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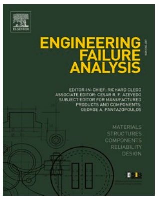

Railway track support condition assessment — Methodology validation using numerical simulations

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ABSTRACT

A novel methodology to evaluate railway track support conditions is currently being developed. This methodology is based on modal analysis of the multi-element system composed by the railway infrastructure and an instrumented railway vehicle. It belongs to the group of vibration-based structural damage identification methods and is focused on observing the characteristic frequencies of this multi-element system, which can be related with changes in the physical properties of the railway infrastructure. As opposed to other vehicle-based track monitoring methods, the proposed methodology should enable condition assessment of the railway infrastructure subgrade, an element that is often neglected during railway monitoring operations. Since this methodology is vehicle-based, it can be used to assess the entire extension of a railway infrastructure to gather data regarding the support conditions of the track. It can also assess the evolution of track support conditions over time by comparing different rides over the same railway stretch. An important aspect of this methodology that still lacks validation is the topic of characterizing track support conditions of a railway infrastructure through its natural frequencies. The suitability of the theoretical model behind this methodology is another aspect that needs to be assessed. Numerical simulations tests using the multibody simulation software Simpack® are currently being performed to address both topics. This paper describes some of the simulations performed in this context, including a description of the numerical models used. The obtained results support the selected theoretical model and the overall validity of the proposed methodology.

1. Introduction

The railway sector is an important part of modern society, even more so due to the current general concerns regarding climate changes. Nowadays, most modern and developing countries still spend considerable resources in creating new railway infrastructures, and on maintaining and modernizing their old railway networks. As part of the maintenance efforts, the assessment of railway track

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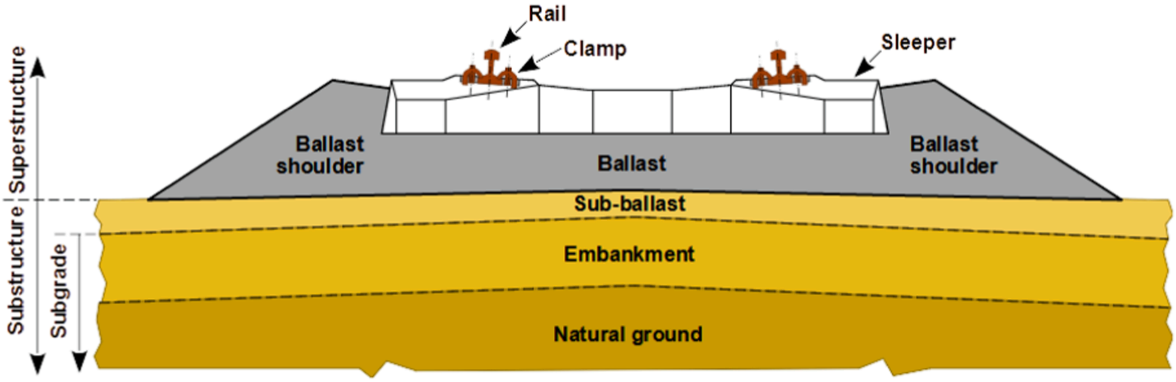

Fig. 1. Schematic representation of a ballasted railway track infrastructure.

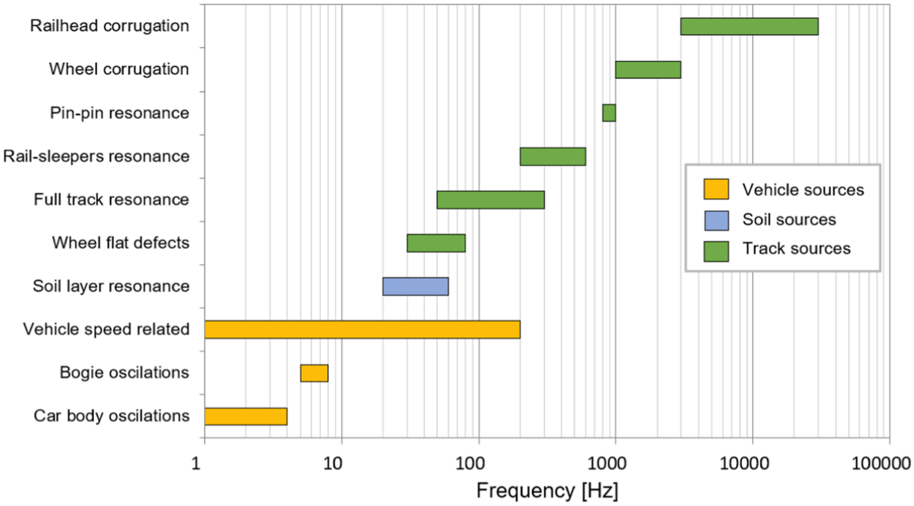

Fig. 2. Typical ranges from the main frequency sources on a railway infrastructure and vehicle.

support conditions is an important task because it has a direct impact on the operational safety, reliability and availability of this service.

In this context, one well established parameter for the assessment of railway track support conditions is vertical track stiffness, which is defined as the ratio between the vertical load applied on the rail and the maximum vertical displacement of the track [1,2]. There are other parameters that can also be used to assess specific aspects of track support conditions, such as monitoring track geometry or track irregularities and defects. While relevant and extensively used in railway monitoring operations, these previous parameters also have some relevant limitations that have been reported over the years [3–5]. For example, vehicle-based monitoring methods based on these parameters are usually more focused on the conditions of the track superstructure [1,6–8]. This focus normally leaves the track substructure (Fig. 1), that also includes the track subgrade, unmonitored or at least poorly assessed [3,5]. This is an important issue since subgrade condition represents one of the main factors that influences track dynamic response and track support conditions [1,6,9,10].

An alternative and novel methodology to evaluate railway track support conditions is now under development in the context of a research study. This methodology is based on modal analysis of the characteristic frequencies of the multi-element system composed by an instrumented railway vehicle and the railway infrastructure. Vibration-based damage detection methods, to which this methodology belongs to, rely on the fact that physical changes on a structure, such as the appearance of damage or defects, cause changes in its modal characteristics. Affected modal characteristics include natural frequencies, mode shapes, and damping coefficients [11,12]. Monitoring these characteristics can be a useful asset in Structural Health Monitoring applications due to this behaviour [13]. A railway infrastructure can also be analysed in such a way, especially if the focus is on specific elements. For example, there are already studies on models to estimate the main natural frequencies of several railway infrastructure elements (Fig. 2), as well as on using the natural frequencies of specific track elements to detect the appearance of damage or degradation of their mechanical properties [10,14–18]. A missing link, relevant for the proposed methodology, is in validated methods that can monitor these modal characteristics to assess overall railway track support conditions of a railway infrastructure, including the subgrade.

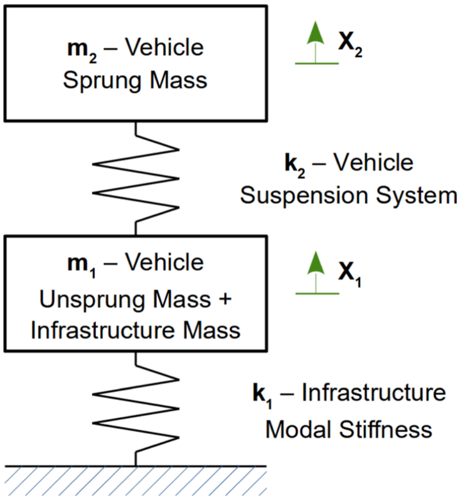

Fig. 3. 2-DoF model used in the current version of the methodology.

In this context, one of the main features of the proposed methodology is that it should be able to assess the conditions of a railway infrastructure's subgrade, regarding its contribution to the track's support conditions [11]. This is the case because both the railway superstructure and the substructure are dynamically excited by the moving vehicle, thus their dynamic response can be monitored and used to gather data on their respective conditions [1,3,5,6]. More specifically, information related with track stiffness should be obtainable by monitoring these characteristics frequencies, since modal stiffness is a parameter that is highly influenced by the presence of damage [11,12]. Although these two types of stiffness concepts cannot be compared directly, they are still related with each other [1]. Thus, information regarding track support conditions can be extracted from these frequencies, which is naturally focused on subgrade condition due to its major influence on the overall track dynamic response [1,5,6,9]. This concept creates a track monitoring methodology that is more focused on the conditions of railway subgrade, potentially fulfilling the need for a vehicle-based method that can adequately assess this element. This is relevant because subgrade condition is often neglected during railway monitoring operations in favour of the more accessible superstructure elements [3,4].

The proposed methodology uses a lumped-elements type model (Fig. 3) to interpret the acquired railway related frequency data. The current version of this model is a two Degree-of-Freedom (2-DoF) model, consisting of an assembly of two spring-mass sub-systems in series, to represent the vehicle, per axle, and the modal properties of the railway infrastructure. The mass elements represent the unsprung mass of one vehicle axle plus the modal mass of the infrastructure that is being dynamically excited by the moving vehicle (m_1), and the vehicle's sprung mass section that is supported by the axle (m_2). These two mass elements are linked by a spring element that represents the vehicle's suspension system (k_2). The last element is a spring that represents the modal stiffness of the railway infrastructure (k_1), combining the contribution from both the superstructure and the substructure. The output of this model are two characteristic frequencies (ω_1 and ω_2), that are related with these four modal parameters [19]. Frequency ω_2 is mainly influenced by the vehicle's modal characteristics and can be attributed to the vertical oscillatory motion of the vehicle's sprung mass, which has typical frequency values between 1 and 5 Hz [20]. Frequency ω_1 is mainly influenced by the modal parameters of the railway infrastructure elements, thus represents the natural frequency of interest for the proposed railway monitoring methodology [21]. Morais et al. [21] provides a more in-depth description on the current stage of development of this methodology and on the motivations that lead to its development.

This theoretical model is intended to serve as a measurement support tool to provide relevant information regarding track support conditions, namely, to interpret the acquired frequency data. Therefore, it does not consider the wheel-rail contact between the vehicle and the railway because the influence of this aspect on the natural frequencies under assessment is negligible. The characteristics of this contact, which is usually described by a high stiffness Hertzian spring on several other models [20], can only create high value natural frequencies that are significantly separated from the frequency band of interest. In this context, these frequencies can be disregarded, thus enabling the presented model [19]. Damping elements are also not included in the current version of the theoretical model. This option was made based on two main reasons: i) for the intended purpose of the model, this type of modal elements do not significantly change the dynamic response of a mechanical system in terms of its natural frequencies values [19]; ii) in the railway context, where obtaining subgrade properties is already a challenge, determining accurate damping properties of the subgrade layers is an even more arduous and unfeasible task [22].

Considering the potential of vehicle-based solutions to provide extensive assessments on a continuous mechanical system such as a railway line, another concept used in the proposed methodology is to monitor the patterns that the characteristic frequencies of interest can create if the resulting spectrums are represented in the time–frequency domain [10,20]. These patterns can represent another source of relevant information on this combined mechanical system through the study of their shapes, in addition to the information extracted just from the values of the characteristic frequencies [23,24]. At this stage, a preliminary application of this methodology has already been implemented with experimental data. This data was used to test the developed data processing tools,

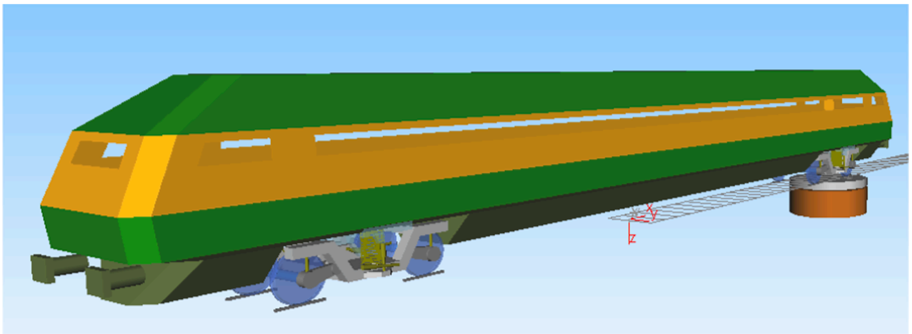

Fig. 4. Base Simpack® model used, containing a generic railway passenger carriage and the railway track.

and to perform preliminary assessment tests on the overall concept [21].

An important aspect of this methodology that needs to be validated is the assessment of track support conditions of a railway infrastructure section through its natural frequencies. More specifically, this methodology is currently based on the assumption that it is possible to observe a dominant resonance frequency related with the railway infrastructure under assessment, and that this frequency is adequate to provide useful information on track support conditions. This hypothesis represents one of the bases of this methodology, due to the intent of trying to assess track support conditions of a railway infrastructure based on monitoring only one resonance frequency (ω_1). Since the proposed theoretical model is naturally dependent on the modal characteristics of the instrumented vehicle, it is also plausible to assume that there would be the need to adapt it based on the number of suspension levels of the instrumented railway vehicle being used [20]. The present model is clearly more suitable for vehicles with only one suspension level, since it only has one spring element assigned to this aspect. Thus, another important aspect that must be assessed is the suitability of this model to work with different railway vehicle types, in terms of suspension configurations. This paper describes a set of numerical simulations that were performed as part of the efforts to assess and validate these two topics. Thus, the following hypotheses were assessed here:

- **H1**: a single dominant resonance frequency related with the dynamic response of an entire railway infrastructure section exists, and is observable in data collected with an instrumented railway vehicle moving over the railway track.
- **H2**: the proposed theoretical model is compatible with instrumented railway vehicles with one or two suspension levels. That is, the dominant resonance frequency from the railway infrastructure can be reasonably estimated with the natural frequency formula to calculate the model's ω_1 frequency, independently of the vehicle's suspension layout.

The optimal situation for H1 would be if this dominant resonance frequency was reliably observable inside the car body, instead of the axles or bogies. This would represent a more beneficial situation for the methodology because the natural filtering effect of the suspensions should provide cleaner data in terms of mechanical noise, thus resulting in better quality frequency spectrums that should be easier to analyse [20].

Additionally, if the previous hypotheses were validated with experimental data, a railway manager could then infer information on track support condition changes on a railway infrastructure just by monitoring the obtained dominant resonance frequency along the track, and over time. This would require that the equivalent modal mass of the infrastructure section that is being excited by the vehicle remained relatively constant, so that direct comparisons between results could be made. But, excluding situations where the railway infrastructure is severely damaged or modified by the presence of a civil engineering structure (e.g., a bridge), this scenario is plausible in typical railway lines [22]. This aspect is important because it means that there would be no need to know specific soil characteristics on each track section under analysis to obtain data on their track support conditions. Major changes on the static and dynamic characteristics of the monitoring vehicle being used would also have to be taken into consideration, but those can be compensated or normalized from the results if adequately recorded. Thus, this correlation between the proposed dominant resonance frequency and track support conditions represents one of the main aspects of the proposed methodology that needs to be thoroughly validated.

2. Numerical models of the vehicle-track system

To assess the validity of the previous hypotheses, a numerical simulation model of a railway vehicle-track system was developed (Fig. 4), using the multibody simulation software Simpack®. The main body elements of this model were a generic railway passenger carriage, with two bogies, and a specific set of elements to represent the presence of a typical railway infrastructure and its influence on the vehicle-track dynamic interactions.

2.1. Base model description

The generic vehicle model used in the following simulations included all the components relevant for these simulations, namely: springs and dampers for the two levels of suspension systems, and mass elements to represent both the sprung and unsprung masses of

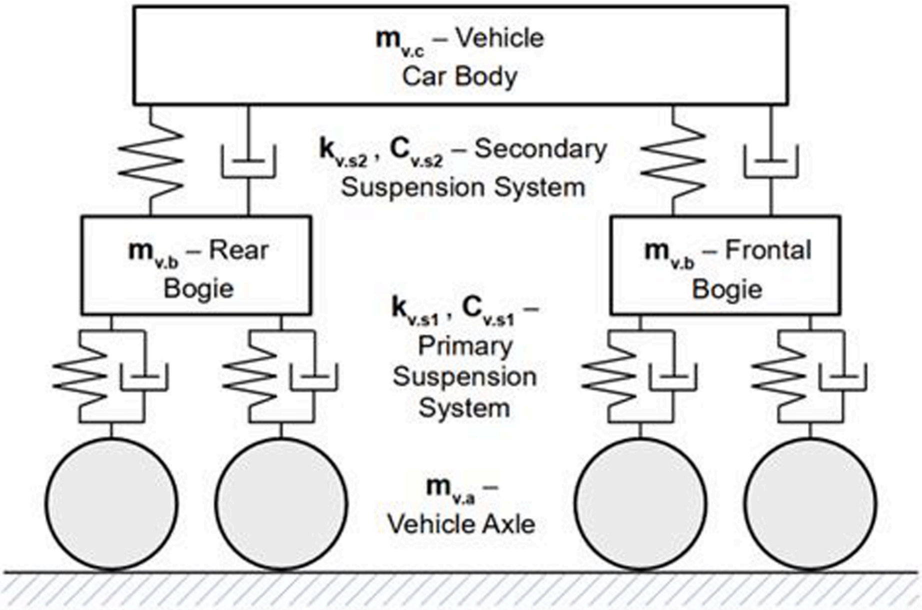

Fig. 5. Schematic representation of the vehicle model used in Simpack®.

Table 1
Main parameters used in the tested Simpack® vehicle model.

Vehicle Parameters	Value
Car body mass ($m_{v.c}$)	35000 kg
Bogie mass ($m_{v.b}$)	2615 kg
Axle mass ($m_{v.a}$)	1200 kg
Primary suspension stiffness ($k_{v.s1}$)	1.82 kN/mm
Secondary suspension stiffness ($k_{v.s2}$)	6.43 kN/mm
Primary suspension damping ($C_{v.s1}$)	42,000 Ns/m
Secondary suspension damping ($C_{v.s2}$)	25,000 Ns/m

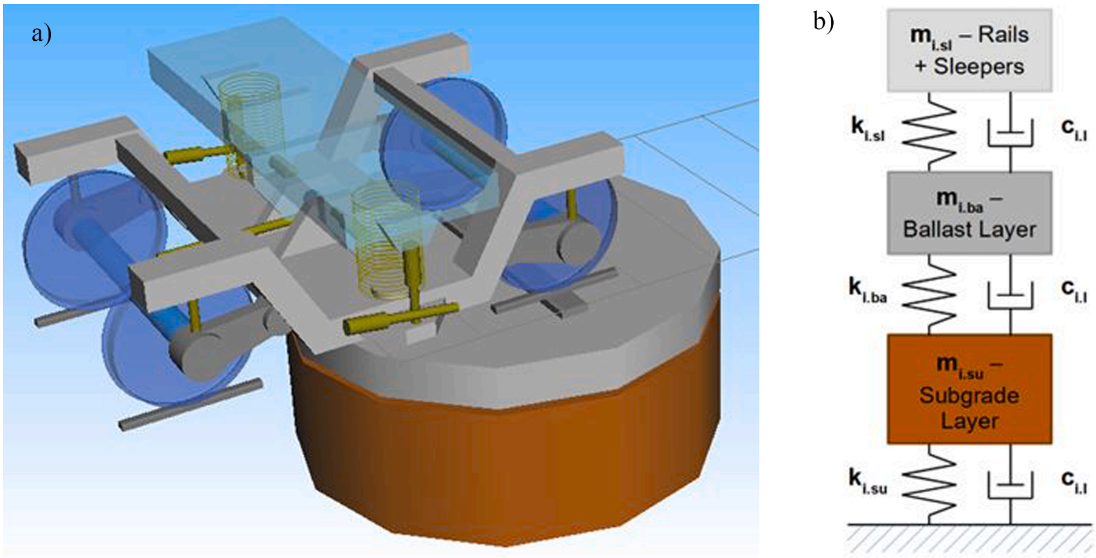

Fig. 6. (a) Sub-section of the Simpack® model used, containing the frontal bogie of the vehicle and the elements representing the railway infrastructure. (b) Schematic representation of the infrastructure model used.

Table 2
Main parameters used in the tested Simpack® infrastructure model.

Infrastructure Parameters	**Value**
Subgrade layer mass ($mi.su$)	13770 kg
Ballast layer mass ($mi.ba$)	3098 kg
Sleeper mass ($mi.sl$)	330 kg
Layered elements diameter (θ_l)	3 m
Subgrade layer height (h_{su})	1 m
Ballast layer height (h_{ba})	0.3 m
Sleeper spacing (L_{sl})	0.5 m
Subgrade layer spring element stiffness ($ki.su$)	150 kN/mm
Ballast layer spring element stiffness ($ki.ba$)	450 kN/mm
Sleeper spring element stiffness ($ki.sl$)	225 kN/mm
Layered elements damping ($C_{i.l}$)	37,600 Ns/m

the vehicle (Fig. 5). No further developments were made in this part of the model because it was not the focus of the present research. Table 1 presents the values used for the main modal parameters of the tested vehicle model. These parameter values are in accordance with typical values used on similar numerical models [20,25].

The railway infrastructure was described by a dedicated group of body elements, specifically: two rails, one sleeper, and two cylinders stacked on top of each other placed directly below the sleeper (Fig. 6). These cylinders were designed to represent different layers of the infrastructure, namely the ballast layer (grey colour cylinder) and a subgrade layer (brown colour cylinder). This part of the model also contained spring-damper elements, coupled to the sleeper element and the two layered elements of the infrastructure, to simulate the equivalent vertical stiffness behaviour from each part. Since the observation point for the simulations was the vehicle, the railway infrastructure was only described by this reduced set of body elements. This is admissible, in the context of a multibody simulation, because this sub-system was made to follow the vehicle as it moved along the cartographic profile of the track. Therefore, the infrastructure elements were always the same during the entire simulations. What changed during the simulations, to model the shifts in the vehicle-track dynamic interactions of interest, were the values of modal track stiffness associated with each layer of the infrastructure. The vertical track stiffness variation created by the spacing between sleepers was implemented using the standard Simpack® procedure available in this type of model configuration (i.e., an additional parallel spring is added between the rails and the ballast layer that introduces a track stiffness variation with the appropriate spatial frequency). These infrastructure elements were placed only below the frontal axle of the vehicle to reduce computational effort. During model development, a model with infrastructure elements below each axle was tested and the obtained results were equivalent to those obtained in the situation presented is this paper, in terms of the frequency spectrum. There was no evidence of any interaction between the vehicle's axles in this regard.

The dimensions of the layered infrastructure elements had to be determined through an iterative process since, to the authors' knowledge, there is no established correlation between the static and dynamic characteristics of a moving railway vehicle and the extent of the railway infrastructure that is dynamically excited by its presence. This was done by comparing the local natural frequencies values of each layered element, calculated by Simpack®, with their respective typical frequency ranges from relevant bibliography [14,23,26]. This process was labour intensive because in this type of numerical simulations the mass and stiffness parameters are typically disconnected (i.e, there are no geometrical and/or mechanical properties that can define both parameters). Thus, for each layer, its dimensions and the stiffness value of the associated spring had to be iterated separately until physically credibly values were obtained, that also resulted in admissible local natural frequencies values according to the bibliography. Due to the nature of this procedure, these dimension values were not selected to replicate any specific scenario, but instead to just create a simulation were both hypotheses could be assessed.

The topic of establishing a correlation between the vehicle's static and dynamic characteristics, and the extent of the infrastructure that is dynamically excited by its presence is a topic that is also currently under research by the author. That is, there is a lack of a model or formulation linking vehicle characteristics relevant for its impact on the railway infrastructure (e.g., its mass), and the depth and span of the infrastructure that is dynamically influenced by the passage of the vehicle over it. Such a formulation might be difficult to obtain because the infrastructure's dimensions that are affected by the vehicle might depend on more aspects than just some vehicle characteristics (e.g., soil characteristics), but even rough estimates would be useful to have in situations such as these numerical simulations. That is, the dimensions of the layered elements of this numerical model could be estimated directly if this formulation existed. Additionally, with this formulation and if the proposed theoretical model was validated, track modal stiffness values for each layered element could also be estimated solely based on typical local natural frequencies values for each layer type and their respective specific mass.

The discretization of the railway infrastructure into the two layered components was done to allow for an adequate assessment of H1. That is, if the infrastructure was described by only a single element, the scenario described in hypothesis H1 would be naturally verified because a single element only provides one direct natural frequency. Thus, the railway infrastructure was described by these two elements, to more adequately represent the main contributors to the natural frequencies of interest [1,9].

Table 2 presents the values used for the modal parameters of the infrastructure model. The modal stiffness and modal damping values implemented on the infrastructure elements are within the stiffness and damping ranges used on consulted bibliography, as are the specific mass values used to calculate the mass for each element of the infrastructure [25].

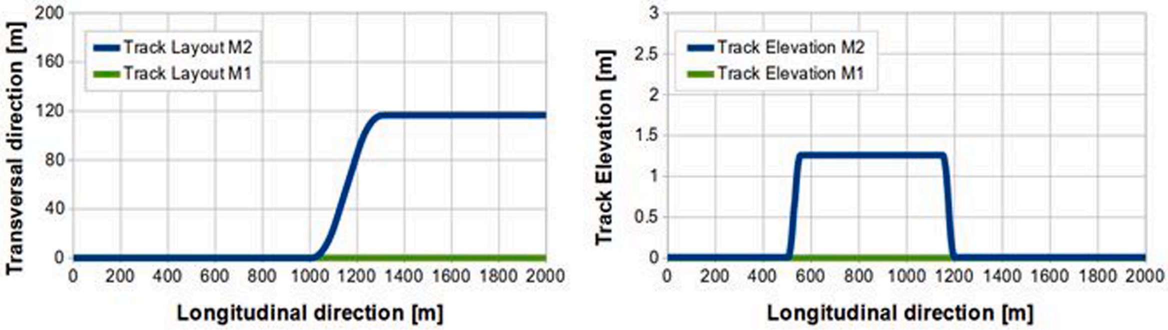

Fig. 7. Cartographic profiles used in simulations M1 and M2: (a) top view and (b) track elevation.

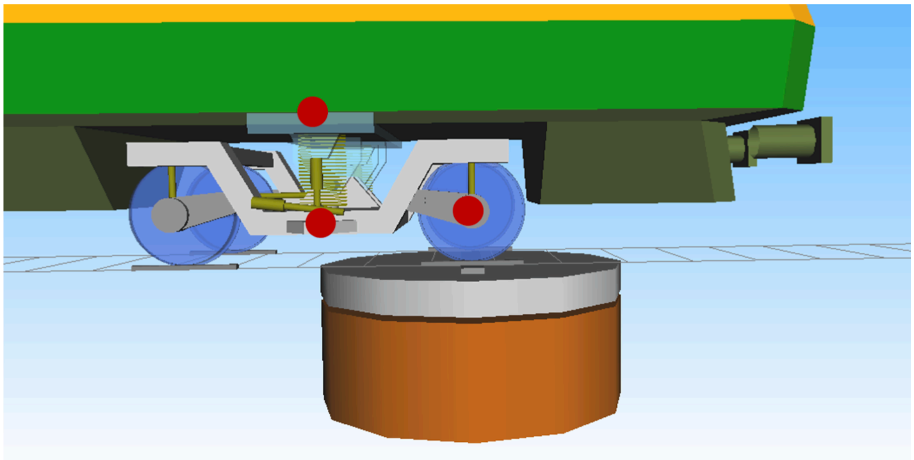

Fig. 8. Positions of the sensors that were placed in the mid longitudinal section of each model (red dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. *Vehicle-track dynamics setup*

Since the main objectives of these simulations required a scenario with varying track support conditions, distinct track stiffness profiles were created for the modal stiffness of each spring element on the infrastructure. These profiles were designed to create situations where significantly different resonance frequency values could be perceived, and not focused on representing any specific real scenario. However, the selected values still attempted to be realistic. The wheel-rail contact forces were implemented in Simpack® using the Hertzian formulation. This model was designed to represent a situation where the track was in good conditions (i.e., a low-level stochastic track irregularities profile was applied in both rails), since this aspect was not the focus of these simulations.

Additionally, a relatively simple vehicle running speed profile was established to create a simulation where the model's frequencies that are dependent on the vehicle's speed could be distinguished from the model's structural frequencies [1]. The natural frequencies of a linear mechanical system are independent from the characteristics of the excitation signal used to assess them [11]. In this context, this means that the system's natural frequencies are independent of the vehicle's running speed. Thus, if the acquired frequency data is represented in the time–frequency domain, such as in a spectrogram, each frequency curve present can be classified whether it depend on vehicle running speed simply by comparing its pattern on the spectrogram with the vehicle's running speed profile in the time domain. Then, the frequencies that are directly related with the vehicle's running speed can be discarded during data processing, thus enabling the analysis to be more focused on the natural frequencies of interest. This procedure will be exemplified in the Results section.

2.3. *Model variants description*

From this overall model, two model variants (M1 and M2) were assembled to create testing conditions where the two previous hypotheses could be assessed. Both variants used the same model parameters and conditions previously described, with only the following exceptions.

In model variant M1, which represented the first step in the test plan, the secondary suspension level of the vehicle was effectively

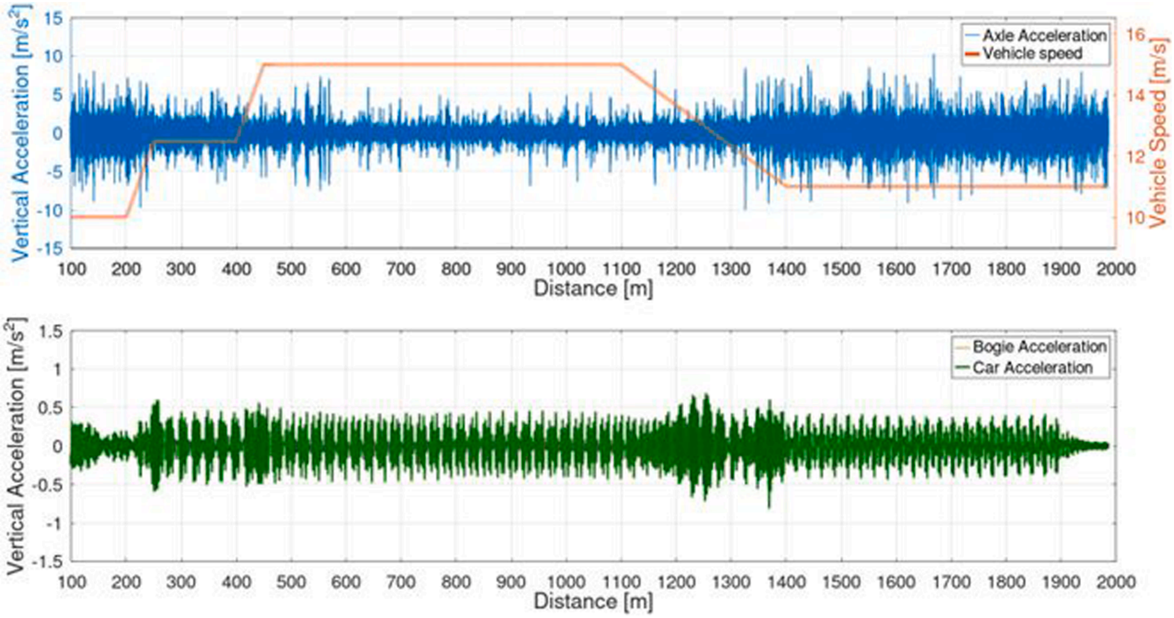

Fig. 9. Raw data from simulation M1 (acceleration data and vehicle running speed).

supressed by increasing its stiffness value by six orders of magnitude, to simulate a vehicle with only one suspension level. This was done to verify if the two hypotheses H1 and H2 were valid for a vehicle with only one suspension level, because it represents the situation that more closely resembles the proposed theoretical model. This model variant used the original two suspension level vehicle with the described modification, instead of using a different vehicle model with only one suspension level, to allow for more direct comparisons between results from the two model variants. Then, for model M2 the secondary suspension level was re-established. This model was designed to check if the proposed theoretical model was also valid for vehicles with two suspension levels, and to check whether the dominant resonance frequency of interest could be observed at the car level in this type of vehicle.

Each of these models had relatively simple track cartographic profiles, in terms of slopes and curves, just to demonstrate that these parameters do not significantly interfere with the frequencies of interest. The track for M1 was completely straight, while M2 had two slope changes and two moderate curves, which can be perceived in Fig. 7a and Fig. 7b. The overall track length for each model was 2000 m.

The simulations were conducted using a data sampling frequency of 1000 Hz and a run-time of 160 s. The integration method used was the SODASRT 2 with an automatic time-step size, imposing a maximum time-step size of 0.5 s. Each model had a virtual accelerometer placed in the frontmost axle of the vehicle, another on the frontal bogie, and a third on the car directly above the instrumented bogie (Fig. 8). These sensors were used to monitor the dynamic response from the infrastructure elements directly below, and to assess the previous hypothesis. This aspect was particularly important to assess where the dominant natural frequency described in H1 could be observed in the vehicle.

3. Results

This section presents the data obtained from the tested models, and all the relevant results obtained by the application of the proposed methodology. All data will be presented in the space domain, instead of the time domain, since this representation is typically more adequate when monitoring railway lines with a vehicle-based solution [6,20]. The first 100 m of both simulations were cut from the following graphical representations to remove the transient corresponding to the simulation's start.

Acceleration data collected with the bogie sensor was only relevant to verify the suppression of the secondary suspension system in simulation M1, since frequency results obtained from this sensor did not present any additional useful information when compared with the results from the other two sensors.

3.1. Simulation M1

Fig. 9 presents the raw acceleration data obtained from this simulation, along with the implemented vehicle running speed profile. As expected, the acceleration data from the axle sensor had significantly higher amplitude values than the data from the other two sensors [20], due to the filtering effect provided by the suspension system of the vehicle. This difference is also present in the respective frequency spectrums. In this model, the acceleration data from the bogie and the car sensors are equal due to the suppression of the secondary suspension system, as expected.

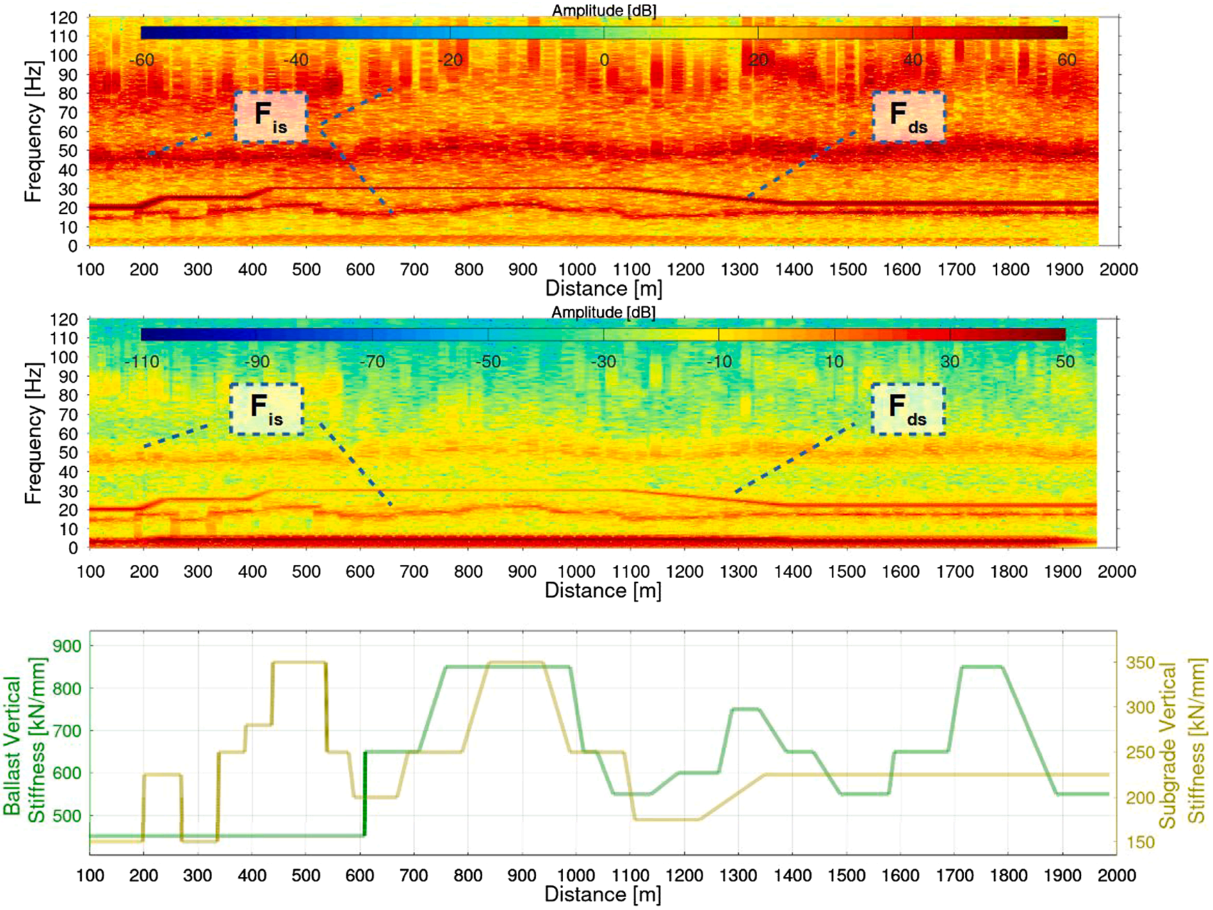

Fig. 10. Obtained spectrograms and applied track stiffness profiles from simulation M1.

Fig. 10 presents the spectrograms obtained from the axle (Fig. 10a) and the car (Fig. 10b) acceleration data, and the vertical track stiffness profiles used on the spring elements associated with the two layered elements of the infrastructure (Fig. 10c). Both spectrograms present mostly the same observable frequency curves, except for two relevant differences. One difference is that spectrogram a) does not present any significant frequency content below 10 Hz, while spectrogram b) presents frequency curves in this area that correspond to natural frequencies of the car [20]. These frequencies do not appear in the axle sensor because of the suspension system. The other relevant difference is that some of the frequency content that appears on spectrogram a) is significantly mitigated in spectrogram b), especially the higher frequency content.

The next step in the methodology was to extract the frequency content of interest from the spectrograms, by discarding the irrelevant frequency curves. In this context, an important distinction to make is between frequencies that depend on the vehicle's running speed (F_{ds}) from those that are independent from it (F_{is}). As previously explained, the characteristic frequencies of this combined mechanical system, which include the frequencies of interest to the methodology, are not dependant on the vehicle's speed. Thus, frequencies that can be correlated with the vehicle's speed profile (Fig. 9) can be discarded. In these spectrograms there is only one F_{ds} curve, which corresponds to the parametric frequency created by the interaction of the vehicle's wheels with the spacing between the sleepers on the track. Additionally, the F_{is} curves present in spectrogram b) below the 10 Hz mark can also be discarded because these correspond to natural frequencies of the sprung mass of the vehicle [20].

Finally, there were still three observable F_{is} curves to analyse, which are identified in Fig. 10. Due to the damping effect of the suspension system, the identified F_{is} curve with the higher frequency values, that is observable in spectrogram a), is barely visible in spectrogram b). But the other two frequency curves are clearly visible in both spectrograms. Using a dedicated Simpack® tool that calculates and represents the kinematics of each natural frequency present on a simulated model, using its initial conditions, these frequencies were identified as three different modes of vibration from the infrastructure elements coupled with the unsprung mass of the vehicle (i.e., the frontal axle). According to this modal analysis tool, these two groups of elements form a sub-system that is dynamically excited during the simulation to present natural frequencies that can be associated with the railway infrastructure. Fig. 11 presents the values given by Simpack® for these three natural frequencies, which match the values presented in the spectrograms with the initial track stiffness values, along with a representation of their mode shapes based on the three main body elements of this sub-system.

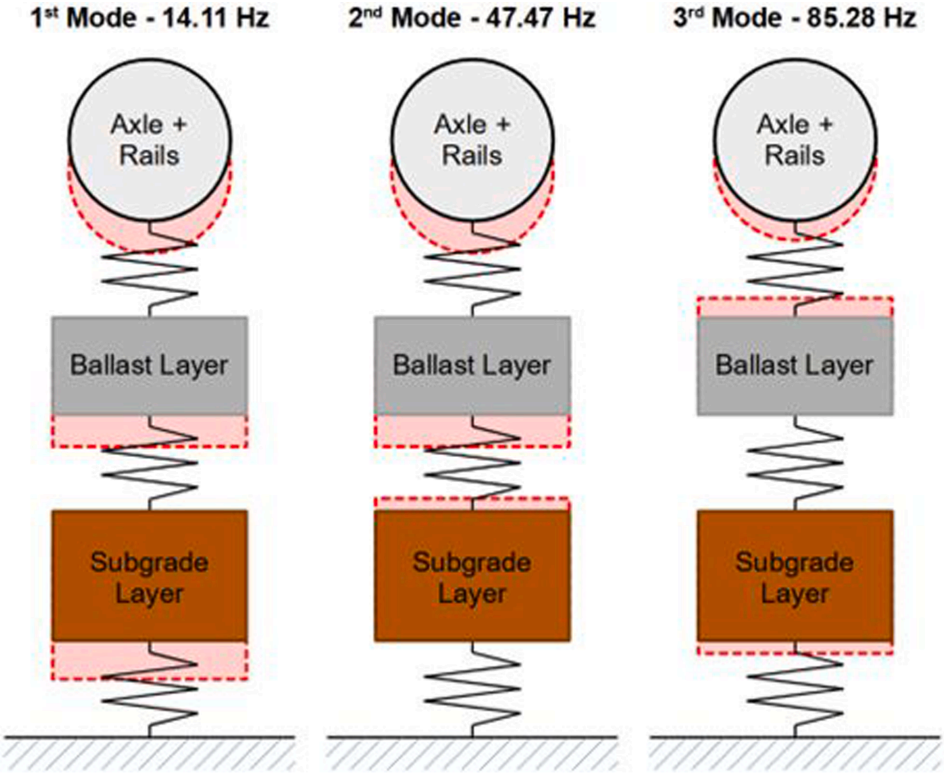

Fig. 11. Representation of the three main infrastructure related vibration modes from the tested model. These elements represent the sub-system that presents the observable infrastructure dynamic behaviour.

The first mode present is the full body oscillation of this sub-system over the adjoining springs, while the two remaining modes represent higher order vibration modes from this three element sub-system. The patterns of these three frequency curves, visible on the spectrograms, resemble the vertical track stiffness profiles applied to the layered infrastructure elements, which further supports the statement that these natural frequencies are related to them. More specifically, the first mode appears to be heavily influenced by the subgrade track stiffness profile, which matches the mode shape description that this vibration mode corresponds to the oscillation of the entire mass of the infrastructure, plus the frontal axle of the vehicle, over the subgrade spring element. The second mode's curve on the spectrograms resembles the ballast track stiffness profile, which also matches with the shape mode's representation in Fig. 11 where it is reasonable that the ballast spring element should be the main influencer. The third mode's curve seems to be a combination of influences from the two track stiffness profiles, which again also matches with the respective shape mode representation in Fig. 11. Thus, taking these results into account, these three natural frequencies could potentially be used to provide information on the track's support conditions of the railway infrastructure model under assessment due to their relationship with the track stiffness profiles of the infrastructure elements.

Furthermore, the first mode of vibration described in Fig. 11 appears to correspond to the intended behaviour of the dominant resonance frequency entailed in hypothesis H1. This natural frequency exhibits the highest average amplitude values from these modes, is highly sensitive to the track stiffness of the subgrade layer, and represents the more appropriate mode shape to describe the expected behaviour of a real railway infrastructure. While it is possible that the soil layers of a real railway infrastructure can present observable individual natural frequencies [1,22], in the author's opinion, the more observable behaviour from the point of view of a railway vehicle should be the full body oscillation of the entire section of the infrastructure that is being excited by the moving vehicle. The assessment and validation of this topic is another important task of this ongoing research since it is a vital aspect of the proposed methodology. The assessment of H1 in this simulated environment represents one of the steps in this process. Thus, from the previous results, hypothesis H1 is validated for this model by selecting the first vibration mode previously described as the dominant resonance frequency of interest. Regarding the validation of H1, another important result obtained from this simulation is that the dominant resonance frequency of interest is observable at the car level. This represents a useful benefit to this methodology, since the frequency spectrums obtainable at the car level are less disrupted by mechanical noise and unwanted frequencies than those obtainable at the vehicle axle, due to the suspension system, as it can be seen in Fig. 10.

3.2. Simulation M2

Fig. 12 presents the raw data obtained for this simulation. Since this model now has two working suspension levels, the acceleration

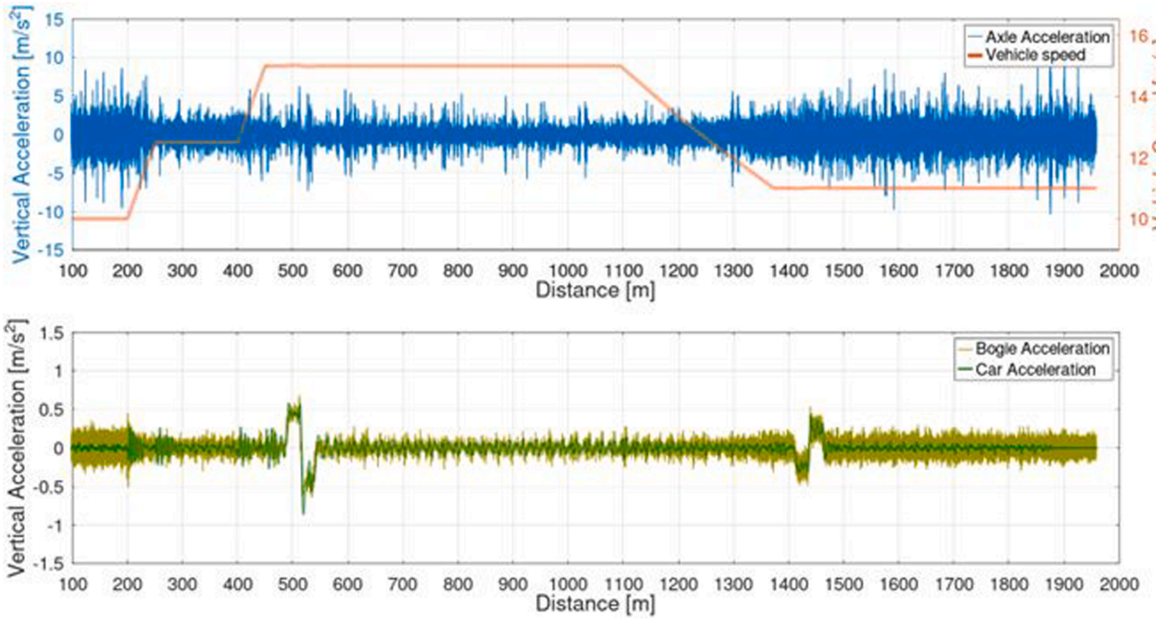

Fig. 12. Raw data from simulation M2 (acceleration data and vehicle running speed).

data from the bogie sensor is now observably different from the data obtained with the car sensor. The bumps in the acceleration data from these two sensors, at around the 200 m and 1150 m marks, correspond to observable effects caused by the presence of the vertical slopes in the cartographic profile of this model's track.

Fig. 13 presents the obtained spectrograms from the axle and car sensors, and the vertical track stiffness profiles used on the spring elements associated with the layered elements of the infrastructure in this model. These track stiffness profiles are the same as the ones used in M1. Both spectrograms also present similar frequency contents between them, just like the M1 results. This includes the same two differences in frequency content that were described for M1. Upon further inspection, these two spectrograms are very similar to the respective spectrograms from simulation M1. They include the same frequency curves that were eventually discarded, and the three observable F_{is} curves of interest identified in the spectrograms from Fig. 10. The frequency values of each of these frequencies are also practically the same as the respective values obtained in M1. From these results, an immediate conclusion is that the different cartographic profile used in this model did not affect the obtained frequency content. As expected, it would require a significantly more extreme cartographic profile, to the point of representing a potential safety hazard for the vehicle, for it to have an observable effect in the frequency curves present in these spectrograms.

From the previous results, hypothesis H1 is also valid in simulation M2 since every consideration made for M1 is also valid here. Thus, hypothesis H1 is validated in the present simulated environment. Expanding the validation scope of this hypothesis, including with experimental data, is something that will be addressed in the future. Additionally, this result also means that the value of this dominant resonance frequency does not depend on the number of suspension levels of the instrumented railway vehicle being used to monitor the railway infrastructure under assessment. This conclusion represents a partial validation of hypothesis H2.

3.3. Validation of H2

To finish the validation process of hypothesis H2, Table 3 presents the frequency value that can be calculated with the formula for the natural frequency ω_1 from the proposed theoretical model, using the relevant mass and stiffness values from the numerical model (Equation (1)). This value was then compared with the frequency values of the first vibration mode obtained in both simulations, which was selected as the H1 dominant resonance frequency.

$$\omega_1 = \sqrt{(k_2 + k_1)/m_1} \cong \sqrt{(k_{v.s1}*2 + k_{i.su})/(m_{v.a} + m_{i.su} + m_{i.ba} + m_{i.sl})} \tag{1}$$

From these results, hypothesis H2 is also validated in the present simulated environment since the obtained error values are within admissible ranges for common engineering applications, in both models. That is, the proposed theoretical model appears to be able to interpret data from railway vehicles with one or two suspension levels, and provide adequate estimates of the dominant resonance frequency of interest for the proposed railway monitoring methodology. Another aspect that further validates H2, that was assessed and verified during the design of these simulations was that the car's mass does not influence the dominant resonance frequency of interest. This is in accordance with the behaviour of frequency ω_1 from the proposed theoretical model [19], thus further validating the claim that this model can be used to adequately estimate the selected dominant resonance frequency from the tested models. A more

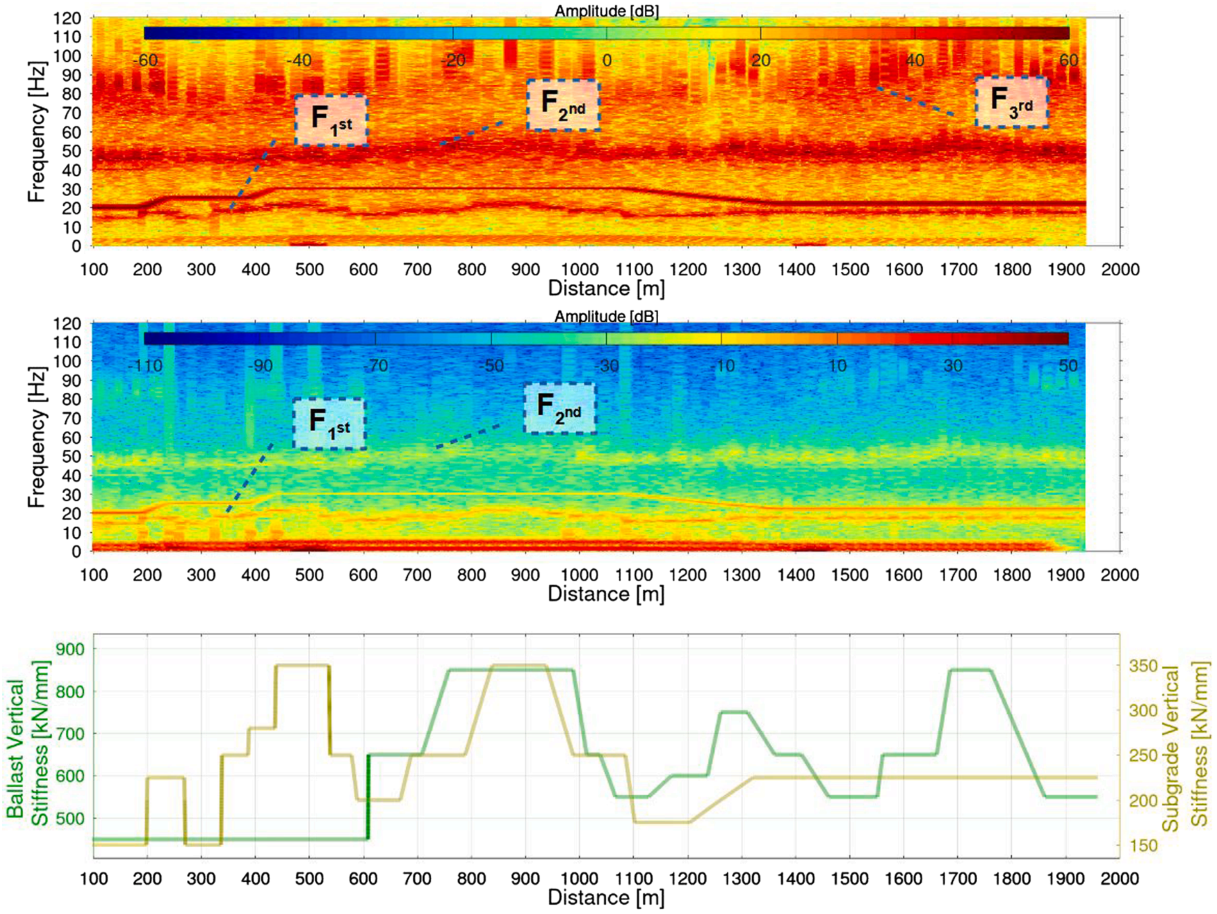

Fig. 13. Obtained spectrograms and applied track stiffness profiles from simulation M2.

Table 3
Dominant resonance frequency estimate and obtained values from the simulations.

	Simulation M1	Simulation M2
Calculated frequency ω_1 (equation (1))	14.54 Hz	
Undamped frequency value for 1st vibration mode (from Simpack®)	14.11 Hz	14.47 Hz
Error percentage	− 3.05 %	− 0.52 %

thorough validation of this topic will be carried out in the future through a sensitivity analysis on the effect that each relevant modal parameter from the Simpack® model has on the selected resonance frequency.

4. Conclusions

An alternative and novel methodology to assess railway track support conditions based on modal analysis of the characteristic frequencies of a multi-element system, composed by a railway infrastructure and an instrumented railway vehicle moving over it, is under validation as part of an ongoing research. The proposed methodology is integrated in the group of vibration-based structural damage identification methods. This methodology should be able to provide information on track support conditions of railway infrastructures, with a special focus on subgrade conditions, by providing the tools to monitor and analyse the natural frequencies of this part of a railway track.

This paper presents a brief description on the proposed methodology, followed by a description of two numerical simulation tests performed as part of the validation process. The intent of these simulations, performed with Simpack®, was to assess the validity of two hypotheses regarding the capabilities of the proposed methodology to adequately assess track support conditions. Namely, the first hypothesis was whether a dominant resonance frequency, related with the dynamic response of the railway infrastructure, could be identified and be reliably observable from the point of view of a moving instrumented railway vehicle. The second hypothesis was to check if this dominant resonance frequency could be reliably estimated with the proposed theoretical model, independently of the suspension configuration of the instrumented railway vehicle being used.

These hypotheses were validated in the presented numerical simulation models, based on the obtained results. But these conclusions can be potentially extrapolated into a wider validation in simulated environments due to generic characteristics of the models used. For instance, even if the infrastructure sub-model had additional layers beyond the two used, as long as this part of the model retained its linear behaviour, these conclusions would still be valid [19]. This overall result represents an important step in the overall validation process of the proposed methodology, but there is still the need to validate these hypotheses with experimental data. If future validations steps also prove to be successful, this methodology would represent an alternative method to assess railway infrastructures with instrumented vehicles, focused on track support conditions and some aspects of subgrade structural health.

Future numerical simulations in this context will include designing a model closer to typical values for the infrastructure parameters, especially those regarding the sub-structure elements. Based on this new simulation model, sensitivity analyses will be performed to check several relevant aspects, including the influence that the model's major modal parameters have on the characteristic frequency of interest. The impact of certain features, such as track irregularities, will also be analysed on how they influence the perceptibility of the characteristic frequency of interest in the obtainable results.

The Authors declare that there is a potential conflict of interest with respect to publication since professor Diogo Ribeiro is a guest editor for the special edition this article is being submitted to.

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Data availability

No data was used for the research described in the article.

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