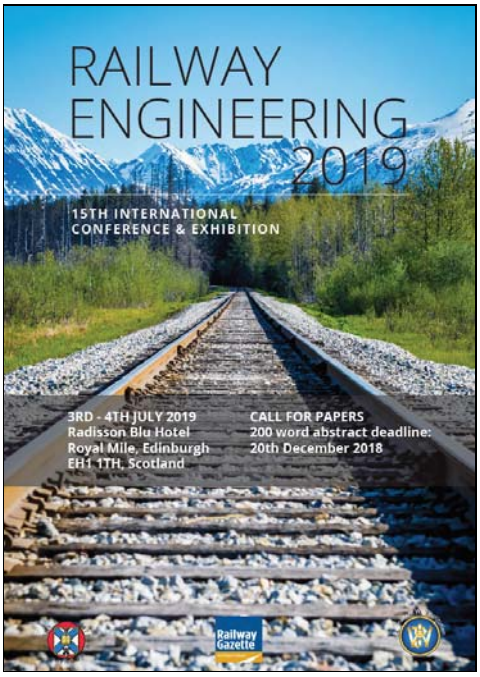
Université de Mons
Faculté Polytechnique – Service de Mécanique Rationnelle, Dynamique et Vibrations
31, Bld Dolez - B-7000 MONS (Belgique)
065/37 42 15 – georges.kouroussis@umons.ac.be



G. Kouroussis, B. Olivier, A. Romero, P. Galvin, P.K. Woodward, D. P. Connolly, A FE-BE model for predicting railway ground vibration from discrete rail defects, *Proceedings of the 15th International Railway Engineering Conference (Railway Engineering 2019)*, Edinburgh (UK), July 4–5, 2019.

A FE-BE MODEL FOR PREDICTING RAILWAY GROUND VIBRATION FROM DISCRETE RAIL DEFECTS

Georges Kouroussis, Bryan Olivier
Department of Theoretical Mechanics, Dynamics and Vibrations,
Université de Mons,
B-7000 Mons,
Belgium

Antonio Romero, Pedro Galvin
Universidad de Sevilla,
Escuela Técnica Superior de Ingeniería,
Seville,
Spain

Peter K Woodward, David P. Connolly
Institute of High Speed Rail and Systems Integration
University of Leeds,
Leeds,
UK

KEYWORDS: Railway ground vibration; singular defects

ABSTRACT
Railway ground vibration is often an issue in urban areas where singular rail defects (e.g. switches/crossings) are present. Therefore this paper outlines a hybrid time-frequency approach to efficiently compute vibration levels in their presence. The time sub-model uses a multi-body vehicle model and explicit modelling of the defect geometry to generate the force densities associated with the wheel-defect contact location. The frequency sub-model uses a 2.5D track-ground approach to simulate the propagation of vibration to the free-field. The force densities from the time sub-model are coupled with the 2.5D model to allow for the analysis of free-field vibrations due to defects. The model is validated using a combination of field results and comprehensive 3D prediction model. The model is also used to simulate the case of the low-floor T2008 tram.

INTRODUCTION

Ground vibrations due to railways are a growing challenge (Connolly et al. 2015). They occur on a wide variety of track types, including tunnels (Lopes et al. 2014), at-grade and embankments (Olivier et al. 2016). In particular though, complaints often occur near singular rail defects such as switches and crossings ((Kouroussis, Florentin, and Verlinden 2016), (Alexandrou, Kouroussis, and Verlinden 2015)). These vibrations then propagate into buildings located in close proximity to the line ((Connolly et al. 2019), (López-Mendoza et al. 2017)).

A challenge with singular defect modelling is that some assumptions commonly used for railway modelling are no longer valid. In particular, ground vibration problems often consider the track invariant in the train passage direction, thus allowing the problem to be approximated as 2.5D. In the presence of a singular defect, solely using a 2.5D approach is challenging.

As an example, Figure 1 indicates vibration originating from the passing of trains. The vibrations occur due to the moving load effect, track and wheel surface imperfections and the singular rail defect. In urban areas singular defects are particularly prominent due to the high number of interacting tracks. Therefore a growing body of research is being performed in this area, including (Kouroussis, Vogiatzis, and Connolly 2017) who proposed a hybrid numerical/experimental assessment dedicated to the urban area to study such defects using the calculation of wheel/rail forces coupled to experimental transfer mobilities of track/soil system. A large amount of sites in Brussels were analysed but no validation was performed due to the lack of field data related to the passing of trams in the tested locations.

The objective of this article is to develop a similar but fast approach using 2.5D coupled boundary element/finite element (BE-FE) model for the track/soil, dedicated to the study of localized defects, instead of experimental mobilities. A validation is proposed using experimental data and results obtained from a full 3D FE model.

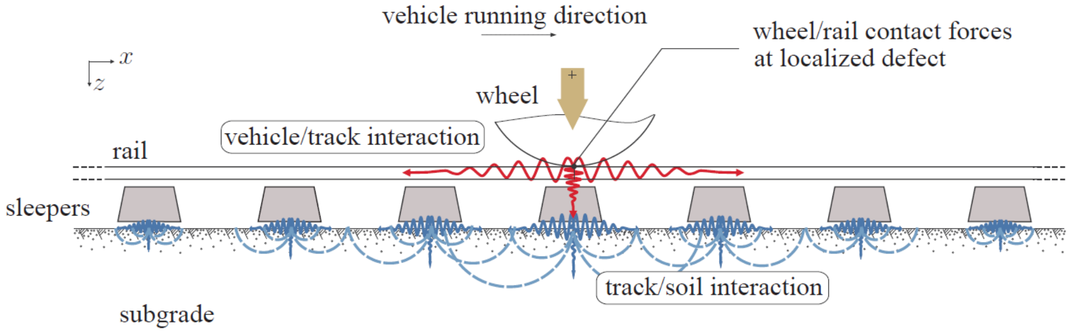


Figure 1 – Wheel/rail and sleeper/subgrade interactions

NUMERICAL MODELLING

To address the problem of vibration from singular defects, a dual-step calculation approach is used.

1. The wheel/rail force is computed at the vehicle defect location. This is undertaken using a vehicle-track model that accounts for the track flexibility and the complex geometry of the defect (e.g. step up or down joint).
2. The track/soil transfer function is computed using a 2.5D finite element-boundary element model. This does not include the contribution of the wheel-rail force at the defect location and instead assumes the track geometry is invariant in the direction of train passage.

Therefore it should be noted that both steps use separate track modelling approaches. Although the approaches are different, they use the same material properties and geometries, thus making the compatible.

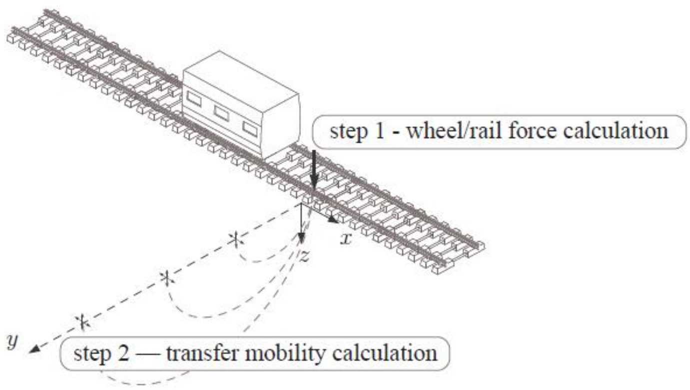


Figure 2 – Modelling approach for ground vibration from singular defects

<u>Time domain vehicle-track sub-model</u>

The time domain model is designed to compute the interaction between wheel and rail at the defect location. This contact mechanism is highly non-linear, thus requiring time domain simulation. The vehicle is modelled as a combination of rigid bodies connected by springs and dampers, thus facilitating the use of a multibody system approach (Figure 3). Using the generalized coordinates defining the motion of each body and the virtual power principle, a system of pure differential equations are built.

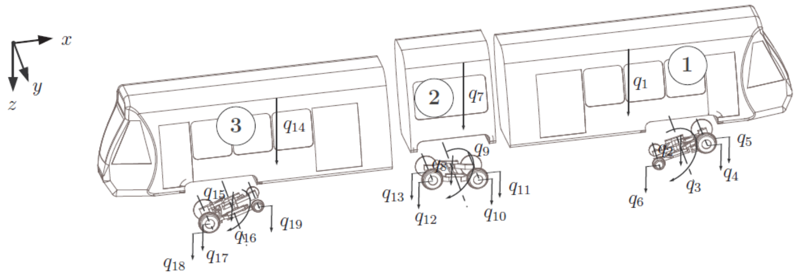


Figure 3 – Vehicle configuration

The track is a 2D two-layer finite element/lumped mass model (Fig. 3(b)). The rail is formed from Euler-Bernoulli beam elements which are supported by railpads which are modelled using springs and dampers (k_p and d_p). The sleepers are modelled as lumped masses with spacing L and the supporting ballast is also simulated using springs and dampers (k_b and d_b). The subgrade is modelled using a coupled lumped mass model which consists of:

- spring and damper elements (k_f , d_f) for the direct foundation stiffness,
- spring and damper elements (k_c, d_c) for the coupling foundation properties.

All subgrade properties are determined by fitting model receptances with a more comprehensive ground model.

The individual rail defect shapes are shown in Figure 5. Four types are considered: step-up joint, step-down joint, positive pulse and negative pulse. They are characterised by their height and/or length. Additional discussion on their shape and the non-linear wheel-rail contact algorithm at the defect location can be found in (Kouroussis et al. 2018).

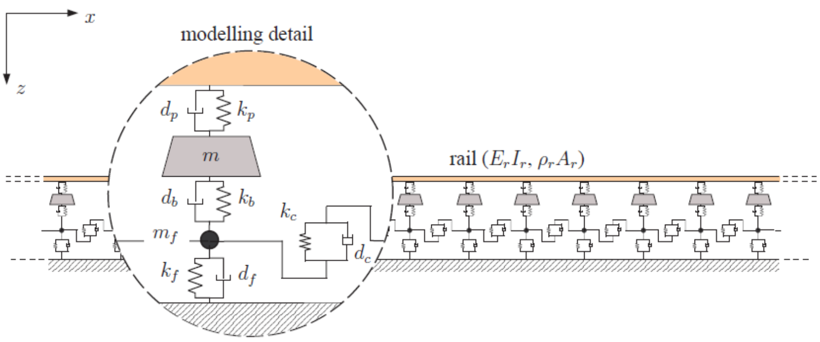
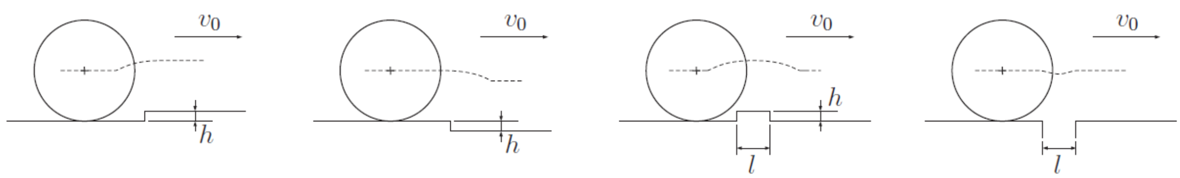


Figure 4 – Track model



(a) Step-up joint (b) Step-down joint (c) Pulse (d) Negative pulse

Figure 5 – Defect shape types

<u>Frequency domain track-ground sub-model</u>

The second model focuses on the track-ground response and is decoupled from the vehicle track model. It is a 2.5D frequency domain approach meaning the track geometry is invariant in the direction of train passage (Galvín et al. 2018). Therefore the methodology is highly efficient for simulating traditional railway ground vibration, however cannot directly simulate the forces arrising due to a singular rail defect. Instead the 2.5D model is used to compute the free-field response and then coupled with the force density results from the time domain model.

The 2.5D track-ground model is shown in Figure 6. It is designed to have the same geometry and material properties as the time domain track model. This ensures that both modelling strategies are compatible.

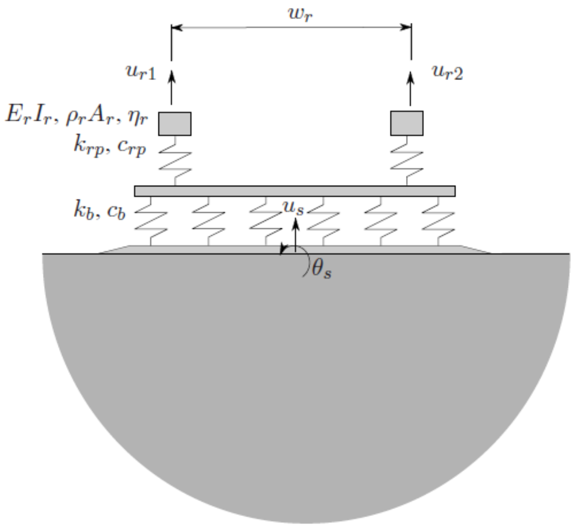


Figure 6 – Track-ground dispersion curve analysis

VALIDATION

The general modelling approach (combined time and frequency models) is validated using a 125 km/h intercity train (AM96) passing over an at-grade track with a localised defect. The vehicle has 2 × 3 cars with articulated bogies and the leading wagon has motorized bogies. The track is ballasted track resting on an embankment. Detailed vehicle, track and soil configuration are provided in (Kouroussis et al. 2016). The singular defect is a rail joint with a height 1mm and a length of 6mm. To account for the defect geometry, the vehicle wheel radius is considered.

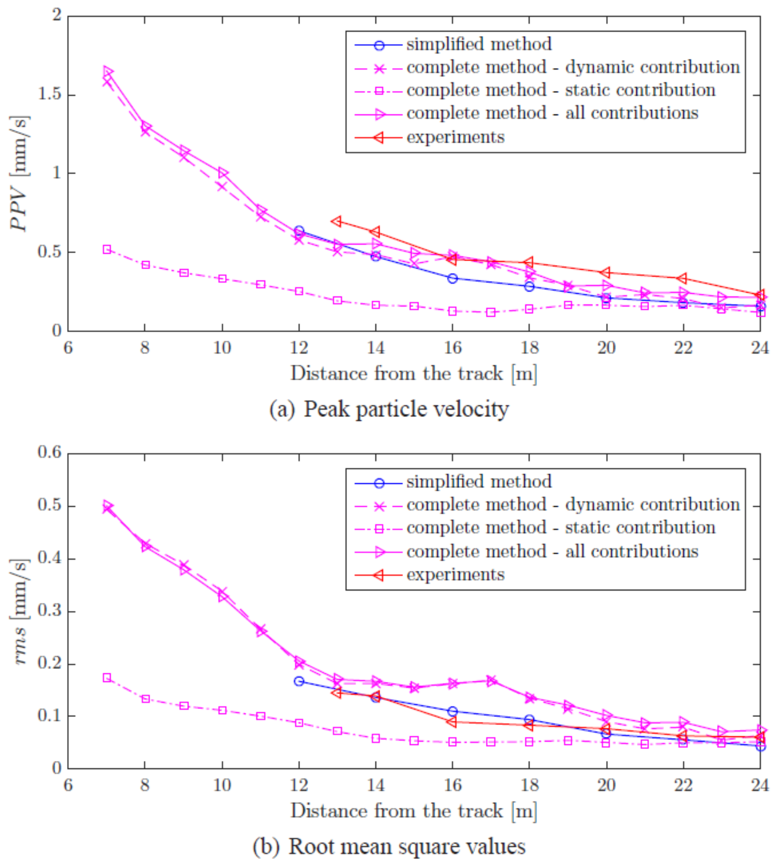


Figure 7 – Numerical and field measured results level versus distance from track

Data for validation was collected on a railway line and Figure 7 compares the results from the newly proposed method against both field results. To analyse the effect of the underlying modelling assumptions on accuracy, Figure 7 shows the case of considering:

1) All sources of vibration
2) Ignoring the localised defect
3) Subtracting the static contribution

The results show that the root-mean-square velocity values are predicted reasonably well by the numerical model. It is also shown the moving load effect has a much less dominant contribution to the overall response in comparison the localised defect. This is important because it is a key assumption of the underlying model.

CASE STUDY

To show the model capability, a case study was performed using a T2008 tram, moving at speeds lower than the critical velocity ((Dong et al. 2018), (Dong et al. 2019), (Alves Costa et al. 2010)). Figure 8 shows the key vehicle geometry. It has a high unsprung mass due to it's low-floor design, thus often resulting in elevated levels of ground-borne vibration. This is particularly true when passing over localized defects. The model was used to compute the vibration at 2m from the track due to a step discontinuity in the rail. Peak particle velocity (PPV) and maximum transient vibration value (MTVV) were computed.

Figure 9 compares the results from the full 3D model, the 2.5D model and field results. It is seen that there is good agreement between the results and that the impact of each wheel-defect contact is visible. Also, Figure 10 compares the same results, however in terms of one-third octave band frequencies (1-100Hz). Again a good agreement is achieved.

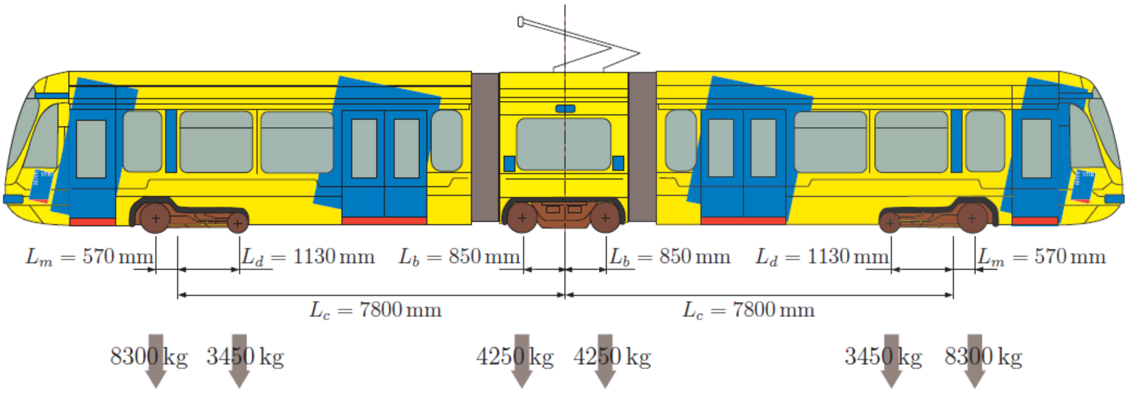


Figure 8 – Dimensions and axle loads of the T2008 tram

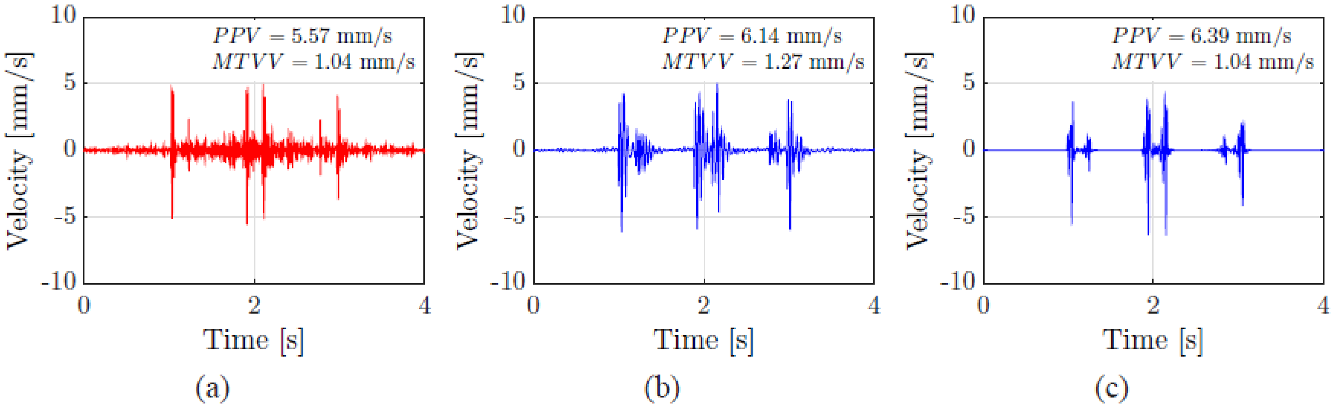


Figure 9 – Vibration time histories due to T2008 tram passage 30m/s at 2m from track, (a) field results, (b) 3D model, (c) 2.5D model

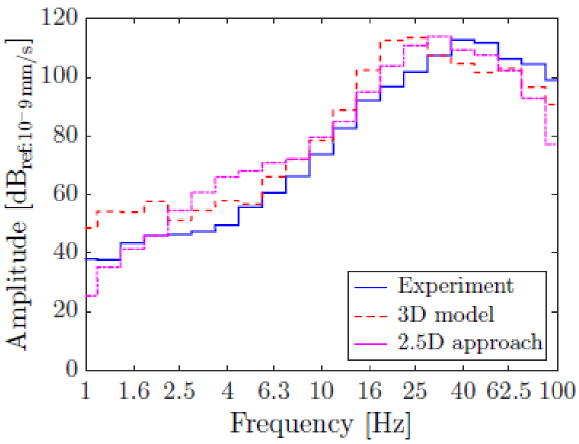


Figure 10 – One-third octaves of ground vibration

CONCLUSIONS

Railway ground vibration is often an issue in urban areas where singular rail defects (e.g. switches/crossings) are present. Therefore this paper outlines a hybrid time-frequency approach to efficiently compute vibration levels in their presence. The time sub-model uses a multi-body vehicle model and explicit modelling of the defect geometry to generate the force densities associated with the wheel-defect contact location. The frequency sub-model uses a 2.5D track-ground approach to simulate the propagation of vibration to the free-field. The force densities from the time sub-model are coupled with the 2.5D model to allow for the analysis of free-field vibrations due to defects. The model is validated using a combination of field results and comprehensive 3D prediction model. The model is also used to simulate the case of the low-floor T2008 tram.

ACKNOWLEDGEMENTS
The authors thank the University of Seville, the Université de Mons and the University of Leeds for the support and resources provided for the undertaking of this research. Funding from the University of Leeds' Cheney fellowship scheme and the Leverhulme Trust (UK) are also acknowledged.

REFERENCES

Alexandrou, G., G. Kouroussis, and O. Verlinden. 2015. "A Comprehensive Prediction Model for Vehicle/Track/Soil Dynamic Response Due to Wheel Flats." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 230(4):1088–1104.

Alves Costa, P., R. Calcada, A. S. Cardoso, and A. Bodare. 2010. "Influence of Soil Non-Linearity on the Dynamic Response of High-Speed Railway Tracks." *Soil Dynamics and Earthquake Engineering* 30:221–35.

Connolly, D. P., P. Galvín, B. Olivier, A. Romero, and G. Kouroussis. 2019. "A 2.5D Time-Frequency Domain Model for Railway Induced Soil-Building Vibration Due to Railway Defects." *Soil Dynamics and Earthquake Engineering* 120(December 2018):332–44.

Connolly, D. P., G. Marecki, G. Kouroussis, I. Thalassinakis, and P. K. Woodward. 2015. "The Growth of Railway Ground Vibration Problems - A Review." *Science of the Total Environment* 568(2016):1276–82.

Dong, K., D. P. Connolly, O. Laghrouche, P. K. Woodward, and P. Alves Costa. 2019. "Non-Linear Soil Behaviour on High Speed Rail Lines." *Computers and Geotechnics*.

Dong, K., D. P. Connolly, O. Laghrouche, P. K. Woodward, and P. Alves Costa. 2018. "The Stiffening of Soft Soils on Railway Lines." *Transportation Geotechnics* 17:178–91.

Galvín, P., D. López Mendoza, D. P. Connolly, G. Degrande, G. Lombaert, and A. Romero. 2018. "Scoping Assessment of Free-Field Vibrations Due to Railway Traffic." *Soil Dynamics and Earthquake Engineering* 114(May):598–614.

Kouroussis, G., J. Florentin, and O. Verlinden. 2016. "Ground Vibrations Induced by InterCity/InterRegion Trains: A Numerical Prediction Based on the Multibody/Finite Element Modeling Approach." *JVC/Journal of Vibration and Control* 22(20):4192–4210.

Kouroussis, G., K. Vogiatzis, D. P. Connolly, and G. Kouroussis. 2018. "Assessment of Railway Ground Vibration in Urban Area Using In-Situ Transfer Mobilities and Simulated Vehicle-Track Interaction." *International Journal of Rail Transportation* 6(2):113–30.

Kouroussis, G., K. E. Vogiatzis, and D. P. Connolly. 2017. "A Combined Numerical/Experimental Prediction Method for Urban Railway Vibration." *Soil Dynamics and Earthquake Engineering* 97.

Lopes, P., P. A. Costa, M. Ferraz, R. Calcada, and A. S. Cardoso. 2014. "Numerical Modelling of Vibrations Induced by Railway Traffic in Tunnels: From the Source to the Nearby Buildings." *Soil Dynamics and Earthquake Engineering* 61–62:269–85.

López-Mendoza, D., A. Romero, D. P. Connolly, and P. Galvín. 2017. "Scoping Assessment of Building Vibration Induced by Railway Traffic." *Soil Dynamics and Earthquake Engineering* 93(June):147–61.

Olivier, B., D. P. Connolly, P. Alves Costa, and G. Kouroussis. 2016. "The Effect of Embankment on High Speed Rail Ground Vibrations." *International Journal of Rail Transportation* 4:229–46.