance of this transport system, in terms of the running behaviour of trains, amplifying the dynamic response of the train-track system, promoting additional track degradation, noise and vibrations, poor ride comfort, and higher risk of derailment [4–8]. To prevent and minimise these consequences, railway infrastructure managers put significant effort into monitoring the track geometry and

maintaining adequate track geometric quality, complying with specific requirements and standards [9, 10]. To that aim, dedicated inspection vehicles are used by infrastructure managers to perform the auscultation of the track geometry (among other aspects) to detect critical situations and to plan maintenance interventions requiring heavy machinery. The reconstruction of track geometry from track inspection cars is a well-established procedure and these vehicles are currently manufactured on an industrial basis by a few suppliers [2]. Different approaches have been developed over the years, from contact-based (measuring axle principle) to non-contact-based, from chord measuring systems to inertial (absolute) systems. Modern inspection cars integrate inertial measurement that uses the known measuring technique by which the spatial position of a measuring sensor is determined by double integration of acceleration measurements. Commonly, the heart of these systems comprises an

inertial measuring system (IMS), consisting of 3 high-precision gyro systems and accelerometers for three orthogonal spatial directions. Through the combination with optical track measuring systems, using laser distance sensors and location systems along the track (distance encoders and GNSS), the required longtime accuracies are established. In Europe, the requirements for these vehicles are standardized according to the European Norm EN 13848-2, since 2006 [11]. A newer version of this norm is currently under discussion prEN 13848-2:2018.

Unfortunately, both the monitoring surveys by the inspection vehicles and the maintenance works are expensive activities that also hinder normal railway traffic. Given the importance of frequent monitoring of the railway track, particularly at critical locations, and taking into account the cost and increasing difficulty to conduct track geometry inspections throughout the rail networks, there is a need to develop alternative and expeditious methods to provide timely information on the performance and condition of the track [12], as implemented in recent years in world-leading railway networks [13].

Due to the increasing sensing capabilities and cost reduction of sensors for smartphones, in recent years, there has been significant development and increase in the application of micro-electro-mechanical systems (MEMS) that can be used to assess the performance of transport systems. Numerous applications can be found in the literature regarding its use to characterise the transport infrastructure and the vehicle's motion [13–18]. Other applications evidence the potential of large-scale surveys to assess the performance of transport networks, in that they can be used to study mobility patterns [19] and to assess the ride quality of transport systems [20–24].

In this study, the authors present an approach for railway track monitoring using sensing capabilities of smartphones or other current low-cost inertial systems, as an alternative to more expensive and dedicated systems [13]. A section of a railway line is used as case study to demonstrate the applicability of this approach. Acceleration measurements performed on-board a passenger train with a smartphone are analysed and compared against the longitudinal level of the track geometry records and its degradation with time. The study also demonstrates further applicability of the approach to assess the structural performance of railway tracks, by assessing how different wavelengths and amplitudes of the geometric irregularities affect degradation, running safety, and ride comfort, supported on dynamic train-track numerical simulations [25, 26].

The contribution of this approach, applied to condition and performance monitoring of the railway track, can provide valuable information for railway infrastructure managers as early detection of track faults and input data for asset management tools to optimise maintenance operations [27, 28].

## 2. Description of the Case Study

The stretch of track that was selected for this study is about 11 km long, located in the Northern Line of the Portuguese

railway network. The track has Iberian gauge (1.668 m) and comprises continuously welded UIC 60E1 rails, Vossloh fastening system, monoblock concrete sleepers (spaced 0.6 m), and ballast layer with minimum thickness of 0.30 m under the sleepers, resting on a 0.20 m subballast layer. In the analysed stretch, the fastest passenger trains, the Alfa Pendular, normally travel at about 220 km/h.

Because this work focuses mainly on the vertical behaviour of the track, its geometric quality will be analysed in terms of the longitudinal level and its standard deviation. In general, this parameter is mostly associated to the track degradation and develops faster with traffic and time. In the scope of this study, it was possible to analyse the track geometry obtained in three different surveys: (i) July 2012, (ii) July 2013, and (iii) March 2016.

Although the stretch is in double line, only one of the tracks was considered in this study—the ascending track. Figure 1 shows the track longitudinal level measured in the third survey (March 2016), namely, the wavelength ( $\lambda$ ) ranges D1 ( $3 < \lambda \leq 25$  m) and D2 ( $25 < \lambda \leq 70$  m), as established in the European Norm EN 13848-5 [10]. It is visible that there are no relevant track defects and the longitudinal level records remain within the threshold values of the alert limits for D1 and D2, which indicates an overall good geometric quality of the track. It is also interesting to note that the locations denoting disturbances in the longitudinal level records of D1 do not match those of D2, which is expected given that the track defects of these two wavelength ranges normally have different sources [2, 29–31].

## 3. Smartphone Setup

To demonstrate the applicability of smartphone's sensing capabilities for on-board railway track monitoring, the authors evaluated the accelerations inside the car body of the Portuguese *Alfa Pendular* passenger train, travelling along the stretch of track under analysis, using MEMS accelerometers (triaxial) found in modern and conventional smartphones. After previous validation tests using different smartphones [32], the measurements were performed with an Android™ smartphone, namely, the Samsung Galaxy®, SIII, GT-I9300, incorporating a MEMS accelerometer from STMicroelectronics®, model LSM330DLC. According to the manufacturer, the sensor is characterised by a power consumption of 0.23 mA, range of  $\pm 19.6133 \text{ m/s}^2$  ( $\pm 2 \text{ g}$ ), resolution of  $0.009576807 \text{ m/s}^2$ , and median sampling frequency of 100 Hz. The LSM330DLC is a discontinued inertial module from late 2012, which comprises a revisited and downsized version of its predecessor module LSM330DL. It has a 12-bit resolution with selectable linear acceleration range of  $\pm 2/\pm 4/\pm 8/\pm 16 \text{ g}$ . It also offers fully programmable interrupt generator, power down mode for low-power operation and SPI/I2C digital interface. This module in particular has been used successfully in other studies demonstrating the smartphone's sensing capabilities to characterise motion of structures and other bodies [33, 34]. After initial tests and following previous experience, the application “Sensor Log” (v1.04) was used to register the measurements (currently available at <https://sensor-log.en.aptoide.com/>). The selected application

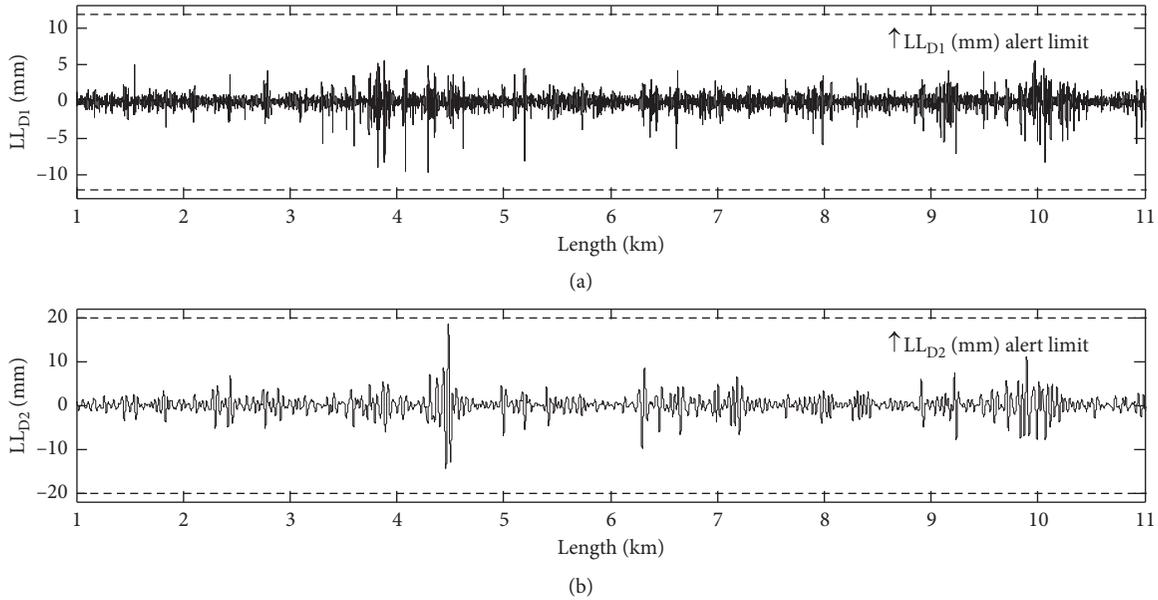


FIGURE 1: Track longitudinal level, LL, for wavelength ranges (a) D1 ( $3 < \lambda \leq 25$  m) and (b) D2 ( $25 < \lambda \leq 70$  m) and respective alert limits [10].

provided accelerometer and GNSS readings from the smartphone at faster sampling frequencies than other similar applications that were also available at the time. Although the GNSS position of the acceleration measurements is useful, its precision is not very critical, and the typical  $\pm 5$  meter error [35] obtained with smartphones (under good atmospheric and multipath conditions) is sufficient for the proposed application, mainly because the data is analysed using sliding windows of variable length. Moreover, the approach is meant to be used on a regular basis on the same track, a few times per day; thus, significant positioning errors could be easily detected and discarded/corrected, particularly when compared with the last measurements performed by the inspection cars. Because the track layout in plan view is well-established, a method to validate the GNSS position could consist in confirming the strong correlation between the track curvature and the lateral accelerations measured on-board.

The measurements were performed inside the fifth coach car of the *Alfa Pendular* train, near the vertical alignment with the rear bogie, on the floor, under the seat, and at the location identified in Figure 2 and aligned with the car so that the orientation of the sensors' axes ( $x$ ,  $y$ ,  $z$ ) matched the transverse, longitudinal, and vertical alignments of the coach car, respectively (see Figure 2(c)).

The smartphone was used to record the accelerations in the three directions ( $x$ ,  $y$ , and  $z$ ) over a few minutes, as the train travelled along the 11 km stretch. At each measurement, the acceleration values in the three directions were recorded, and a timestamp was assigned. In the tests performed by the authors, the recorded data were stored internally in the smartphone memory, but other alternatives are possible, for example, transmitting the recorded data via on-board Wi-Fi or cell phone network. Because the sampling frequencies of the smartphone were not always constant, the measurements were resampled to 100 Hz.

#### 4. Acceleration Measurements

Acceleration measurements and respective frequency content is presented in Figure 3, where it is clear the influence of the curvature of the track alignment in the lateral accelerations ( $x$ -direction) measured with the smartphone. It is also visible that most frequency content is below 15 Hz, which evidences the capabilities of the primary and secondary suspensions of the train in filtering higher-frequency contents from rolling contact [2, 4–7, 31, 36]. Nevertheless, it is noted a frequency peak at about 25.4 Hz, which is probably the consequence of a sleeper-spacing excitation: considering that the excitation frequencies of the train-track system,  $f$ , can be estimated as  $f = v/\lambda$ , where  $v$  is the train speed (220 km/h or 61.1 m/s) and  $\lambda$  is the sleeper spacing (equal do 0.6 m), we obtain a sleeper-spacing excitation frequency of  $f = 101.85$  Hz. The frequency of 25.4 Hz is a submultiple of that frequency when multiplied by 4, thus corresponding to the span of 4 sleepers.

#### 5. Correlation with the Track Geometry

It is common practice by railway infrastructure managers to calculate the standard deviation of the longitudinal level, to assess the track geometric quality, to study its degradation evolution, and to plan early maintenance operations, for which threshold values are established in European norms [10]. To demonstrate that the vertical accelerations measured inside the coach car are correlated to the longitudinal level of the track, Figure 4 presents three plots, each comparing the standard deviation of the longitudinal level,  $SD_{LL,D1+D2}$ , regarding wavelength ranges D1 + D2, and with the standard deviation of the vertical accelerations,  $SD_{a,z}$ , considering three sliding-window sizes: 10 m, 75 m, and 200 m. The normalised cross-correlation ( $\text{Corr} - \text{norm}_{y_1, y_2}$ ) and

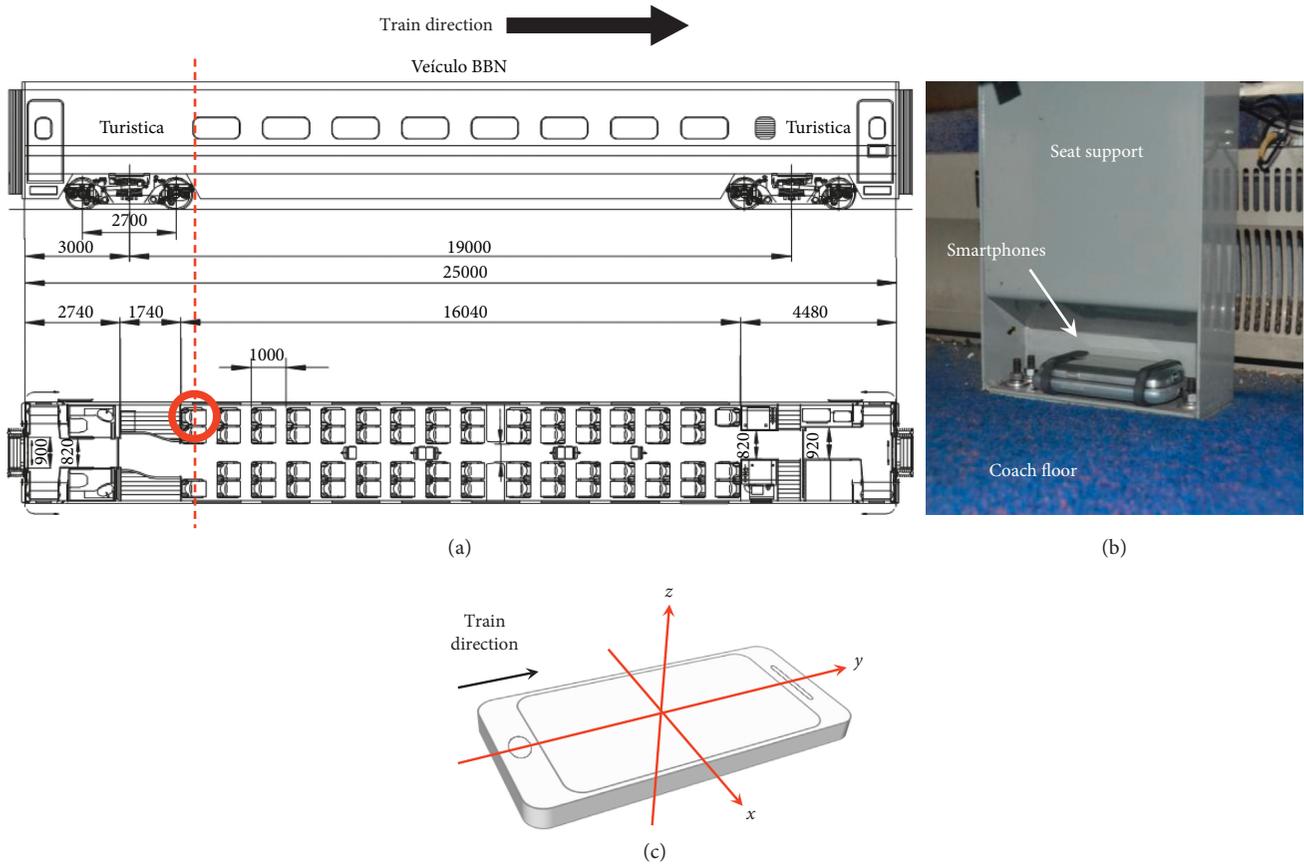


FIGURE 2: Location of the smartphone inside the coach car (a, b) and schematic representation of the orientation of the accelerometers' axes  $x$ ,  $y$ , and  $z$  (c).

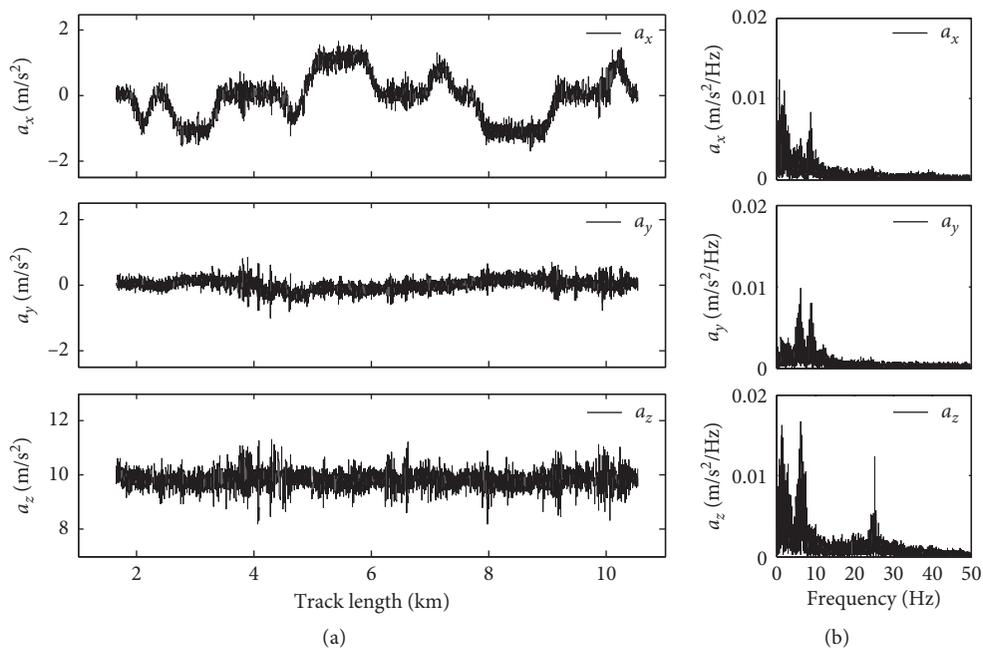


FIGURE 3: Acceleration measurements: (a) measurements along the track; (b) frequency content.

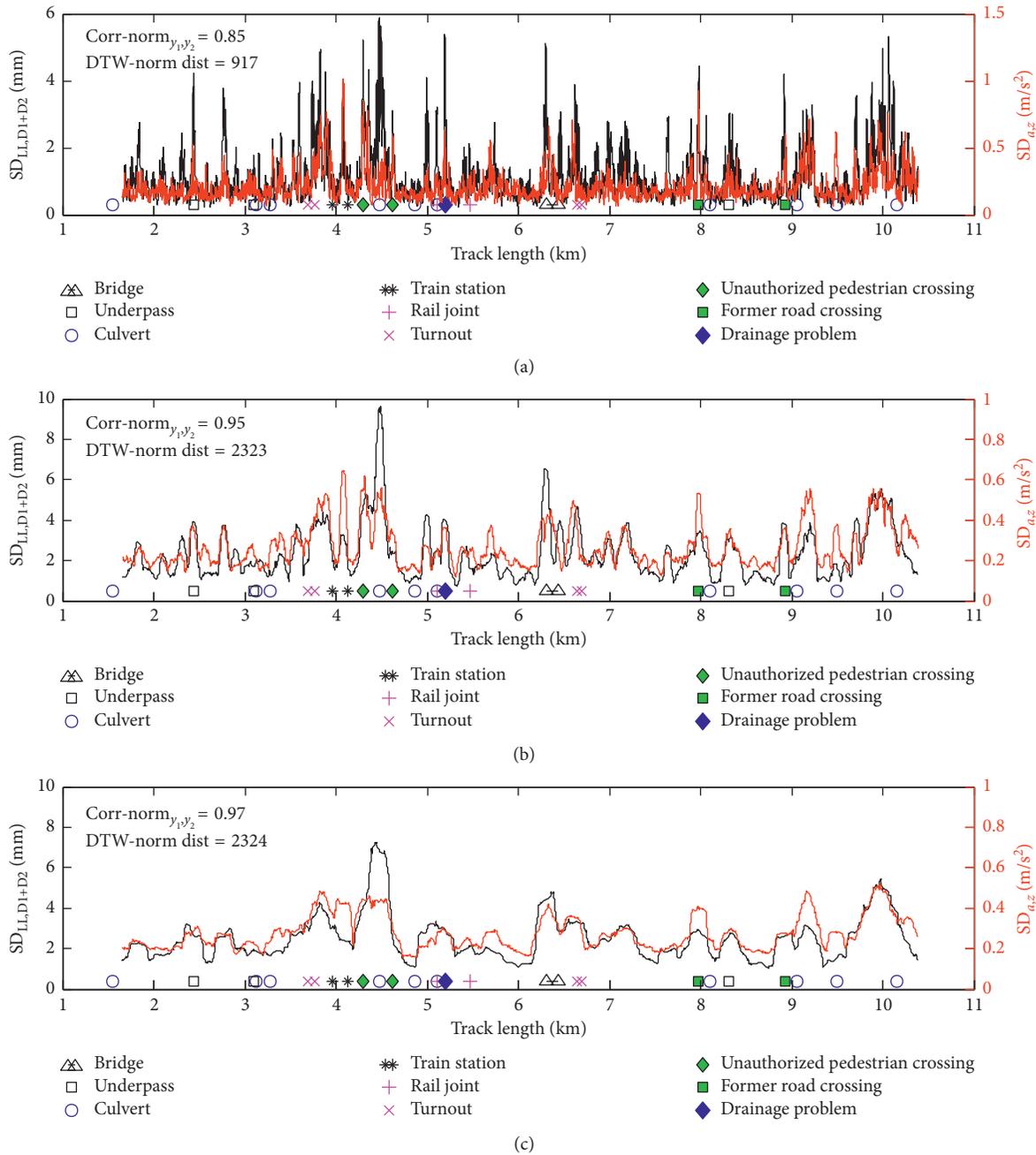


FIGURE 4: Comparison between the standard deviation of the longitudinal level ( $SD_{LL,D1+D2}$ ) and of the vertical accelerations ( $SD_{a,z}$ ), considering three sliding-window sizes: (a) 10 m, (b) 75 m, and (c) 200 m.

dynamic time warping distance (DTW-norm dist) values [37, 38] between  $SD_{LL,D1+D2}$  and  $SD_{a,z}$  are also indicated in the plots. It is visible the very good correlation between the variables, particularly for larger window sizes.

In order to justify the peak values of  $SD_{LL,D1+D2}$  and  $SD_{a,z}$  in the three plots in Figure 4, the authors analysed the characteristics of the track, looking for any relevant structural aspect or sudden changes in the track structure (track discontinuity or singularities). In fact, about 30 relevant discontinuities were identified, including transition zones, rail joints, turnouts, bridges, underpasses, culverts, and

stations, among others. Figure 5 presents examples of these discontinuities, and their location was also added to Figure 4. It is visible that, in general, they correspond to the location of peak values of  $SD_{LL,D1+D2}$  and  $SD_{a,z}$ . This suggests that these locations experience higher geometric degradation and affect passenger comfort, which is in agreement with other studies [4–7, 36, 39].

Subsequently, to assess the actual track degradation rates, the authors analysed the evolution of the  $SD_{LL,D1+D2}$  between the surveys of 2013 and 2016,  $\Delta SD_{LL,D1+D2}$ . In Figure 6, it is visible that most of the locations denoting

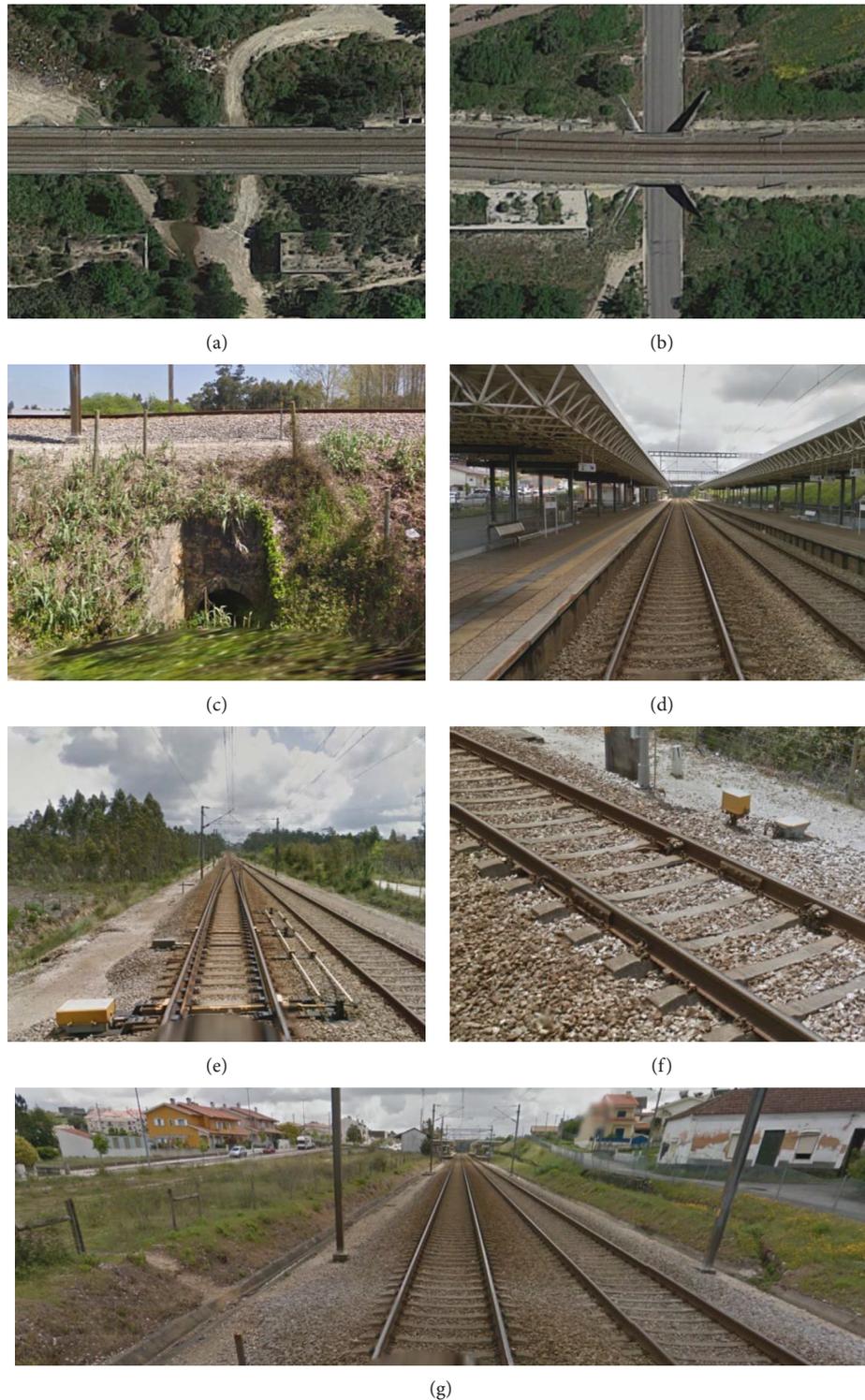


FIGURE 5: Different types of track discontinuities found along the line (Imagery: Google Street View): (a) bridge, (b) road underpass, (c) culvert, (d) train station, (e) turnout, (f) rail joint, and (g) unauthorized pedestrian crossing.

higher degradation rates (higher values of  $\Delta SD_{LL,D1+D2}$ ) generally also correspond to the locations where higher values of  $SD_{LL,D1+D2}$  are observed in Figure 4, for example, between km 3.5 and 4.5 and between km 9 and 10.5. It is also interesting to note that most of  $\Delta SD_{LL,D1+D2}$  peaks are also centred on the track discontinuities identified above.

## 6. Track Geometry Data to Assess the Structural Performance

In addition to monitoring the condition of the track, the data obtained by smartphone-based or low-cost inertial systems may be analysed further to assess the structural performance

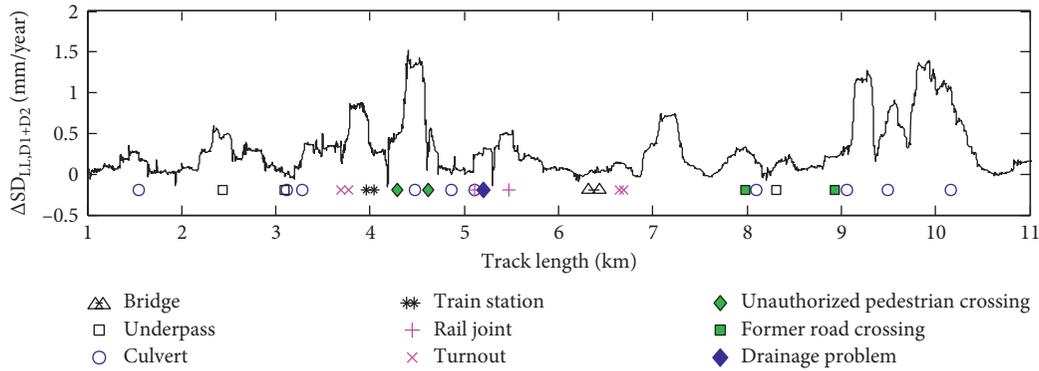


FIGURE 6: Evolution of standard deviation of the longitudinal level ( $\Delta SD_{LL,D1+D2}$ ) between 2013 and 2016, considering a sliding window of 200 m.

of railway tracks. One possible application is its contribution to the early detection of critical locations in railway tracks that negatively affect the performance of this transport system. This approach can be supported by a method proposed by the authors [26] that analyses how different wavelengths and amplitudes of the irregularities of the longitudinal level affect different critical aspects of the track performance, namely, (i) its degradation, (ii) the train running safety, and (iii) the passenger ride comfort. That method has been successful in anticipating the development of critical locations that affect the performance of the infrastructure in a previous railway line case study and, therefore, can be a valuable tool in maintenance and asset management activities of railway infrastructure managers. This is achieved by integrating the information concerning the track geometry records, the characteristics of the track superstructure and substructure, and the information from numerical train-track interaction simulations. The track geometry data, specifically the longitudinal level, can be obtained from normal inspection surveys or calculated by inverse analysis of the car-body acceleration obtained by smartphone-based or low-cost inertial systems, as demonstrated in other applications [40–42]. The effect of track irregularities (with different wavelengths and amplitudes), caused by differential settlements, on the dynamic train-track interaction is assessed by parametric numerical simulations, as in [25]. Because the characteristics of the track and trains of this present case study are practically the same as those for which the method was firstly demonstrated [26], the results of that parametric numerical study may also be used here to identify possible critical situations, based on the information regarding the analysis of track geometry records.

The three criteria for the identification of the critical situations depicted in Figure 7 are as follows:

- (i) “Higher risk of train derailment”: situations of offload values (ratio of the offload vertical wheel-rail force to the static vertical wheel-rail force) lower than the threshold value of 0.6, considered in other studies [43]
- (ii) “Rapidly increasing track degradation rates”: cases of higher vertical accelerations in the sleepers and in

the trains’ axles, as well as increasing train-track forces and sleeper-ballast contact pressures [25, 44, 45]

- (iii) “Lower passenger comfort”: situations of vertical accelerations inside the car body higher than the threshold of  $1 \text{ m/s}^2$  [46]

Firstly, the authors calculated the longitudinal level (LL), depicted in Figure 8, as the sum of the wavelength ranges D1 ( $3 < \lambda \leq 25 \text{ m}$ ) and D2 ( $25 < \lambda \leq 70 \text{ m}$ ), presented earlier in Figure 1. The figure also shows the position of transition zones and the other discontinuities mentioned in Figure 5.

Then, the longitudinal level was analysed, in terms of defect length and respective amplitude. In practice, for each position on the track, various amplitudes of the defects were calculated based on a range of overlapping chord lengths between 3 m and 35 m, as explained in detail in [26]. Each pair of (amplitude and chord length), denoted here as an “occurrence,” was plotted in Figure 9 against the three critical regions described earlier (Figure 7).

From the analysis of Figure 9, most occurrences fall outside the three critical regions identified above (Figure 7). However, there were some occurrences associated with both higher risk of derailment and rapidly increasing track degradation rates, and even others with lower passenger comfort. To identify which locations in the track were associated with lower track performance, the method consists in intersecting the contour of the abovementioned regions with the list of occurrences in Figure 9.

Figure 10(a) shows the locations of the track discontinuities mentioned in Section 2 and the only location (a culvert at about 4.467 km mark) that was found to have a high number of the occurrences denoting lower passenger comfort. At that location, the results suggest vertical accelerations inside the coach car of the *Alfa Pendular* above  $1 \text{ m/s}^2$ , a threshold value established in [46].

Figure 10(b) shows the locations of the track discontinuities mentioned in Section 2 and the only location (a turnout at about 3.821 km mark) that was found to have a high number of the occurrences denoting higher risk of derailment of the train. At that location, the results suggest offload values (ratio of the offload vertical wheel-rail force to the static vertical wheel-rail force) of the *Alfa Pendular* train

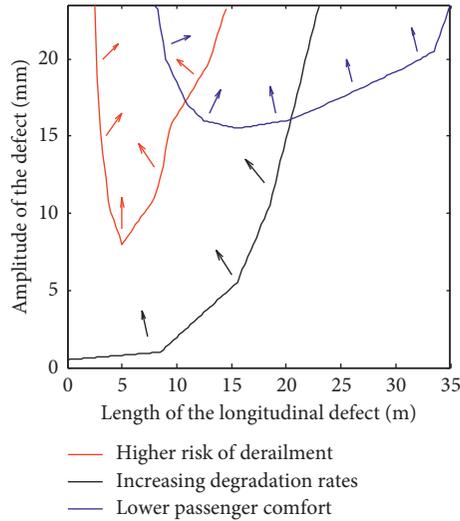


FIGURE 7: Identification of the regions that negatively affect the track performance, analysed in terms of amplitude and length of the defects: (i) regions with higher risk of derailment (lower train running safety) in red, (ii) regions with increasing track degradation rates in black, and (iii) region with lower passenger ride comfort in blue (adapted from [25]).

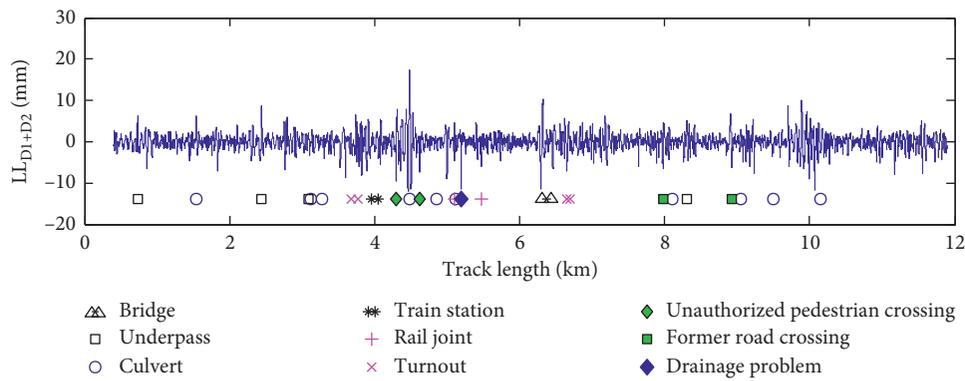


FIGURE 8: Track longitudinal level, in terms of the sum of the wavelength ranges D1 ( $3 < \lambda \leq 25$  m) and D2 ( $25 < \lambda \leq 70$  m),  $LL_{D1+D2}$ , and position of track discontinuities, often associated with track faults, below the longitudinal level plot.

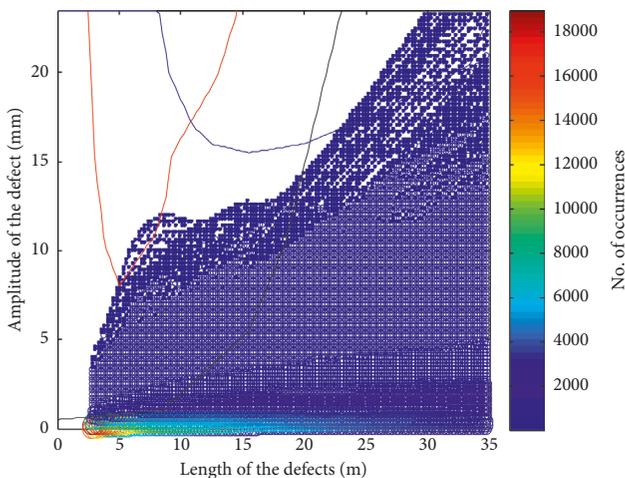


FIGURE 9: Overlay of the regions identified in Figure 7 with the scatter plot of the density of occurrences.

lower than the threshold value of 0.6, considered critical in other studies [43].

Figure 11(a) also shows the locations of the track discontinuities mentioned in Section 2 and the location of the occurrences that fall inside the region associated with increasing degradation rates. Due to the large number of occurrences in this case, it was decided to remove the less relevant points to improve readability of the figure, namely, those denoting both amplitudes smaller than 1 mm and chord lengths smaller than 7.5 m. Some concentration of occurrences may be related to the presence of transition zones or other discontinuities, while many others seem to be of random nature or related to additional factors for which no obvious justification was found.

To assess the degradation rates, the authors also calculated the variation of the standard deviation along the track between two surveys (2016 and 2013) and compared the results against the locations with track discontinuities and

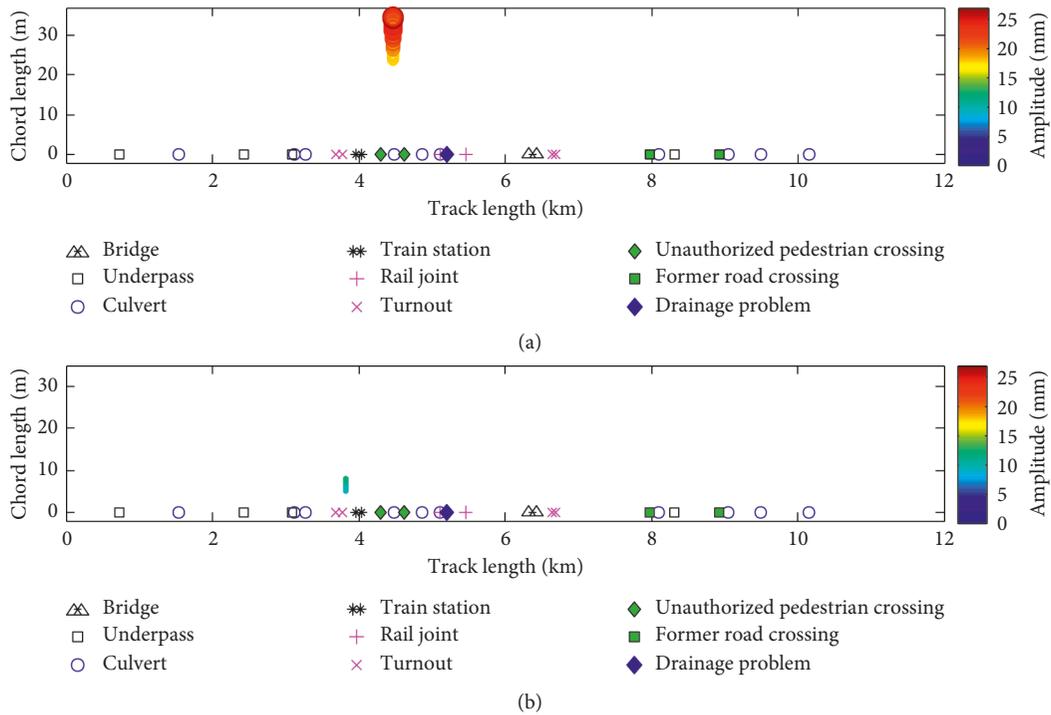


FIGURE 10: Locations that may be causing (a) significant lower passenger comfort and (b) higher risk of derailment of the train.

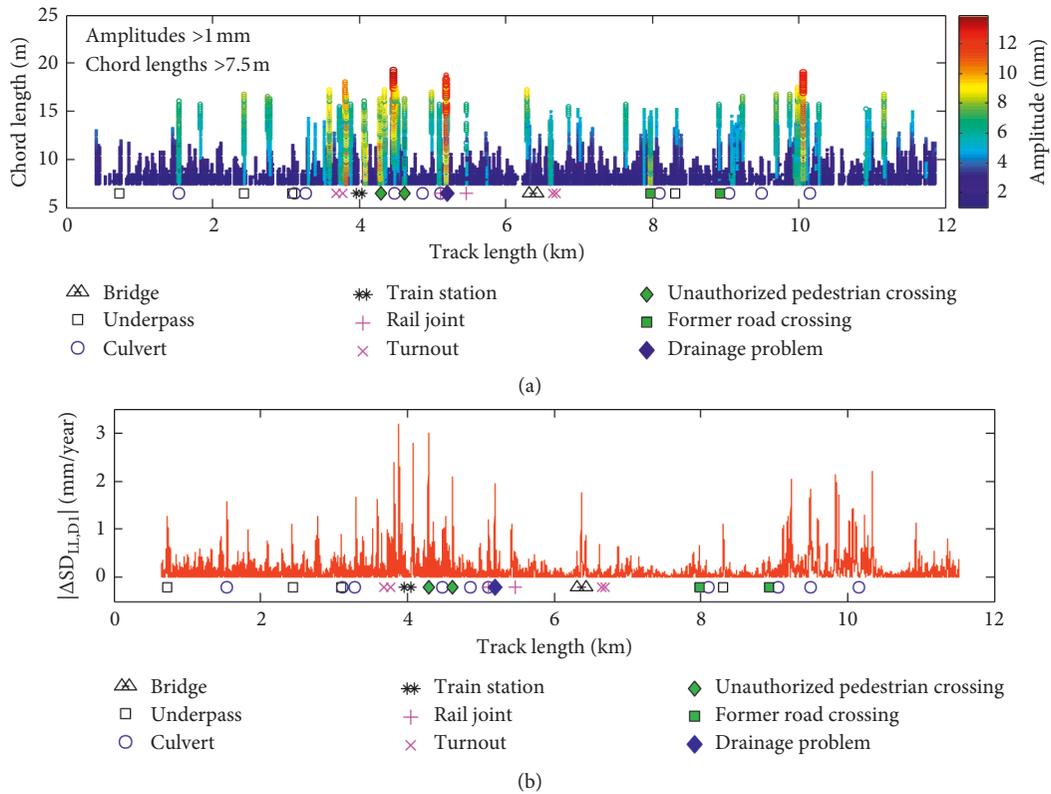


FIGURE 11: Track degradation: (a) locations associated with higher track degradation; (b) actual degradation in terms of the absolute value of the annual variation of  $\Delta SD_{LL,D1}$ .

TABLE 1: Track discontinuities evidencing poor performance.

Description	Location (km)	Chord range (m)	Maximum amplitude (mm)	Critical aspect
Culvert	1.5	6.75–16	6	Higher degradation
Road underpass	2.4	14–17	8.5	Higher degradation
Culvert	3.3	7–14.25	5	Higher degradation
Around turnout	3.6–3.8	5–8	12	Derailment risk
		3.5–18.25	12	Higher degradation
Train station exit	4.1	4.75–16	10	Higher degradation
Unauthorized pedestrian crossing	4.3	3.75–17.25	10.5	Higher degradation
Culvert (old masonry)	4.5	23.25–34.75	23.5	Passenger discomfort
		7.75–19.25	14	Higher degradation
Unauthorized pedestrian crossing	4.6	4.5–16.75	8.5	Higher degradation
Rail joint and culvert	5.1	6.25–15.75	6	Higher degradation
Drainage problems	5.2	4.75–18.75	13	Higher degradation
Rail joint	5.45	4.25–16	6	Higher degradation
Bridge approach	6.3	10–17.5	10	Higher degradation
Near turnout	6.6	5.5–15.25	8	Higher degradation
Former road crossing	8	4.25–15.25	8.5	Higher degradation
Culvert	8.1	13.5–15.25	6	Higher degradation
Road underpass	8.3	12.5–15.25	5	Higher degradation
Former road crossing	8.9	10–15.75	7	Higher degradation
Near culvert	9.1	4.75–14.75	7	Higher degradation
Near culvert	10.1	7–19	13	Higher degradation

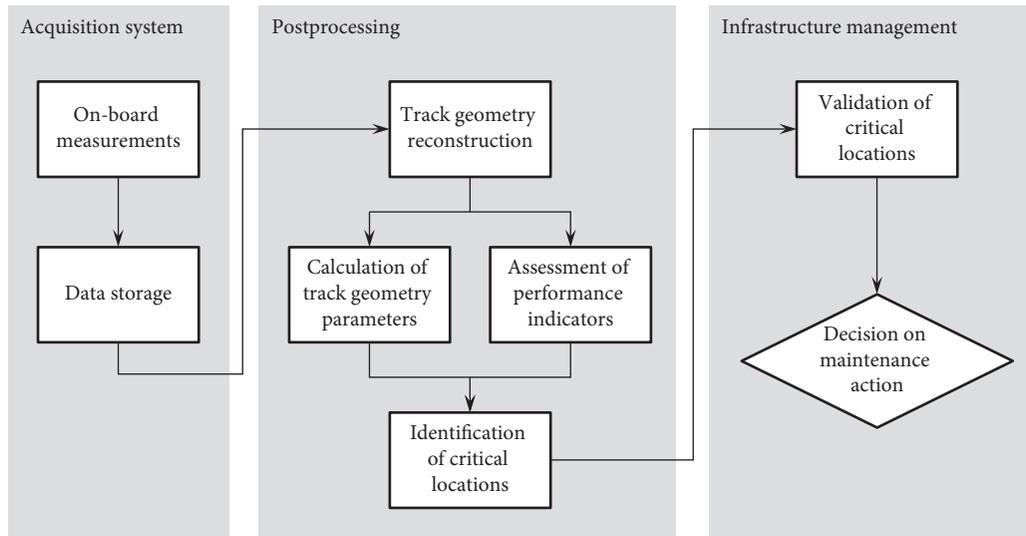


FIGURE 12: Schematic representation of the proposed method for complementary monitoring of railway tracks.

concentrations of relevant occurrences (Figure 11(b)). Here, the authors used a shorter 10 m sliding window, instead of the 200 m sliding windows, for compatibility with the wavelength ranges analysed by the method and to be more sensitive to the influence of the track discontinuities. It is visible that most track discontinuities identified in Section 2 matched locations with concentration of occurrences and with higher rates of track degradation. These locations are listed in Table 1.

On the other hand, the two road underpasses at km 0.73 and 3.09 and the three culverts at km 3.1, 4.86, and 9.50 did not evidence poor track performance, which suggests that these structures are evidencing adequate structural behaviour.

## 7. Conclusions

The results presented in this study suggest that incessant and continuous monitoring of the vehicle's motion, either using smartphones from crew/passengers or low-cost on-board sensing systems inside in-service trains, can provide valuable information for asset management activities of railway infrastructure managers.

The case study presented by the authors demonstrates that the standard deviations of the longitudinal level and the experimental vertical accelerations were very well correlated: cross-correlation values between 0.85 and 0.97 were obtained for sliding-window sizes of 10 m to 200 m. The study also showed that peaks of these two variables were often

associated with sudden changes in the track, such as the presence of transition zones, rail joints, turnouts, bridges, underpasses, culverts, stations, and other track discontinuities. The track at these locations also evidenced higher degradation rates. Further analysis of the longitudinal level was performed in terms of how different wavelengths and amplitudes of the geometric irregularities affected the performance of the track, following a procedure established in [26], associating the results with numerical train-track interaction scenarios simulated in a previous parametric study [25]. The approach allowed identifying scenarios along the track that suggested (i) higher risk of derailment, (ii) increasing degradation rates, and (iii) lower passenger comfort, based on established criteria. The results showed that many track discontinuities mentioned above seem to be associated with lower geometric quality of the track and with high degradation rates.

This approach may comprise a constant and daily monitoring complement to the general current practice of track geometric inspection by dedicated vehicles, which only performs a few surveys per year on a given railway line. In this way, this approach can contribute to an earlier detection of track malfunctions and, consequently, to a more efficient maintenance planning and asset management by implementing the system configuration diagram presented in Figure 12. For example, in the event of the identification of a critical location with a significant track defect, even if its position is not accurate, an alert could be triggered for the infrastructure maintenance team to analyse the situation and decide on further actions, such as visual inspection to the site to confirm the occurrence, performing precise track geometry measurements with the dedicated inspection car, and schedule corrective intervention to restore adequate track geometry if needed. World-leading railway networks seem to have implemented similar approaches in recent years [13], thought using more expensive and dedicated systems. Moreover, the current approach has the potential to be implemented as a smartphone- and crowdsourced-based system, similar to those presented by other authors [22, 23], but to monitor the track geometry and assess its structural performance.

### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

### Disclosure

Part of the work was conducted in the framework of the TC202 National Committee of the Portuguese Geotechnical Society (SPG) "Transportation Geotechnics," in association with the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE-TC202).

### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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