TOWARDS THE NUMERICAL GROUND-BORNE VIBRATIONS PREDICTIVE MODELS AS A DESIGN TOOL FOR RAILWAY LINES: A STARTING POINT

Andrés García Moreno
PhD Applicant. Railways & Track Civil Engineer
University of Cadiz, Algeciras, Spain
Juan Jesús Ruiz Aguilar
Department of Industrial and Civil Engineering, Politechnic School of Engineering,
University of Cadiz, Algeciras, Spain
José Antonio Moscoso López
Department of Industrial and Civil Engineering, Politechnic School of Engineering,
University of Cadiz, Algeciras, Spain

ABSTRACT

In recent decades, High-Speed Railway (HSR) lines have become one of the most extended and environmental-friendly ways to plan new mass transport networks. These systems are directly influenced by its operational speed generated dynamic effects and the areas where it runs through. This necessarily requires to predict ground-borne vibrations generated by trains passing-by populated areas and its influence zone.

Trends in ground-borne measurements, prediction models, and isolation systems are usually performed for maximum operation speed. This method implies the maximum dynamic forces which are suitable for structural calculations (generally developed in time domain) but not necessary for vibration related issues (emission and/or transmission). Additionally, these studies are mainly focused on urban areas where maximum operational speed are frequently far from railways service’s top speeds.

Related to frequency domain, it is known that upper frequencies are not the most disturbing ones. In fact, European structural standards usually cut frequencies off at 30 Hz, so much relevant information for vibrational prediction is ignored due to it does not influence structural issues.

Moreover, current common predictive numerical models usually apply punctual loads (birth & death) that are disposed to run in certain speed conditions. This method, which is considered valid for time domain analysis, are identified to be incomplete for frequency domain components due to its discontinuous application of loads.

The implementation of contact theories in the wheel-rail interface implies a continuous load application, refining the obtained results but increasing computational cost.

In this study, different scenarios are compared varying inner and boundary conditions of a model, with the aim of validate results and optimize resources by obtaining a parametrical influence study that will show how different assumptions and cases could condition ground-borne vibrational studies results.

1. INTRODUCTION

1.1 Ground-borne vibrations generated by railways. State of the Art.

It is known that railways running along the track produces important vibrations -noise & vibration Pollution- not only in the track but its surroundings, as well as air-borne and structural noise. Assuming the common ‘noise & vibration’ binomial, it is capital to note that two different concepts are then considered.

Regarding the air-borne noise, so many consolidated and standardized methods are sufficiently defined in order to guaranty its measurement and/or prediction models. However, vibrational measurement or prediction modelling is not as standardized due its inner complex phenomena, because its transmission is made along non-homogeneous materials -ground and soils- which is definitely more difficult to analyse or mitigate.

Some particular characteristics about railway related vibrations are:

- Short term events

- Intermittent and repeated sequences due to bogies and axles passing-by. Frequency spectra variable depending on operational issues.
- Moving forces applied
- Non-linear events
- Conditioned by:
    - Track typology -slab or ballasted tracks-
    - Subgrade typology -earthworks, structures, tunnel-
    - Soil characterization
    - Track grade of maintenance

Vibrations are initially generated by wheel–rail contact, subsequently this wave propagates through track components, subgrade and soils to surrounding buildings. Vibrations effects are basically originated by:

- Rolling stock moving loads (quasi-static) and produced deformations
- Wheel and/or Rail unevenness effect
- Punctual track defects
- Axles passing-by effect
- Other track components effect

Aforementioned, one of the major needs for vibrations prediction is to accurately define the transmission media between the source and the receptor. Following image shows common way of generated vibration. As could be seen there, once vibrations are running along soil, any kind of discontinuity as layers or punctual issues, must affect the wave transmission and subsequently, the immission results.

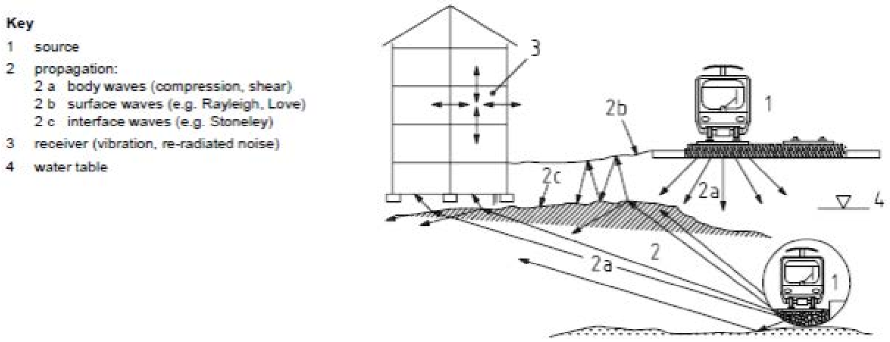
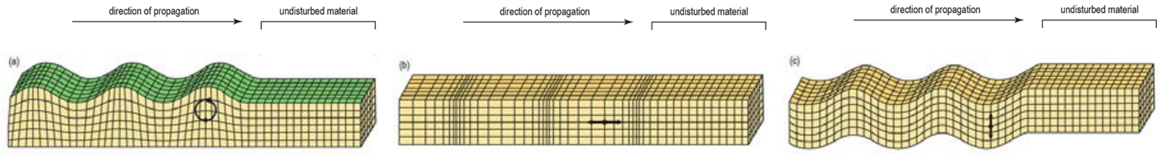


Figure 1. Generation, transmission and immission scheme. Source: ISO 14837-1:2005 Standard

Additionale, each transmitted wave along the soil is mainly divided into three typologies, a) Surface waves, b) P-Waves and c) S-Waves. The following Table shows the main ones and its shape:



a) b) c)

Figure 2. Rayleigh, P & S waves. Source: http://www.kgs.ku.edu/Publications/PIC/pic37.html

Additionally, other capital parameter to completely analyse how these waves moves and its possible attenuation, is to study not only Time domain but Frequency domain.

- Geometrical attenuation: reduction produced by the distance between the source and the measure point. It is not related to frequency domain.
- Material typology attenuation: reduction produced by traversed materials properties. This is directly related to frequency response.

It is important to note that, nowadays, this kind of vibration phenomena is not sufficiently known or modelled due to a non-possible media total characterization.

Vibrational energy arises in structures from its foundations and is distributed througthout it as structural noise and vibrations. In fact, it is common to use empirical formulations.

1.2 Effect of vibrations on humans

With the aim of developing a regulating standard for railway vibrations, structural issues and its influence over humans should be studied. It is capital to analyse possible harmful effects.

Firstly, with the aim of determining the most annoying situations, not only time domain must be done, but a deep frequency domain study must be realized to obtain enough information to evaluate its consequences.
Secondly, one of the most used concepts to analyse frequency domain and ponder it, is the Root Mean Square acceleration -RMS- weighting, that penalizes the identified most harmful frequencies for humans.

Then, due to the wide range of perceptible frequencies, it is not possible to analyse it one by one, thereby it is necessary to agglutinate the spectrum in bands -1/3 octave bands-. Moreover, this bands could be ranged from 1 to 250 Hz for human’s perception .

Finally, based on scientific literature and experience, some reference values are the following:

- Generally, the natural frequency of the most common structures is between 5 and 30 Hz.
- The most annoying frequencies for humans are under 8 Hz.
- Although railways-related vibrations do not show a clear and defined spectrum, maximum energy peaks are generally between 40 and 80 Hz.

2. VIBRATIONAL PREDICTION STUDIES

When carrying out vibrational prediction studies or measurements some stages should be completed before starting works to reach a proper characterization of the existing situation. Previous background and the applicable standards should be determined depending on the location. This process will determine affections and/or existing limit values.

Otherwise, a structural evaluation along the surroundings of the track must be done to identify possible affections. Note that some variances could appear when analysing possible environment affection depending on applicable standard values.

In order to obtain reference values, it is necessary to obtain the existing vibrational values by at-field measuring. Every possible existing source such as surrounding tracks, roads, industrial facilities, and others will be considered.
Once the base plane is fully characterised, a future scenario modelling and prediction is started. With the aim of optimizing time scale and computational cost, a two-step sequence is generally performed:

1. First approach. Analytical models are used to reach some initial rough numbers of vibrational conditions. This kind of modelling does not need important computational resources or time to make a first approach for fencing possible structural affections.
2. Numerical modelling. With the aim of considering the most reliable prediction by modelling existing subgrade, soil or surrounding structures, a numerical specific model is developed.

Finally, some possible necessary solutions for attenuation would be tested to select the optimized system for each detected case. The following list shows presented process:

1. Background and applicable standards
2. Obtain Reference Values
3. Potential affections pre-analysis
4. Future situation analytical modelling
5. First modelling results and initial affections proposal
6. Ad-Hoc soil and structures characterization
7. Detailed numerical modelling
8. Results study and affections refinement
9. Corrective and absorption solutions where necessary are proposed

3. EXISTING STANDARDS

Only European ISO recommendations or guidelines are standardized, so each country and/or region apply its own standard.

Most extended Methods are generally related to a called *K* parameter, which was regulated by ISO 2631-2 (1989). Note that this parameter was deleted in the most recent versions of the standard.

4. MODERN PREDICTIVE MODELS

Due to recent consciousness about these vibrational issues and the increase of operational speeds with High-Speed Railways, deeper studies are necessary to predict future possible effects.

Consequently, vibrational predictive models come up as a tool to simulate railways passing-by and the vibration phenomena generated, and identify possible planification not only for new lines but for track maintenance or renewal.

In recent times, different models arose with this aim. These models are commonly subdivided into independent submodels that are finally interrelated. As represented in Figure 3, three different models are involved in the process: Vehicle model, Subgrade model and surrounding structures model (in case of existing).

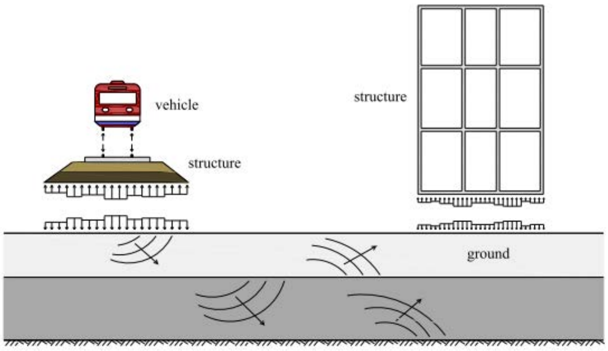


Figure 3. Submodels pipeline to complete a prediction model (Correia dos Santos et al., 2017)

4.1 Vehicle Modelling

For rolling stock modelling, the ‘Quarter-car’ model is the most extended. It is a Discrete Elements formulation to compose the vehicle model as shown in Figure 4.

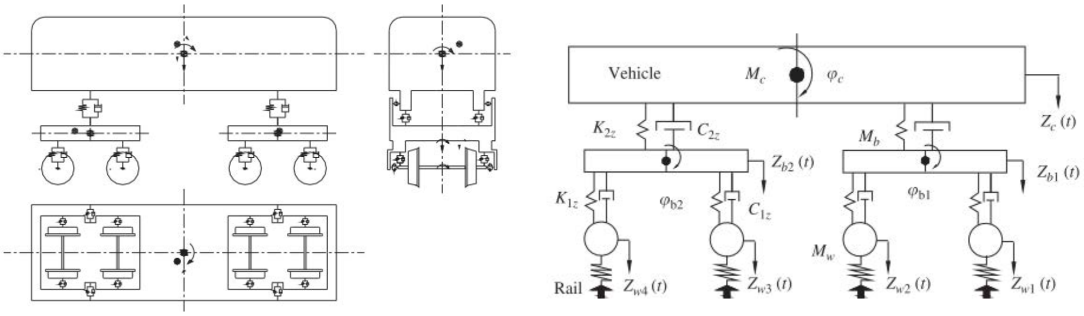


Figure 4.- Comparison between vehicle -left- and its mechanical model -right- (Xin & Gao, 2011)

These representations assume each element of rolling stock as vehicle car mass, suspended mass, unsprung mass, axles or bogies distribution.

4.2 Subgrade Modelling

Regarding track and terrain modelling, two main trends are generally developed depending on the analysis stage or needed accurate. These typologies are the analytical ones and the numerical ones.

4.2.1 Analytical Models

Analytical models (Koziol et al., 2008; Metrikine & Vrouwenvelder, 2000; Salvador et al., 2011) solve the wave equation for a 2-Dimension terrain and assuming viscoelastic layers and linear behavior soils.

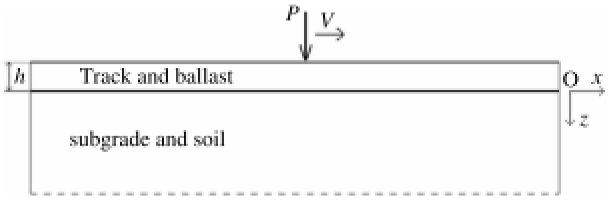


Figure 5.- Diagram for the track & soil model (Salvador et al., 2011)

These kinds of models are also able to consider the static load of the rolling stock and its harmonic without needing high computational resources or processing time.

In contrast, these models are severely limited to be considered a reliable tool to make accurate predictions to be used for planning new infrastructures because they are not able to model non-linear scenarios and punctual situations.

It could be concluded that the use of Analytical models is advisable for a vibrational first approach, initials pre-dimensioning, and/or relative comparisons between comparable track systems due to many analyses could be done in a short-term period.

4.2.2 Numerical Models

Numerical models are based in Finite Elements Method (FEM) and/or Boundary Elements Method (BEM) (Dijckmans et al., 2014; François et al., 2014; Galvín & Domínguez, 2007; Galvín & Romero, 2014; Gupta et al., 2006; Lombaert & Degrande, 2009; Romero et al., 2010, 2013), that provide precise time-domain track responses and their surroundings for accurate future planning predictions, assuming a 3-Dimension model.

Numerical models are feed through track elements geometry & materials specific properties as well as soil layers and environmental elements. These mentioned models mainly subdivided into the rolling stock FEM model and the track & soil BEM model. FEM-BEM coupling is made by Hertzian contact by applying an extra component of rail unevenness.

Usage of BEM reaches several computational savings respect FEM models by avoiding internal mesh points when calculating, and time-domain results are consciously validated by on-site measurements.

In contrast, it is necessary to note that the coupling of models is made by a discontinuous loads time-domain sequence to represent the train movement (loads birth-death process). Figure 6 shows how loads are modelled as punctual at each point depending on time. This discrete loading method commonly ballast the obtained Frequency-domain results due to the instant change of situations.

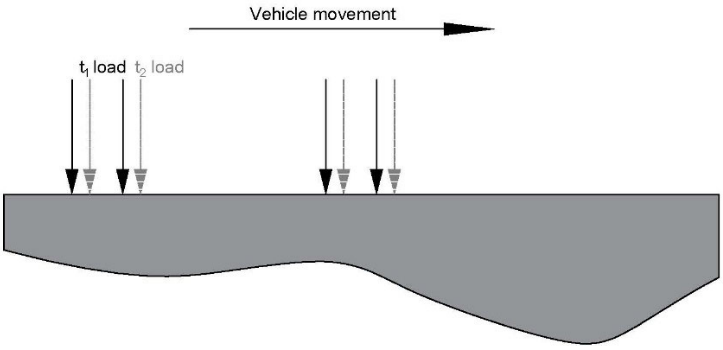


Figure 6. Common practice of numerical model's vehicle loads representation (own elaboration)

5. CONCLUSIONS

Prediction models are nowadays positioning as the elemental tool in railway networks planification and operation. These elements are able to clarify the track surroundings influence of vibrations generated by trains passing-by and also to evaluate possible means to absorb and attenuate these vibrations.

Regarding numerical models' possible future research, there is much work to do, because there are no common standards in the EU or different countries that clearly characterize this necessary process.

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