



Smartphones and tablets applications in railways, ride comfort and track quality. Transition zones analysis

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ARTICLE INFO

Keywords:

Track transition zones
Passenger comfort
Vertical acceleration
Mobile devices
Smartphones
Ballast track
Slab track
Mobile application
Apps

ABSTRACT

Measurement process in railways is an expensive and difficult task which involves several steps. In some cases, costs can be reduced by using conventional devices such as smartphone and tablet applications. The following paper presents first a complete revision of the use of these devices in track measurements and secondly, it analyses the methodology to measure ride quality and track monitoring by simplifying it and making it more cost-effective. Accelerations were measured inside the train body in a simple and accessible way by using conventional smartphones apps. Results showed the feasibility to measure ride comfort, to study the track condition and locate singular points along the track. The proposed methodology tries to determine track monitoring and analyse passenger comfort by using these 'everyday' tools to take measurements in an easier, faster and cheapest way. The case studied showed that the acquired data in a track section can be used not only to model some important parameters of track performance but also to model riding comfort, which can help in the assessment of the track maintenance and ride quality. In addition, an alternative, new and simpler way of evaluating passenger riding comfort through vertical accelerations has been formulated, based on the current regulations and guidelines in Spain.

1. Introduction

When designing and planning railway infrastructures it is necessary to make them attractive to passengers. One of the main aspects that affect passengers' perceptions is their comfort. Several factors need to be considered when passenger comfort is analysed such as noise, temperature inside the car and even the smell inside the vehicle. However, in terms of infrastructure design engineering, the main factor affecting passengers' comfort is the vibration and acceleration of the vehicles [1,2]. Therefore, measurements of accelerations are going to be used in this study to assess passengers' comfort. It has been shown in previous studies that the cost of measuring and analysing recorded data in a conventional way can be reduced around a 30% at least when using methods that involves smartphones and tablets technology [3].

Frequently, the measurement process in railways is an expensive and difficult task which involves several steps and specialised works, complex fastening systems [4], and also contact and messenger wires could

be needed [5]. Sometimes, for some track elements it is conducted manually, which is laborious and error-prone [4]. This paper develops a good tool for a real-time geometric parameter measurement system and a methodology for track maintenance assessment.

The era of building new infrastructures is ending and nowadays, the maintenance of the existing civil infrastructures is becoming more relevant. Monitoring the existing infrastructures plays a key role in maintaining the safety and serviceability conditions as well as in mitigating any consequences due to ageing factors and in detecting possible structural failures [6].

Comfort and quality are directly related. They can be calculated with sophisticated methods and tools which have given really good results, for example ride comfort with vertical accelerometers [7,8], ballast geometry with a mounted laser scan on the vehicle [9], or track inspection [10,11]. These processes are time-consuming and expensive in most cases. The natural evolution has been to reduce cost and, in some cases, to change the data acquisition process by using smartphones [12].

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<https://doi.org/10.1016/j.measurement.2021.109644>

Received 25 January 2021; Received in revised form 22 April 2021; Accepted 21 May 2021

Available online 6 June 2021

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This has evolved to the possibility of performing the whole process of data acquisition, track quality assessment and vehicle comfort evaluation, with smartphone and their applications. Table 1 resume the most important works and findings related to these topics.

Mobile tools have been used for many purposes in addition to measure track quality and ride comfort. For example, they have been typically used to control transport schedule and timetables in real time and on board for users [13]. They are also used to measure congestion levels in railway stations [14] and other purposes consist on locate metro trains during underground operation to estimate location and speed [15].

Researchers have realised that comfort and safety are mutually related aspects [16]. In this sense it is interesting to develop an application and a procedure or methodology to join both perspectives and to monitor quality of the infrastructures.

Several studies have demonstrated the validity of the measurements taken with these devices by comparing accelerometers and smartphone

Table 1
Resume of smartphone applications to measure ride comfort and track quality.

Ride comfort	Field of study	Description of the research
Suzuki (1998) [1]	Railways	Evaluation of riding comfort in Japan.
Islam and Johnston (2013) [17]	Roads	Monitor Road Roughness.
George, Gadhia (2013) [18]	Railways	Investigate the discomfort of standing passengers.
Muñoz de Diego (2016) [19]	Railways	Develop a mobile application to register accelerations
Azzoug and Kaewunruen (2017) [20]	Railways	feasibility of the use of smartphones to measure vibration-based ride comfort on trains.
Lee and Parsuvanathan (2017) [21]	Bus	Measure ride quality comfort in buses.
Gómez Coma (2019) [3]	Railways	Analysis of riding comfort in track transitions.
Zhao, Nagayama (2019) [22]	Road	Road profile estimation method
Nunez, Popa (2018) [23]	Railways	Measuring ride comfort. The objective is to obtain track data to reach a cost-effective inspection and management to minimize maintenance interventions without time/cost inspection vehicles.
Cong, Gao (2020) [24]	Railways	Obtain vehicle running stability Spurling index (SI) and weighted acceleration index (WAI). Subway rail transit.
Tien Do, Haji Abdulrazzagh (2020) [25]	Railway	Ride quality assessment conducted on a VIA Rail route in the province of Ontario Canada.
Track quality	Field of study	Description of the research
Douangphachanh and Oneyama (2013) [26]	Roads	Estimate road roughness condition
Vittorio, Rosolino (2014) [27]	Roads	Monitoring road surface quality
Forslóf and Jones (2015) [28]	Roads	Determine the conditions of roads and the ride comfort associated with it.
Nunez, Popa (2018) [23]	Railway	Development of smart technology solutions for lower density railway lines. Low cost and efficient inspection.
Paixão, Fortunato (2019) [29]	Railways	Perform constant acceleration measurements inside in-service trains to complement the assessment of the structural performance and geometrical degradation of the tracks.
Wang, Cong (2019) [15]	Metro/ Railways	Proposition of a novel data fusion approach for speed estimation and location calibration of a metro train
Cong, Gao (2020) [24]	Railways	Obtain real-time data on vehicle acceleration, velocity, and location through the development of an application software

measurements of vertical accelerations [17,20,23,29]. Fig. 1 taken from [20] shows this comparison. Although this study does not focus on demonstrating its validity, it compares values of accelerations measured with smartphones and the ones captured by accelerometers employed in methodologies that are more traditional. Values recorded by both procedures show a good agreement as both have the same trend.

As previously said some studies have been focused on measuring vertical accelerations on roads using smart devices. Other authors in 2013 monitor the quality of the road by means of mobile devices, they establish a linear relationship between the accelerations captured by the device accelerometer and the road potholes [27]. This last work was based on the creation of an algorithm that detected irregularities on the road through the collected data, namely the vertical accelerations measured in the vehicle. Therefore, these preliminary studies shed light on the use of this type of apparatus for the measurement of vertical accelerations.

Douangphachanh and Oneyama (2013) [26] investigated the connection between the accelerations collected via a smartphone (using a GPS to record the position of the vehicle) and the state of the road. In their study they analysed the data in the frequency domain and concluded that mobile sensors have a great potential to estimate the state of the pavement.

In relation to studies of passengers' quality perception, the suffered vertical accelerations are most of the times not considered. A study carried out to measure the influence of vibrations on the train on the activities that passengers most like to do on their journeys (reading and writing), showed that a frequency close to 4 Hz was the maximum bearable one when working on a table [30]. However, the previous value depends on the person's posture, as well as on the specific activity. In addition, when passengers read or write on their lap, the average bearable frequency, drops to 2.5 Hz. The study concludes that an improvement on the design of the track, as well as on the furniture of the car, can have an impact on the comfort of the traveller [30]. Sundström and Khan (2008) research showed that person's posture is a key factor when studying their comfort [31]. In addition to that, in other cases, the quality of the service or the degree of comfort is determined as a function of the temperature perceived by the passenger, the comfort of the seat and the ease of rest, which includes the vibrations experienced [32]. Not only the track structure, but the train itself, can generate motion sickness and riding discomfort, tilting trains, for example [2].

Current regulations indicate several aspects that need to be considered when analysing the layout of a railway track such as, chosen materials and transition zones. The final beneficiary of the infrastructure, the passenger, is not considered in most projects. However, it is necessary to make the new infrastructures attractive to passengers when designing and planning them. As presented before, their comfort is one important variable and from the engineering point of view it is affected by the vibrations and accelerations suffered [1].

The economic importance that lies in the fact of saving costs in the measurement campaign, and the attempt to simplify the process of obtaining the riding comfort have motivated the present study where mobile devices are used to take measurements of vertical accelerations instead of accelerometers installed in vehicles.

In this work, the comfort of passengers is analysed in terms of movement and acceleration of the vehicles. For this reason, a quantitative analysis is carried out in a particular area. Precisely, vertical accelerations are measured in the passenger's car in a transition zone. A transition zone has been chosen as they are one of the most compromised points of the track and they are usually the ones that deteriorates the most [33]. The chosen section is a tunnel access and exit zone where the track changes from a ballasted structure to a slab structure and vice versa.

Vertical accelerations are measured in a fast, cheap, easy, comfortable, and precise way; using an easy to acquire tool (i.e., a mobile device and one application or app). The great advantage of this methodology is that it is a simple and economical alternative. These measurements will

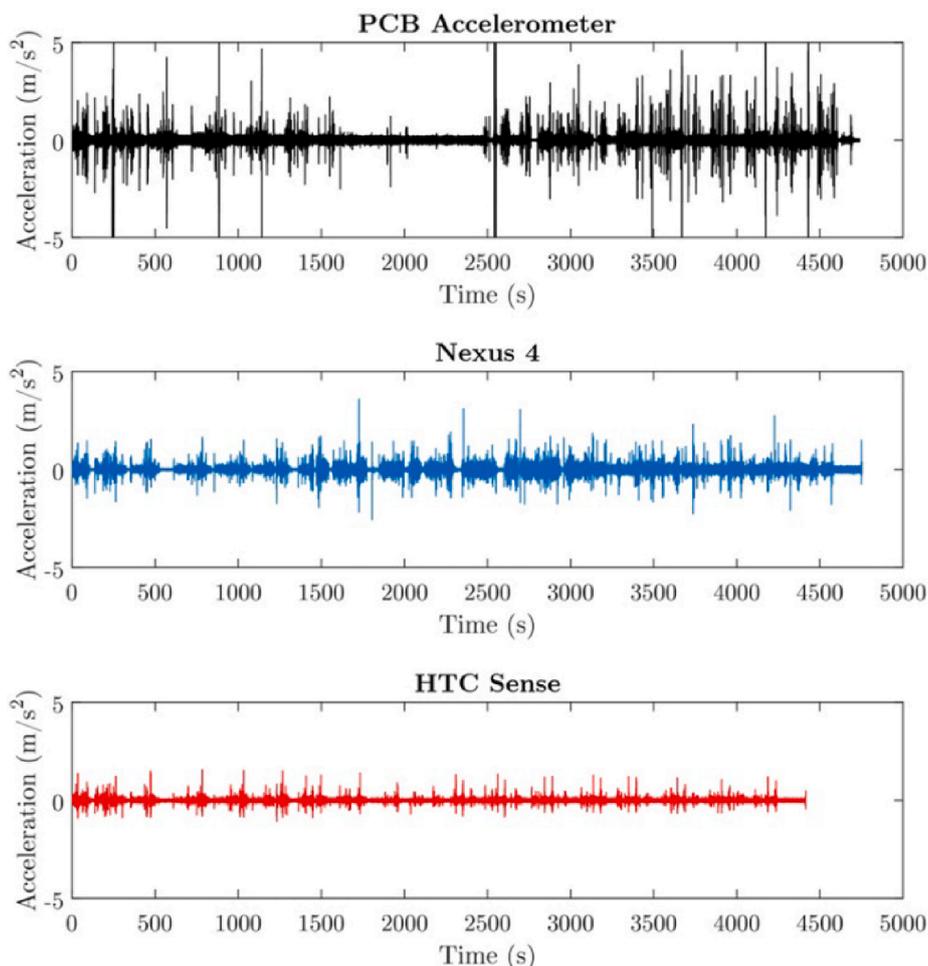


Fig. 1. Comparisons between vertical accelerations with accelerometers and smartphone devices [20].

be as well employed to carry out a preliminary analysis of the infrastructure condition without the need to use sophisticated technology or measuring equipment with the cost that this entails. Along this line, the work performed has allowed to propose an alternative way of evaluating track quality through vertical accelerations, based on the regulations currently used in Spain, such as UNE EN 12299 [34]. Additionally, the possibility of measuring the evolution of the deterioration of the track through successive comparisons of vertical accelerations measured in the railway vehicle separated by a certain interval of time between them has been studied.

The article is structured as follows. This section reviewed the feasibility for the use of mobile applications to measure vertical accelerations, followed with the description of the motivation of the study. Section 2 describes the area of study where the measures are taken. The next section shows where and how authors obtained experimental measurements. The results obtained with all data analysis and discussion are explained in Section 4. Authors provide a methodology to monitor the track quality, to calculate passenger comfort and propose a new methodology to obtain it. Section 5 presents a discussion of the methodology, review the most important findings of this analysis and it gives possible solutions to mitigate high vertical accelerations in the area of study. Finally, the key conclusions are extracted and new lines for future work are presented in Section 6.

2. Area of study

The area of study is one that presents a railway track discontinuity, namely transition zone. The chosen section is the tunnel entrance and

exit zones where the track changes from a ballasted structure to a slab structure. The location was chosen because a) it is a transition zone and therefore it is a good example where there is different track stiffness in a narrow gauge network (called metric gauge in the north of Spain); b) It is in an area which provides several track discontinuities in a short time and space interval; c) The railway line has a high traffic intensity all days of the week, as commuter trains goes at a rate of 30 min from 6:30am to 10:00 pm every day. This makes it easier to perform on board measurements, and the last and most important factor is d) the loss of comfort experienced by passengers in this area.

The length of the section is 645 m and consists of 200 m of traditional ballast track (sleepers spacing 0.6 m) before the entrance to the tunnel, 245 m on slab track along the tunnel and 200 m of ballasted track at the tunnel exit, as presented in Fig. 2. The changes from ballast to slab track are solved with the Stedef system (slab track). Its description is out of the scope of the paper but details about it can be found in [35,36,39].

The commuter train is a self-propelled unit consisting of 4 bogies. Vertical accelerations were measured in several points on the vehicle in order to characterize the front bogie, the centre bogie and the rear bogie. This issue is deeply explained in the next section. The study was developed in different trains of the same railway operator as shown in Fig. 3. Three different series of trains (from series 3600 to 3800) serve this railway line.

3. Experimental measurements

According to UNE-EN 12299 [34], accelerations at one point on the vehicle depend on its location. For this reason, measurements must be

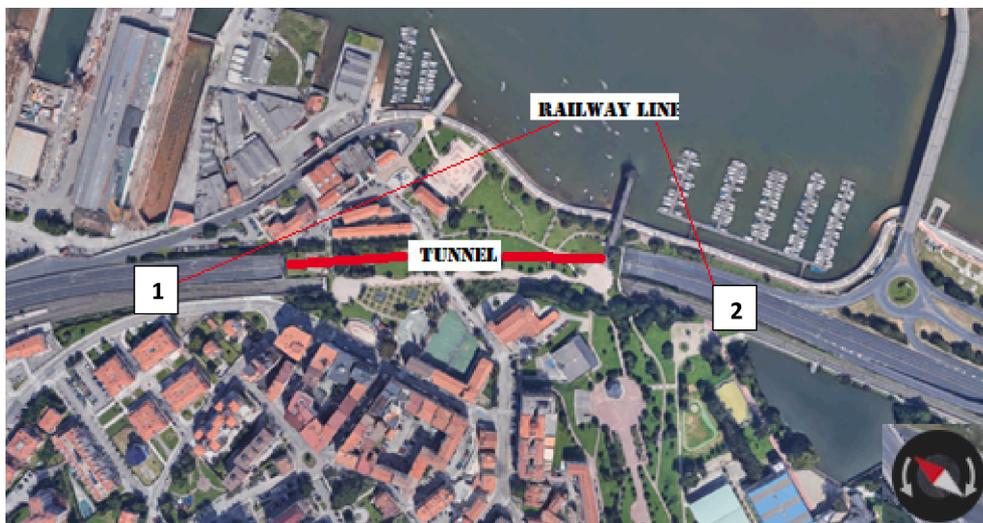


Fig. 2. Track section analysed (from 1 to 2). The track section consists of is 200 m long before the tunnel, the tunnel itself and 200 m after the tunnel.



Fig. 3. Trains of the study.

carried out, at least at the centre and at the ends of the vehicle. It also specifies that the accelerometers should be placed under the seats closest to these positions as shown in Fig. 4.

The element where the recording device is placed plays an important role [34]. To minimize its effect and have measured data as real as

possible, it is placed directly on the floor by using a two-side adhesive, easy to place and easy to remove. Fig. 4 shows the exact locations of the three points where measures were taken. These are in middle, forward, and rear bogie just stacked to the bottom and placed facing up to be able to see the measurements during the recording time.

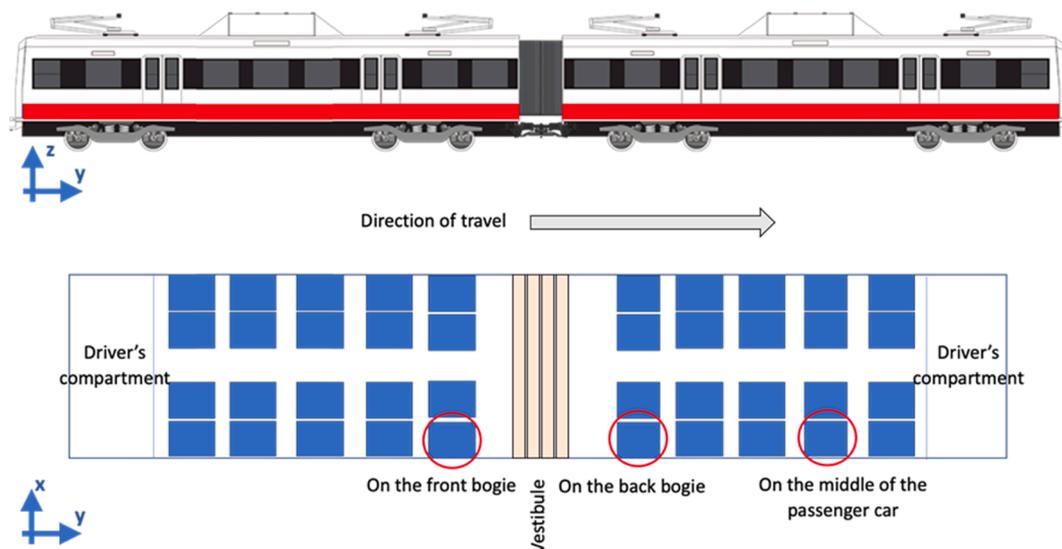


Fig. 4. Measuring points and location according to UNE-EN 12299 [34] (left). Vehicle scheme and measuring points (right).

The device employed to measure the accelerations is a tablet, in particular a Galaxy Tab 3 Lite T113 by Samsung (Fig. 5) equipped with a Bosch Sensortec accelerometer. Its built-in accelerometer has a measurement range of $\pm 19.62.m/s^2$ (approximately $\pm 2 g$), with an accuracy of $0,1 .m/s^2$, and can make up to 400 measurements per second. However, the refresh rate of the chosen app is just 30 measurements per second.

Measurements taken in this study are around 75% of the full-range of the sensors used. Three identical tablets were used with the same hardware and software to minimize discrepancies between measurements. In addition, their time was synchronized at the beginning of the journey to have the same reference and the accelerometers were calibrated afterwards. The measurements taken in the automotive passenger vehicle were mainly vertical accelerations, although accelerations on the other two axes were also recorded and used in this study.

4. Data analysis. Track quality and passenger comfort

This research proposes a methodology to obtain rail track parameters and passenger comfort in a continuous track monitoring by using mobile technology.

In order to monitor and control riding comfort, guidelines regarding this issue are needed [34] (in relation to passenger comfort). Thanks to this initial premise to control riding comfort going further then it is possible to see how the track evolves and if this evolution is under or over certain limits given by the current norms and regulations.

Fig. 6 tries to picture the overall proposed methodology. Thanks to the easy process to obtain the track data the methodology is simple. First of all, it is necessary to obtain initial track measurements to have an initial data to compare. This initial stage should be analysed with the current guidelines in track quality and passenger riding comfort to see if it is acceptable or not, and corrections should be proposed. When no corrections are needed a second measurement campaign should be performed and results will be compared with the first one to see the differences and stablish it acceptable condition or propose corrective measures. This process will be repeated until the renewal of the track is due.

Following this methodology is possible to check the track quality and passenger comfort at the same time with easy procedures at low cost, which is the main objective of this research.

This section firstly shows how mobile technology can be used to estimate the track quality, differentiate, and monitor the performance of the track superstructure elements such as track transitions, tunnels, bridges, switches, and crossings in a railway line; and secondly, how to measure passenger comfort.

4.1. Track elements

The track section in Fig. 7 (left) shows the track section where measurements were taken. Fig. 7 (right) shows the vertical acceleration recorded in the front, rear and middle bogies. Several discontinuities in

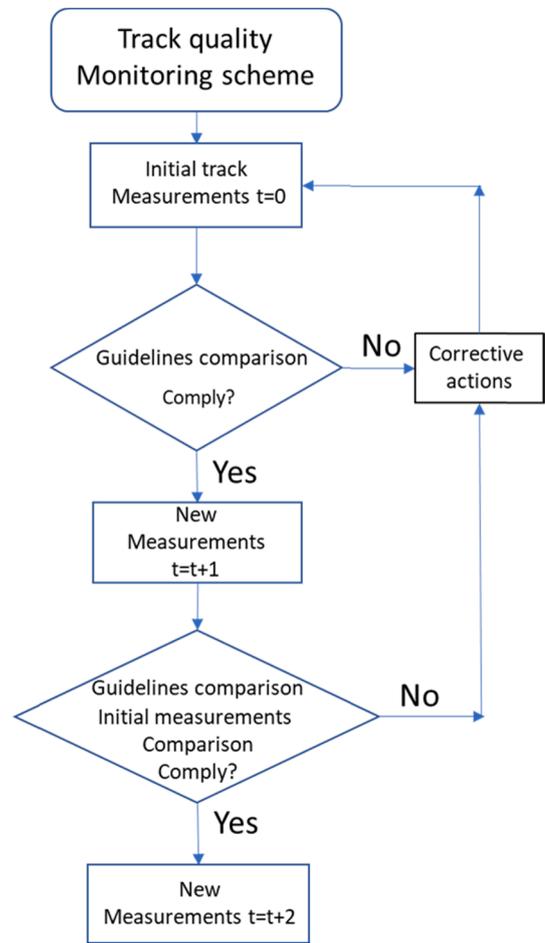


Fig. 6. Proposed methodology for track continuous monitoring with mobile tools.

the vertical acceleration signal are noticeable and they correspond to different structures and discontinuities on the track. The entrance and exit to the tunnel coincide with changes in the track structure (track transition zones) points D and E. These points present high acceleration values, but they are not the only ones. The amplitude of the wave is also high between points A and B where there is a metal bridge and the track changes from being ballasted to a track over a metal bridge. The other point where the magnitude of accelerations is high is point C where there is a fish plate, the last part of a switch. By analysing the wavelength of the signal, the distance between track elements and sleepers spacing can be analysed [37]. Finally, the lower values between C and D corresponds to a station, the train stops but vibration remains.

The opposite direction gives the same results in terms of track discontinuities. These measurements can be taken over one rail or the other

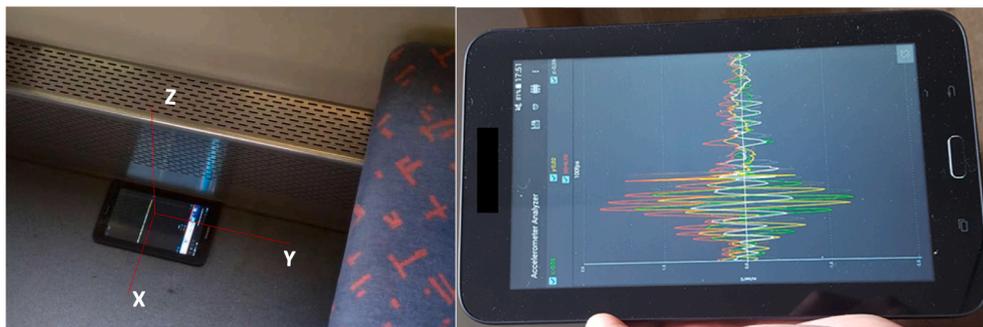


Fig. 5. Tool device used in measurements from train body. Location (left), device (right).

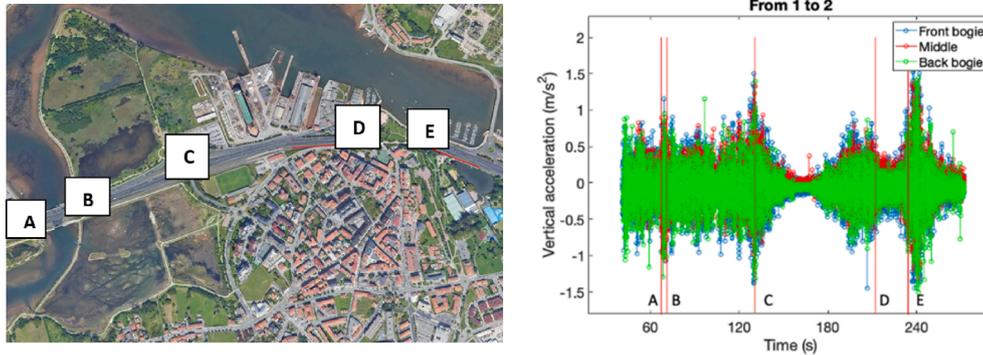


Fig. 7. Track discontinuities during measurements in the body of the vehicle. AB shows a small steel bridge, point C a fish plate (the last part of a switch), points D and E shows the entrance and exit of a slab track tunnel. Red lines show the analysed section to measure passenger comfort. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

or in the track longitudinal axe, if the tablet is placed in the middle of the vehicle body. The only limitation is that measurements must be taken with the same reference from the track and the same place in the vehicle. For example, if we make measures over the left rail in one direction must keep this position for the next measurements.

Therefore, looking closely to the measured values not only the transition zone can be identified, but also different discontinuities and structures on the track line (from A to E). This shows that, recording data with these devices might help to locate and obtain an initial order of magnitude of the most conflictive points of the track layout.

Vertical accelerations measured just on the tunnel area in the front, rear and middle bogies are presented in Fig. 8, where each graph correspond to one train travel direction. Comparing the different measurements points within the car, the front, rear and middle bogie it is easy to see that their trend is similar and there are no big differences between them. Thus, the first axle of the bogie (in the direction of movement) has been chosen as the representative one and the data recorded just by this accelerometer is presented in Fig. 9, for the shake of simplicity and to clarify visually the results.

Measured accelerations in both train-running directions are presented. In both cases, the areas of transition zones are the ones that shows higher acceleration amplitudes. However, they show higher values when the train runs from slab track to ballasted track, around point 2 in the first train running direction and point 1 in the opposite direction. This is in line with previous studies wherein the behaviour of transition zones depends on the train running direction [40–42]. In this case, amplitudes are even 50% higher when train goes from slab to blast

track than vice versa. As expected, vertical acceleration amplitudes are almost double in the transition’s zones than in the central part corresponding to slab track inside the tunnel.

4.2. Comfort estimation using mobile devices

According to the UNE EN-12299 standard guidelines, the comfort of the journey is a complex sensation produced by the movements of the body of the railway vehicle. This feeling can be assessed by means of the perceived comfort level, which is defined as Medium Comfort and it is expressed by means of a comfort index NMV (Mean Comfort) [34]. The comfort index considers the accelerations in the three axes (x, y, z). However, it is also possible to calculate a comfort index only for each direction (NMVx, NMVy and NMVz). The procedure used is the so-called Normal method [34]. This method considers the vibration on the floor of the vehicle body. Therefore, it is the most suitable for this study. In addition, the Continuous Comfort of the passengers on the vertical axle: CCz has also been evaluated. According to the standard, Continuous Comfort is the set of quadratic-average values of accelerations in the three directions during an interval of 5 s.

4.2.1. Continuous comfort

The standard summarizes in six points the steps leading to the calculation of Measured Comfort and Continuous Comfort from taking acceleration measurements, the application of signal filters, frequency analysis and calculations of mean values for intervals necessities to obtain the required values.

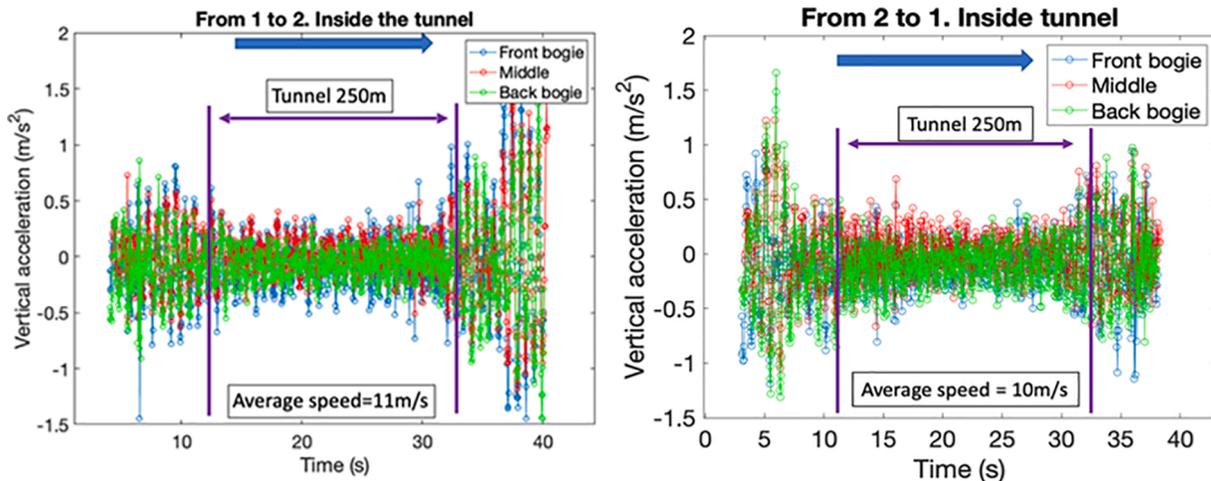


Fig. 8. Measured vertical accelerations in both train directions; left) from point 1 to point 2 right) from point 2 to point 1 of the (Fig. 2). Measures were made at the front at the middle and the rear of the vehicle.

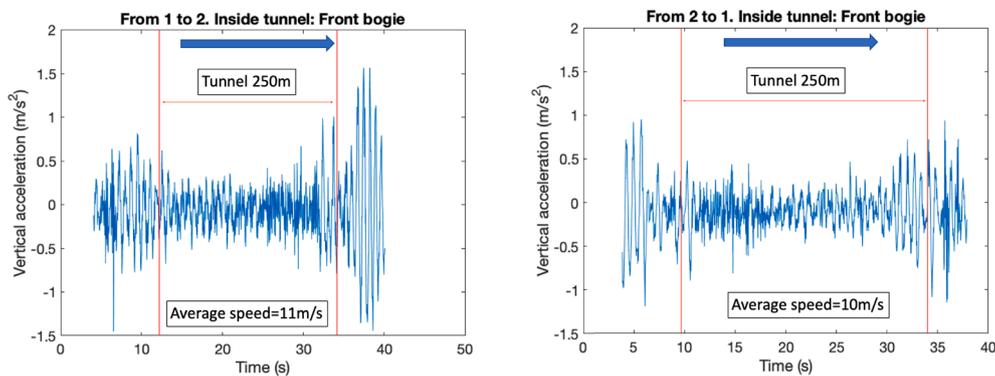


Fig. 9. Front bogie recorded vertical accelerations.

- (1) Measurement of the accelerations on the ground of the vehicle.
- (2) Digitization of these and application of an appropriate anti-step filter.
- (3) Frequency weighting of signals.
- (4) Calculation of the quadratic mean values every 5 s (hence continuous comfort).
- (5) Calculation of the 95th percentile over each 5-minute time interval.
- (6) Calculation of the average comfort index (NMV). An index is obtained for the area of the train where the measurement has been carried out. Used in the next section for the medium comfort.

Usually, the accelerations must be recorded for at least 5 min in order to correctly assess the Mean Comfort. However, due to the orography and the disposition of the stops along the route, it is hard finding 5-minute spans with constant speed. Thus, the area selected for this study is a track section of about 400 m long (Fig. 2), where trains run at low velocities (around 10 m/s). This means that the passage of each train lasts around 40 s. Since standards stipulate that train speed should be constant, only those records where the speed of the train was between 10 and 11 m/s have been considered. More details related to the calculation of comfort in passenger trains can be found in [35].

Fig. 10 shows the graphs for Continuous Comfort obtained from measurements for each axle during the outward journey. It corresponds to the tunnel section from C to D in Fig. 7. Fig. 8 and Fig. 9 shows, with a sampling interval of 5-seconds, the evolution of the vertical accelerations as registered by the devices located in the 3 previously defined positions on the train, while it passes through the tunnel in the area of study. As a general rule, the most unfavourable comfort data are seen in the first section (Area 1 Fig. 2). This is probably due to the existence of the final part of the transition area in this section. Another unfavourable section is C (Fig. 7), which generally shows high values in all measurements. At this point the train starts braking at the station. This track section has some turnouts.

The UNE 12299 [34] standard offers a scale (Table 2) to evaluate the comfort in the z-axis and in the y axis. This scale is based on experience and its values do not fully correspond to the NMV comfort index.

4.2.2. Medium comfort

In addition to Continuous Comfort, as indicated above, Medium Comfort has been evaluated. Table 3 contains the scale provided by the standard to establish the comfort index. For this work, a scale of colours has been set depending on the comfort as can also be seen in Table 3.

Table 4 below shows the comfort indexes obtained using the acceleration measured for each direction, as well as the global one. The methodology employed to obtain Table 4 is taken from [34] as well. However, there are some differences as for the calculations to obtain continuous comfort explained in 4.2.1. The steps are the same as the

ones presented before.

The results obtained show high levels of no comfort, especially on the x-axis. Conversely, the lowest indices are on the z-axis. In terms of the overall index, the path can mostly be considered as “very uncomfortable” for all the bogies in the car. The results that affect the most the final value are those obtained by the accelerations on the x-axis, while the z-axis of vertical accelerations shows the best measures of comfort for users. Although the tunnel appears to be a straight line, it has a slight curvature which is likely to affect the results obtained in terms of comfort.

4.3. New comfort calculation approach

As it has been shown in the previous section, obtaining the comfort index is not something that can be obtained quickly and easily. The latest version of the UNE EN-12299 standard [34] has introduced some small changes to calculate this index. It was made in accordance with the 12299-00 but the process has not been simplified. As the procedure described in the regulations is time consuming, a potential simplification by an approximation has been performed with the recorded data. This has been done with the aim of creating an easily programmable method applicable to all acceleration records in a quick way.

To set the boundaries (maximum acceleration limits) in Fig. 11 at 0.40 m/s^2 (following the Spanish guidelines [34]) the NMV index (shown in Table 3) has been utilized. As already mentioned, there is not a full correspondence between this value and the one provided by the Spanish regulation UNE 12299:2009 (shown in Table 4). Using the NMV index and working with the measurements taken, three areas on the recorded data have been differentiated. They have been limited by the defined average comfort value (0.40 m/s^2), positive and negative, and also by the maximum obtained values, positive and negative. This division is presented in Fig. 11, where two horizontal lines for the maximum and minimum recorded accelerations are also drawn.

This procedure was applied for the studied section in both train running directions, and for the three positions of the train for which data were available. Then, if we look at Table 5, there are five numeric columns. The first corresponds to the comfort index calculated in the previous section (on the basis of the standard), the three following the resulting areas (upper, lower and intermediate area) and, finally, the fifth column is the proposed new index. The way of calculating it is as it appears in the table, adding the upper and lower areas and dividing that result by the middle area. In this way, it is intended to establish a relationship between the data of the curve that escapes from the mean comfort and those that do not. The proposed formula for the New Comfort index (NCI) is presented next:

$$NCI = (A_{up} + A_{low}) / A_{mid} \quad (1)$$

It should be noted that, as indicated, the reference value of the mean comfort (0.40 m/s^2) is not a value that fully corresponds to the comfort

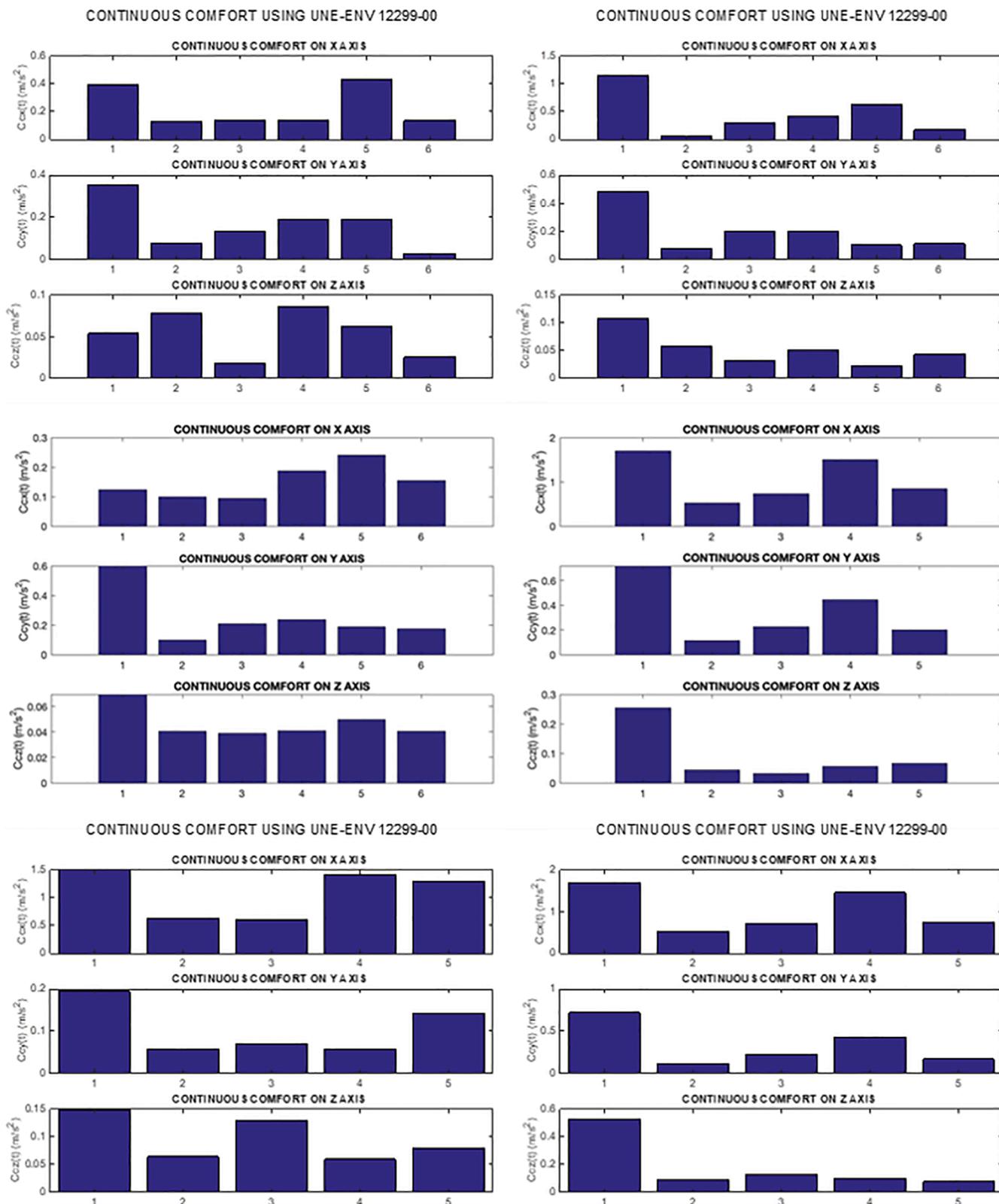


Fig. 10. Continuous comfort calculation according to [31] in the evaluated track section (red line Fig. 8). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

index calculated with the standard but is based on experience. This may therefore explain why there is no reciprocity between the comfort index of the standard and the calculated comfort index.

By looking at Table 4 it can be seen that values taken from the front and back bogies give the same comfortability level in correspondence

with comfort levels of Table 2.

On the other hand, it is also important to mention that, if this method is to be applied in the future to other types of work, it would be indispensable to define the space of time between records, as this has a direct impact on the area of the curve.

Table 2
Comfort scale from indexes Ccy y Ccz from UNE 12299: 1999 [34]

UNE 12299 INDEX	Comfort level
$Ccy(t), Ccz < 0,20 \text{ m/s}^2$	Very comfortable (VC)
$0,20 \text{ m/s}^2 \leq Ccy(t), Ccz < 0,30 \text{ m/s}^2$	Comfortable (C)
$0,30 \text{ m/s}^2 \leq Ccy(t), Ccz < 0,40 \text{ m/s}^2$	Neutral (N)
$0,40 \text{ m/s}^2 \leq Ccy(t), Ccz$	Less comfortable (LC)

As this work focuses on the study of transition zones, and those at the entrance and exit of a tunnel, the on-site data time span is short as it does not even reach the minute. Therefore, no major conclusions can be drawn about this methodology for calculating the vertical comfort inside the train within these areas of the railway track.

4.4. Track quality

Smartphones have been used for multitude of applications. Some authors used them to support other analysis such as congestion levels of people in stations [14], control speed and train position in metro lines [15] or give real time arrivals [13] and as it was previously said to measure ride comfort. Other authors in [29] have checked mobile technology for track inspection with satisfactory results.

There is another possible application to this vertical acceleration measurement by using this technology. Vertical accelerations can also help to monitor the track status comparing the current situation with measures taken at different times in the future of the same area. This signal comparison can provide an idea of the wear of these zones. This can be done by filtering the signal or just comparing the raw signals with the original one. By using maximum values or obtaining a deviation of all measurements along the observed track line. The general idea is presented in Fig. 12.

Fig. 6 shows how this methodology can be useful when monitoring track elements or track quality. Railways infrastructure administrators can make quick decisions based on data acquired by mobile phones. In

Table 3
Comfort scale index according to [34].

N_{MV} VALUES ACCORDING TO [34]	COMFORT LEVEL	SYMBOL
$N_{MV} < 1$	Very comfortable	(VC)
$1 \leq N_{MV} < 2$	Comfortable	(C)
$2 \leq N_{MV} < 4$	Neither comfortable non-uncomfortable	(N)
$4 \leq N_{MV} < 5$	Uncomfortable	(U)
$N_{MV} \geq 5$	Very uncomfortable	(VU)

Table 4
Comfort indexes regarding train direction and position in the vehicle body.

Direction of travel	Train place	N_{MVx}	N_{MVy}	N_{MVz}	N_{MV}
From 1 to 2	Front bogie	3,4	2,1	0,5	4
	Middle	3,2	3,6	0,5	5,0
	Back bogie	6,9	2,9	0,6	7,4
From 2 to 1	Front bogie	7,6	1,7	1,6	7,9
	Middle	10,2	4,3	1,5	11,2
	Back bogie	9	1,2	0,9	9,1

order to show the proposed methodology Fig. 12 shows a section (not real) along the track with different measurements in different periods of time. The difference between them could help us to understand track behaviour. It is usual to establish a track intervention threshold to preserve riding comfort [38].

For example, looking at Fig. 12, the black line is the first measured signal (the initial measurements o base measurement, in the first month). By making the same measurements in a n month later the orange signal is obtained, this corresponds to the second measurement, taken one n month later and the green signal was obtained in month n + 1. These signals should be analysed as it is, obtained from the

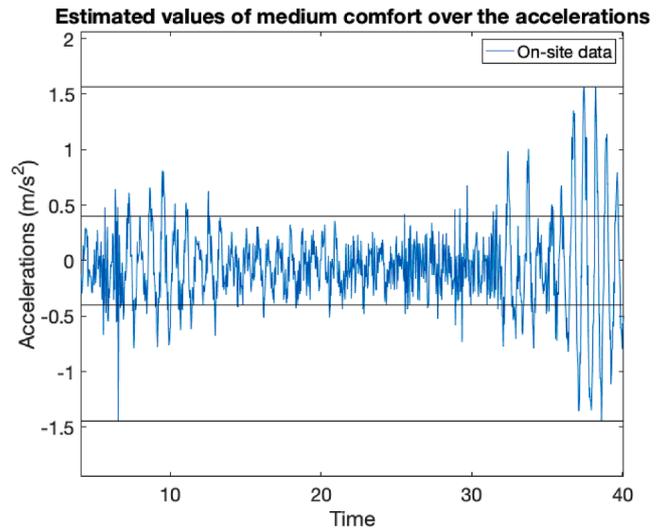


Fig. 11. Estimated values of comfort mean over the initial graph of mean of measured accelerations taken from the train. Defined areas for one and the other direction (small values defined by UNE 12,99 INDEX: highest values directly taken from measurements).

Table 5
Comparison of the new comfort rates together with the previous for each travel direction and location of the tablet in the train body.

Direction of travel	Train place	N_{MVz}	A_{up}	A_{low}	A_{mid}	Equation (1)
From 1 to 2	Front bogie	0,5	1,1279 $\times 10^{-5}$	1,2583 $\times 10^{-5}$	8,5941 $\times 10^{-5}$	0,2777
	Middle	0,5	8,9357 $\times 10^{-6}$	7,2922 $\times 10^{-6}$	7,3163 $\times 10^{-5}$	0,2304
	Back bogie	0,6	6,0362 $\times 10^{-6}$	9,5736 $\times 10^{-6}$	7,5055 $\times 10^{-5}$	0,2080
From 2 to 1	Front bogie	1,6	6,9230 $\times 10^{-5}$	7,8107 $\times 10^{-5}$	1,1970 $\times 10^{-4}$	1,2309
	Middle	1,5	5,1988 $\times 10^{-6}$	3,7562 $\times 10^{-6}$	7,3268 $\times 10^{-5}$	0,1222
	Back bogie	0,9	1,2547 $\times 10^{-5}$	1,7822 $\times 10^{-5}$	7,4482 $\times 10^{-5}$	0,408

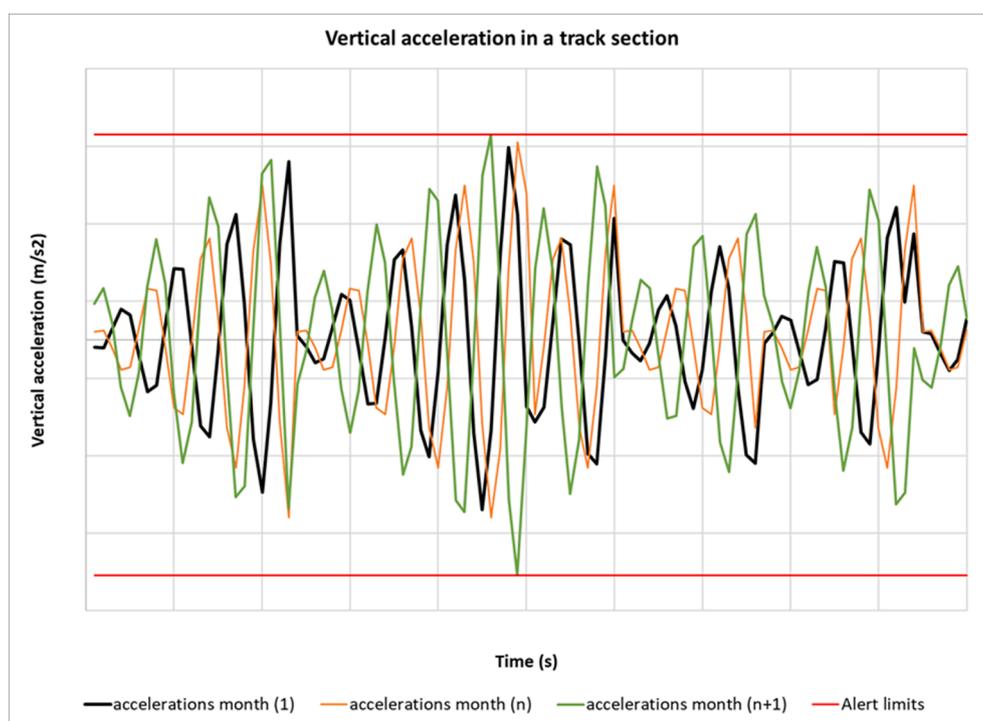


Fig. 12. Scheme of the methodology to monitor track quality during time with mobile devices.

accelerometer, without applying any filter, which would remove valuable information. Maximum values can be located in the figure (alert limits, horizontal red lines) and railway infrastructure managers can establish limits or thresholds for the difference between both signals that would trigger the need of maintenance of that section.

Authors are working to establish a threshold between signals measurement to achieve better results. Authors consider that to have good results, it is desirable to obtain at least measurements within three periods separated enough in time, (desirable between one and three months with enough time between them). This methodology will be helpful to the railroad industry, especially for railway infrastructure administrators, and railway construction companies in order to get fast measures during track construction, maintenance and renewal operations.

5. Discussion. Limitations

The analysis carried out in this paper shows a lot of benefits of the

proposed methodology. It has been probed that it is feasible to obtain measurements in real time during conventional passengers or freight trains travel. Railway engineers can get a lot of data thanks to the rapid deployment of these conventional tools. The data is obtained in an easy and economical way. Savings of more than 30% have been estimated [3].

Users only need a smartphone or tablet with a built-in accelerometer accurate enough to provide consistent measures which can help by a fast, convenient and accessible procedure to discover comfort problems, as well as, detecting other problems or defects on the track. It has to be understood that this methodology does not try to compete with conventional measurements (measurement device on board or measurement device installed on the track). This methodology wants to complement it by making continuous monitoring and help to detect a possible track problem which should be analysed in depth by using more accurate technology. In other words, this methodology wants to give a first approach to locate problematic points along the track. The evolution of a track section can be compared with the punctual measurements

over time.

It is also possible to extrapolate results from real accelerations measured in situ with those obtained in numerical simulations. This allows to forecast and study other track or vehicle parameters without the need of making many measurements, such as vertical displacements and vertical stresses providing additional cost savings. The authors' investigation in this field is ongoing, aiming to define the boundaries of this technology and to provide tools to help with predictive maintenance.

It is also important to remark the limitations that have been noticed during this experimental test: It is essential to measure at the same position inside the vehicle and with the same orientation since, depending on the area of the vehicle, they can vary considerably (closer to the bogies or the vehicle extremes). The mobile device must be well placed, and it cannot move during the data acquisition (additional adhesive materials are necessary to fixed it to the vehicle floor). It is better to fix the device from above in order to place it directly in the coach floor. Authors realised that soft layer between the device and the train floor can attenuate and dump the original signal.

It should be taken in consideration that the real mobile system of the vehicle can suffer variations. Its springs and dumping system can vary over time suffering deterioration and looseness, which can distort the measurements. To solve this problem, it is necessary to decompose the wave obtained in the measurements taken from inside the vehicle, making measurements from axle box of the train and performing more comparisons to distinguish between signals and noise. This is proposed as a line of future work. Detailed and specific monitoring such as fastening losing or sleeper cracking cannot be tracked by using this technology yet. There are technologies which go further. For example, using distributed and discrete fibber optic sensors to evaluate determined behaviours of specific concrete structures, which is described in [43]. The proposed methodology will complement this by detecting problematic areas instead.

Authors think that mobile technology can help in a lot of areas of infrastructure engineering. In particular in railways it can help: (1) to define by signal classification all track elements and railway structures (tunnels, bridges, viaducts, track transitions, etc...), (2) to measure ride quality comfort and (3) to measure rail track quality (Fig. 13).

The major contributions of this research are the development of a new methodology for continuous track monitoring analysis and track inspection together with the proposition of a simpler and novel way to estimate riding comfort.

In relation to ride comfort this study analyses it in a railway track section from Spanish metric gauge according to the Spanish standards [34,36] not only in one direction but in both travel directions. In order to do this, this analysis uses tablet devices instead of smartphones and proposes a new way of evaluating the riding comfort easier and simpler. In relation to the track quality, this study presents a new methodology for a continuous track monitoring analysis and track inspection from the data obtained is taken at different points on the coach floor. It introduces new extra locations for the smart devices which, in other works, are usually located in one position. The placement of the device is different as well because to reduce noise during data acquisition the smart device

is directly posed over the coach floor glued to the floor.

The data acquired allows to identified punctual structures such as steel bridges, rail turnouts, track transition and railway tunnel just analysing the vertical acceleration signal. The special case of track transitions problems in the vicinity of a tunnel were analysed.

The methodology is based on the estimation of track quality directly by comparison without filtering or using specific signal filtering, the comparison is made with the original signal from smartphone accelerometers. The track quality estimation is directly made by comparison between the last and the previous data acquired.

6. Conclusions and further research

This study presents the use of mobile applications to assess the quality and comfort of a railway section track (narrow gauge) in northern Spain. This methodology is based on collecting the acceleration data measured by the accelerometers incorporated in most of the commercial mobile devices nowadays (smartphones, tablets, etc.). The aim of this study is to analyse the methodological feasibility and establish a starting point for the evaluation of track quality and riding comfort following and easy, fast, and cheap procedure.

A complete state of the art for smartphone applications to measure riding comfort and track quality has been performed and it has shown that it is possible to use this devices to get data in a simpler and more cost effective way After carrying out this work, it can be stated that if the conditions, devices and the place of measurement are controlled (i.e. same train, same apparatus, same position, same analysed section, no device movements) it is possible (1) To locate specific points areas in track structures, bridges, tunnels, and track transition zones (which need to be monitored). (2) To measure the passenger riding comfort conditions inside the vehicle in a quick, comfortable, and simple way with the new methodology proposed and 3) to measure track quality by using these common devices

This data acquisition can be modelled in order to see and predict track wear and their evolution with circulations. By performing continuous measures with in-vehicle devices to monitor the infrastructure allowing to establish the evolution of the quality of a track section over time.

The methodology proposed give reasonably good values (in line with those from the guidelines), therefore it seems feasible and reduces the costs of the actual ones.

The study also has corroborated with the measurements obtained that the behaviour at the entrance and exit of the tunnel is not symmetrical, thus demonstrating existing theories on behaviour in these areas [40–42]. In this case the accelerations at the entrance from 1 to 2 give higher values close to 1.5 m/s^2 while if train goes from 2 to 1 in the opposite travel direction the measured values go from 1 to 1.2 m/s^2 .

This work has showed the potential of using these conventional devices to calculate riding comfort with enough accuracy and perform the monitoring of the track which could be very helpful in the railway's maintenance in the future. All the studies have been developed between 2019 and 2020 so the way for using this technology is really novel. This analysis demonstrates that the process can be improved and simplified,

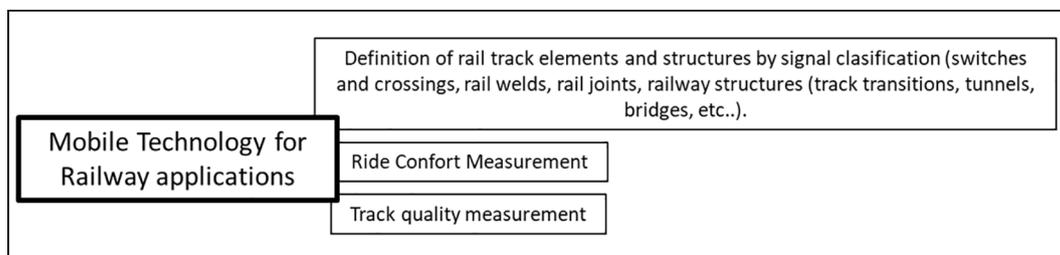


Fig. 13. Mobile technology proposed for railway applications scheme.

and it can be integrated in the own device. However, a further analysis needs to be performed before it can be fully developed and used in the day to day infrastructure life. In this line, a future line of work would be to carry out this separation of the raw signal and see how the imperfections of the track can be studied through measurements with mobile devices in a fast, economic, and precise enough to be useful way.

It is necessary to establish a link between ride comfort index and the evaluation of track quality by a continuous monitoring using these devices (smartphones and tablets).

Further work with longer time intervals will be needed. Analysis the influence of different spacings between sleepers is another use for this methodology that authors are exploring nowadays by applying it to its previous and current research [37].

CRedit authorship contribution statement

Andrés Rodríguez: Methodology, Investigation, Data curation. **Roberto Sañudo:** Funding acquisition, Conceptualization, Supervision. **Marina Miranda:** Writing - review & editing, Supervision. **Ana Gómez:** Investigation, Software, Formal analysis, Data curation. **Juan Benavente:** Resources, Investigation, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Authors would like to thanks to the Spanish Ministry of Science, Innovation and Universities, (Call for Grants 2018, RETOS INVESTIGACION) for its support with the project reference RTI2018-096809-J-I00 within the Spanish Grants of Research Development and Innovation oriented to Challenges for Society (Young Researchers, JIN Type).

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