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

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Railway vibration mitigation measures: a case study based on the T2000 tram circulating in Brussels.

Slimane Ouakka, Olivier Verlinden, Georges Kouroussis[1]
Department of Theoretical Mechanics, Dynamics and Vibrations, Faculty of Engineering, University of Mons, Mons, Belgium.

ABSTRACT

The sustainability of the railway systems makes it is one of the fastest developing means of transport. Their expansion is further justified by the fact that trains can enter directly into urban areas. On the other hand, this increases vibratory annoyances in the neighbourhood, particularly in densely populated centres. This paper focuses on the T2000 LRV tram operating in Brussels and the possible vibration mitigation measures, by using a combined vehicle/track/soil prediction dynamic model. The proposed model is based on a two-step approach, already validated in the past. This considers in a first step a vehicle/track subsystem taking into account the wheels/rail contact in local irregularities and, secondly, the response of the soil to the ground forces determined in the first step with the help of a finite element approach. The simulations of different measures are analysed to mitigate the induced vibration generated by the rail/wheel contact. For each level of the model, a specific measure is investigated: the use of resilient wheels (vehicle), the use of dynamic vibration absorbers (vehicle and track) or the placement of seismic metamaterial (transmission path). Then a parametric investigation is conducted to evaluate the efficiency and the level of reduction of each of the considered measures, and possible combinations of these are examined.

Keywords: Ground vibration mitigation, Train-track-soil interaction, Resilient wheels, Dynamic vibration absorbers, Seismic metamaterial.

INTRODUCTION

The last years have been characterized by the exponential growth of the rail systems in terms of the transportation sector on a global scale. Furthermore, this trend is expected to increase in the following future due to the sustainability of this means of transportation and its capacity in terms of passengers and/or goods, which is in line with the global decarbonization target that Europe, and not only, wants to achieve by 2050 (i.e., to cover 50% of the total land transportation by rail lines). To prepare the rail lines (new and existing ones) for this important goal it is of crucial importance to overcome all the negative effects that those can generate to the neighbourhood in urban areas (Ouakka et al. 2021).

Among the possible negative effects that can be generated by the rail traffic, ground-borne vibration and noise (GBV/N) are the ones that could be a real obstacle for the desired target, due to the public concerns arising because of them. These two effects are generated at the rail-wheel interaction in the form of vibrations, and they then propagate through the transmission path (generally soil) until reaching the surrounding buildings' foundations. By the oscillation of the latter, the residents inside these constructions are subjected to the vibration or noise generated by these movements, as can be noticed in Fig. 1. These two effects are negative to both humans and buildings. For what concern to the influence on humans is either in their daily activities

[1] Slimane Ouakka, M.Sc., Olivier Verlinden, Prof., Georges Kouroussis, Prof.

(e.g., sleep, communication etc.) or in their health (Maclachlan et al. 2018; Croy et al. 2013). Whereas the impacts on buildings are mostly cosmetic or directly to their equipment.

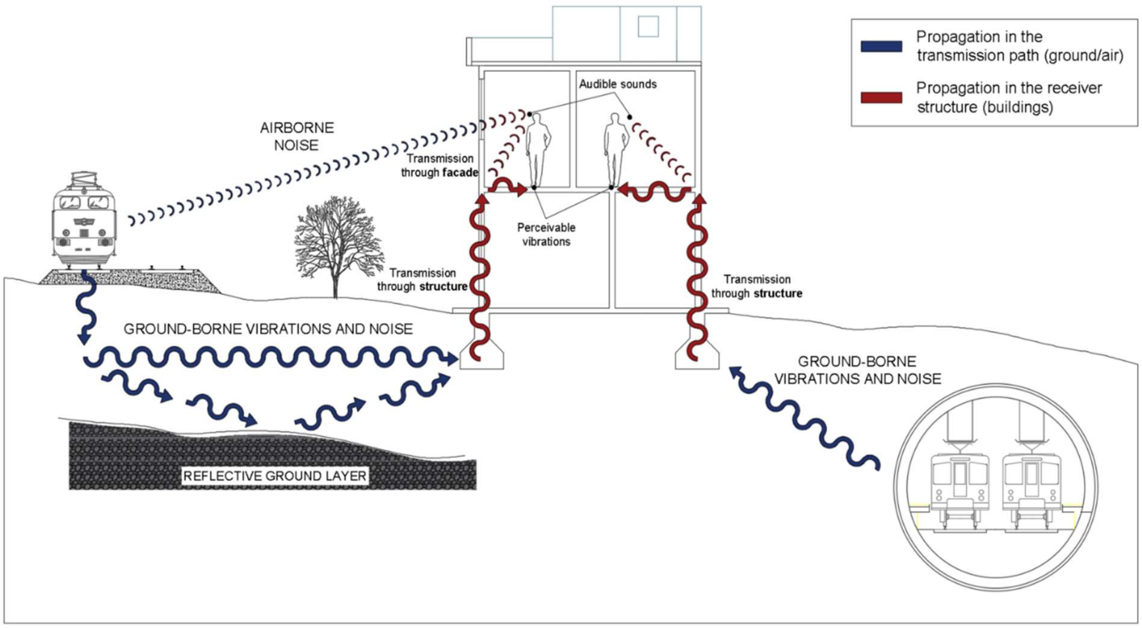

Figure 1. *Railway mechanism effects and transmission paths of ground-borne vibration and noise*

Different studies have been conducted in the last years to investigate the effects of the induced vibration generated by the railway traffic to come out with possible mitigation measures that could cancel or at least attenuate them (Lombaert et al.2015; Baziar et al. 2019). Most of these measures apply to the following three subsystems of the railway environment (Ouakka et al. 2022):

- Vehicle
- Track
- Propagation path

In this study, for each of the sub-systems, mitigation measures will be analysed, as follows: resilient wheels (RES), dynamic vibration absorbers (DVA) and a seismic metamaterial respectively (SMM).

To give an evaluation of the performance to mitigate the effects of the induced vibration caused by the passage of the rail, the T2000 tram circulating in Brussels will be considered. This tram is a medium-size system formed of three cars two large on the sides and a small one in the middle, its dimensions together with its axial loads are illustrated in Fig. 2. The T2000 vehicle will be modelled with a complete vehicle/track/soil based on the two-step approach (Kouroussis et al. 2012; Kouroussis et al. 2014).

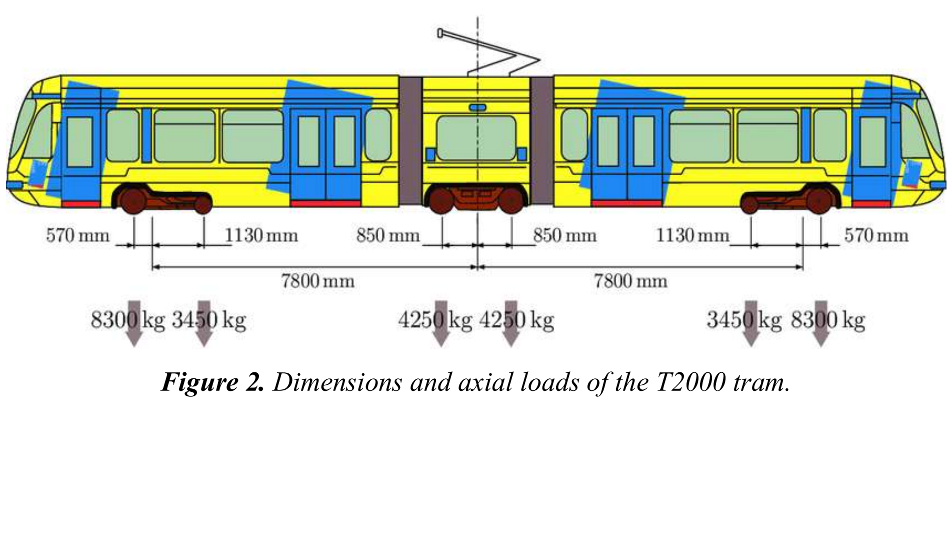

Figure 2. *Dimensions and axial loads of the T2000 tram.*

NUMERICAL APPROACH FOR VIBRATION PREDICTION

The Vehicle/track/soil model used for the simulations in this paper is the two-step model proposed by (Kouroussis et al. 2012). This model is particularly suitable for the aim of this study because is made up of three different subdomains, where will be introduced the intended mitigation measures, organized into two distinct parts, the vehicle-track subsystem and the soil subsystem, as reported in Fig. 3.

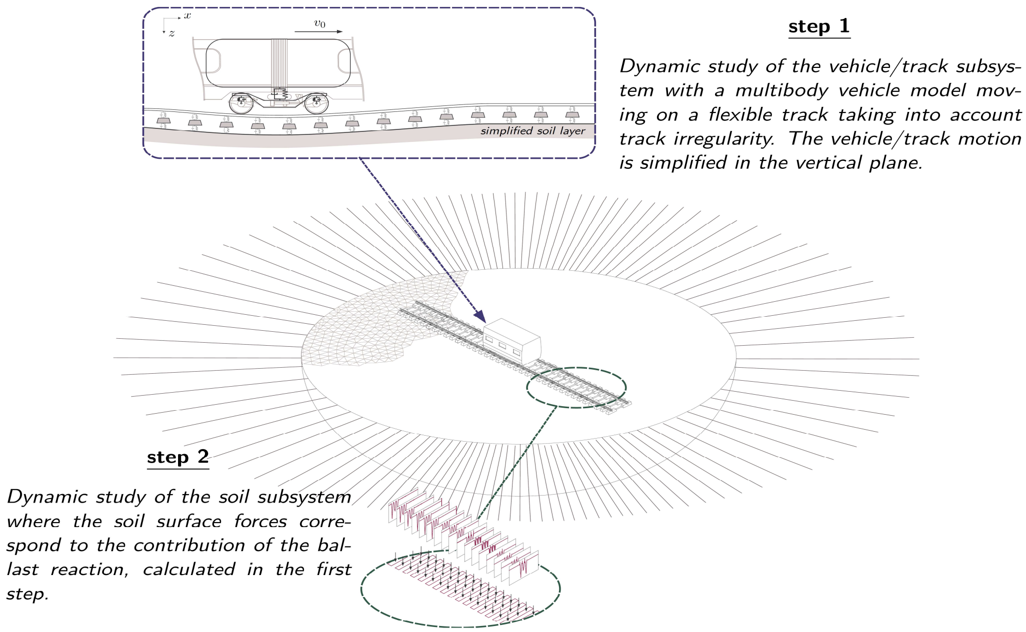

Figure 3. *Vehicle/track/soil model, decoupled between the ballast and the soil.*

The two-step approach, as the name suggests, is composed of two different steps. Firstly, the vehicle-track subsystem is time-integrated, with the multibody software Easydyn (Verlinden et al. 2005), using the minimal coordinates approach that computes the forces applied by the track to the soil. Whereas, in the following step, the calculated loads are applied on the soil model implemented in the commercial Finite Element Software ABAQUS.

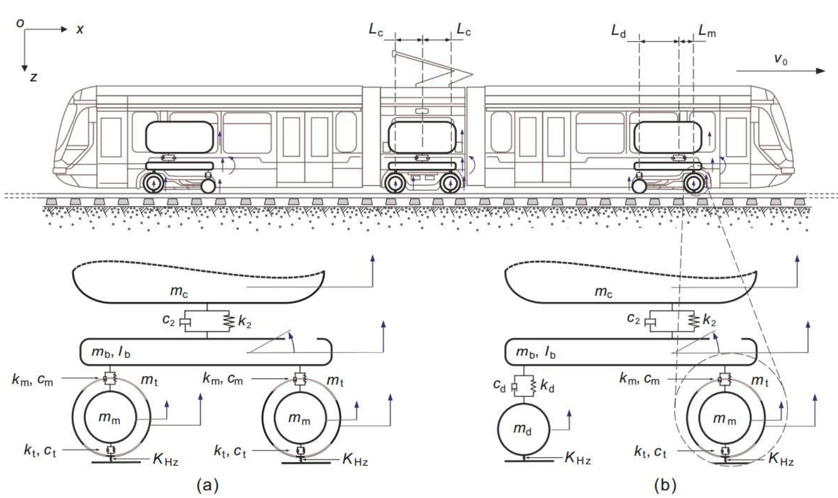

Figure 4. *T2000 tram multibody model: (a) central bogie; (b) leading bogie.*

In this research, the two-step approach is used to model the study case related to the T2000 tram as done by Kouroussis et al. 2019. In particular, the dynamics of the vehicle-track subsystem is simulated by considering a multibody rigid vehicle model with visco-elastic suspensions (Fig. 4) moving at the speed v_0 on a flexible track (Fig.5) including a rail irregularity. The wheel/rail forces are defined using non-linear Hertz's theory and allow the vertical coupling between the vehicle model and the track. In particular, the dynamics properties of the T2000 tram and the track are reported are the ones considered by Kouroussis et al. 2011.

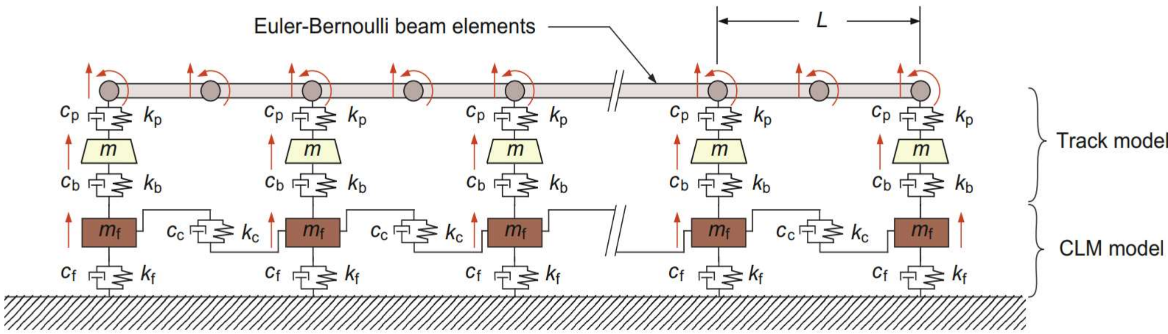

Figure 5. *Track/foundation coupling.*

Whereas the soil is represented by the half-sphere made up of classical finite elements, enveloped by infinite elements (see Fig.6) as presented by Kouroussis et al. 2012, with the soil characteristics and layering according to Degrande et al. 1996.

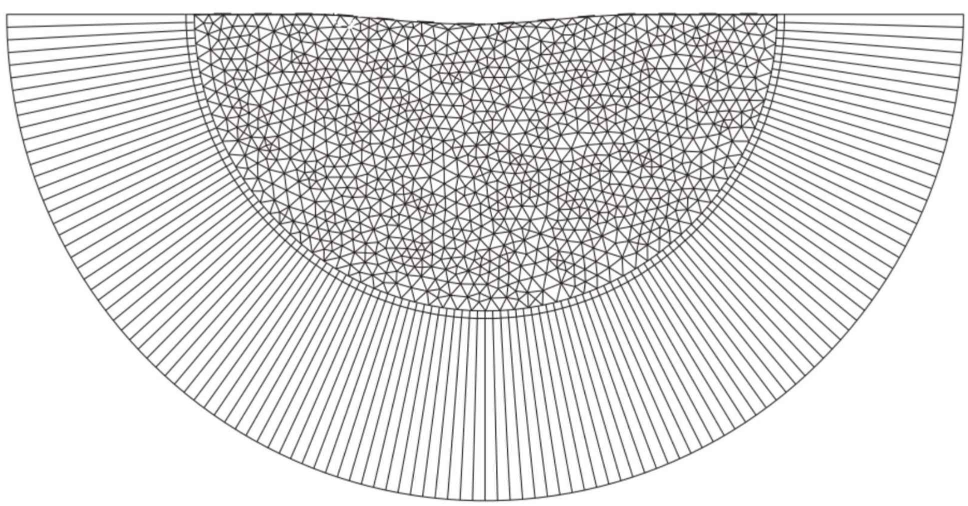

Figure 6. *Half-sphere finite element model of the soil*

MITIGATION MEASURES INVESTIGATED

There are different mitigation measures reported in the literature and just as many are put into practice in the railway industry, to minimize the effects of the ground-borne vibration coming from rail traffic (Ouakka et al. 2021). For the sake of the objective of this paper, one measure will be investigated for each one of the three subdomains modelled. These will be presented in the following sub-sections, as follow:

- Resilient wheels (measure in the vehicle)
- Dynamic vibration absorbers (measure in the track)
- Seismic metamaterial (measure in the transmission path)

Resilient wheels

Resilient wheels are well speared in railway systems for their beneficial effects, especially in terms of noise impact (Bouvet & Vincent, 2000). In addition, this type of wheel has demonstrated good results also towards the ground-borne vibration in the T2000 (Kouroussis et al. 2011). Resilient wheels are composed of a rubber layer inserted between the web and the tread, generally manufactured by viscoelastic pads arranged in circular pairs, see Fig. 7.

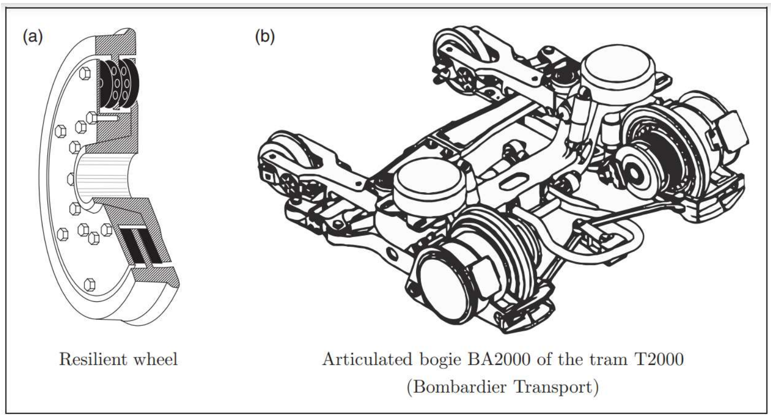

Figure 7. *T2000 Details: (a) Resilient wheel and (b) BA2000 bogie.*

In this paper, a single variant of the resilient wheel has been investigated. These wheels have the same mass, as the T2000, but thanks to the change of the rubber configuration, a different equivalent stiffness is obtained from k_t=145 MN/m (nominal) to k_t=13 MN/m (measure investigated).

Dynamic Vibration Absorbers

The use of Dynamic Vibration Absorbers (DVAs) in railway tracks to attenuate induced vibration is becoming widespread due to the reduction of the rail corrugation and therefore vibration mitigation (Grassie & Elkins 1998). The concept of DVA has been previously applied to the T2000 by Kouroussis et al. 2019.

In the present model, the DVA is identified by the following its mass m_a(20 kg), spring $k_a(10^6\ \mathrm{N/m})$ and dashpot $d_a(10^3\mathrm{Ns/m})$, associated with the motion in the same direction as the undesired motion of the primary system, see Fig. 8.

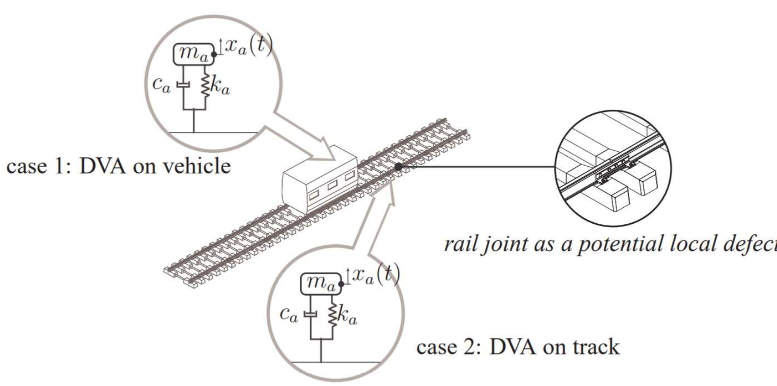

Figure 8. *Schematic representation of a damped DVA attached to the vehicle/track system.*

Note that as shown in Fig.8 the DVA could be attached either to the track or the vehicle, in this research the DVA on the track will be considered.

Seismic Metamaterial

Considering a group of piles put in an array to mitigate the effects of vibration waves is a novel concept in railway application and are often called seismic metamaterials (SMM) barriers, as presented by Li et al. 2020. In this paper, a group of four-by-four concrete pile array is introduced in the ABAQUS soil FE model. Fig. 9 provides the geometrical characteristics of the group piles, with an initial distance between the front edge of SMM and the centre line of the track of 10 m. The material properties of the inserted piles are as follow E=70000 MPa, ρ=2700 kg/m and $\nu = 0.2$.

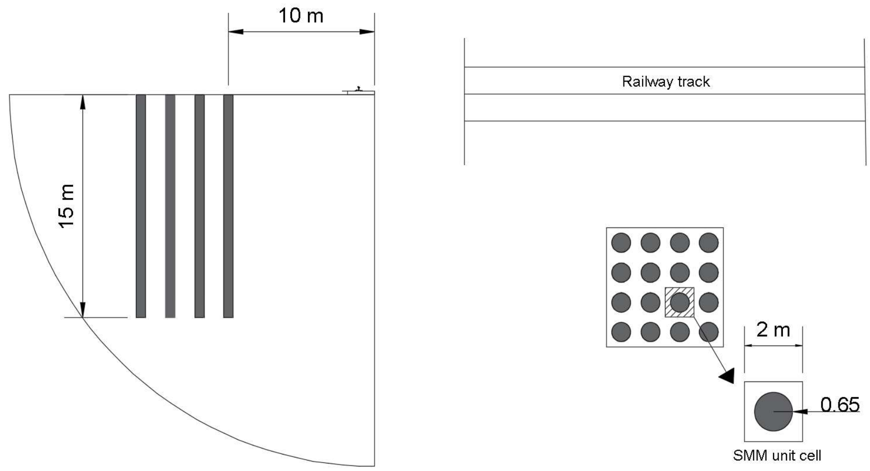

Figure 9. *Distribution of the array pile in the model, with details of the SMM units.*

VIBRATION TIME HISTORY ANALYSIS

In the first stage, the time history of the reference case (i.e., without any mitigation measure introduced) has been analysed to be able to evaluate the level of attenuation of each of the mitigation measures investigated in this study as depicted in Fig. 10. The tram speed at which the results are shown is 60 km/h for an observation point located at 18 m (just at the end of the SMM that will be inserted) from the centre of the track to be able to evaluate and compare the three mitigation measures considered on this paper with the reference case of the T2000 tram.

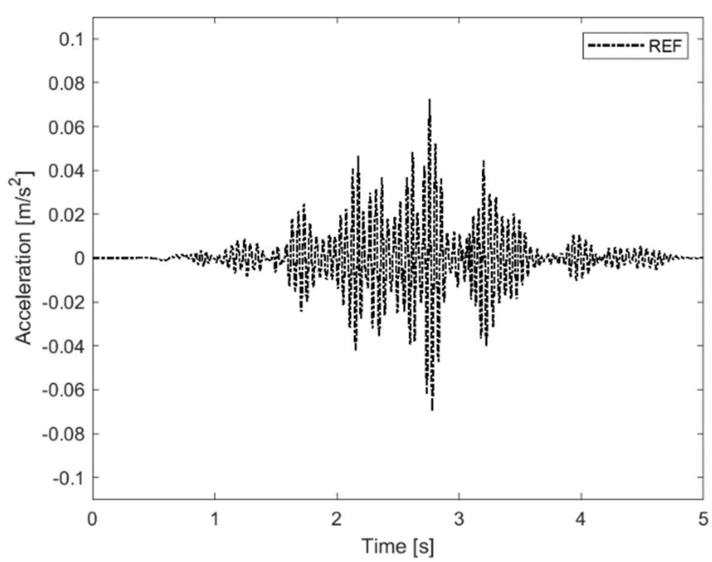

Figure 10. *Reference time history of vibration accelerations at 18 m with tram velocity of 60 km/h.*

Fig. 11 shows the time history curves of the vibration acceleration at the free field for the three mitigation measures. Resilient wheels - RES, dynamic vibration absorber - DVA, and seismic metamaterial – SMM Fig. 11 (a), (b) and (c) respectively. These have been overlapped to the reference case - REF to be able to evaluate the attenuation in terms of acceleration. Whereas Fig. 11 (d) overlap the acceleration of the three mitigation measures and REF of the T2000.

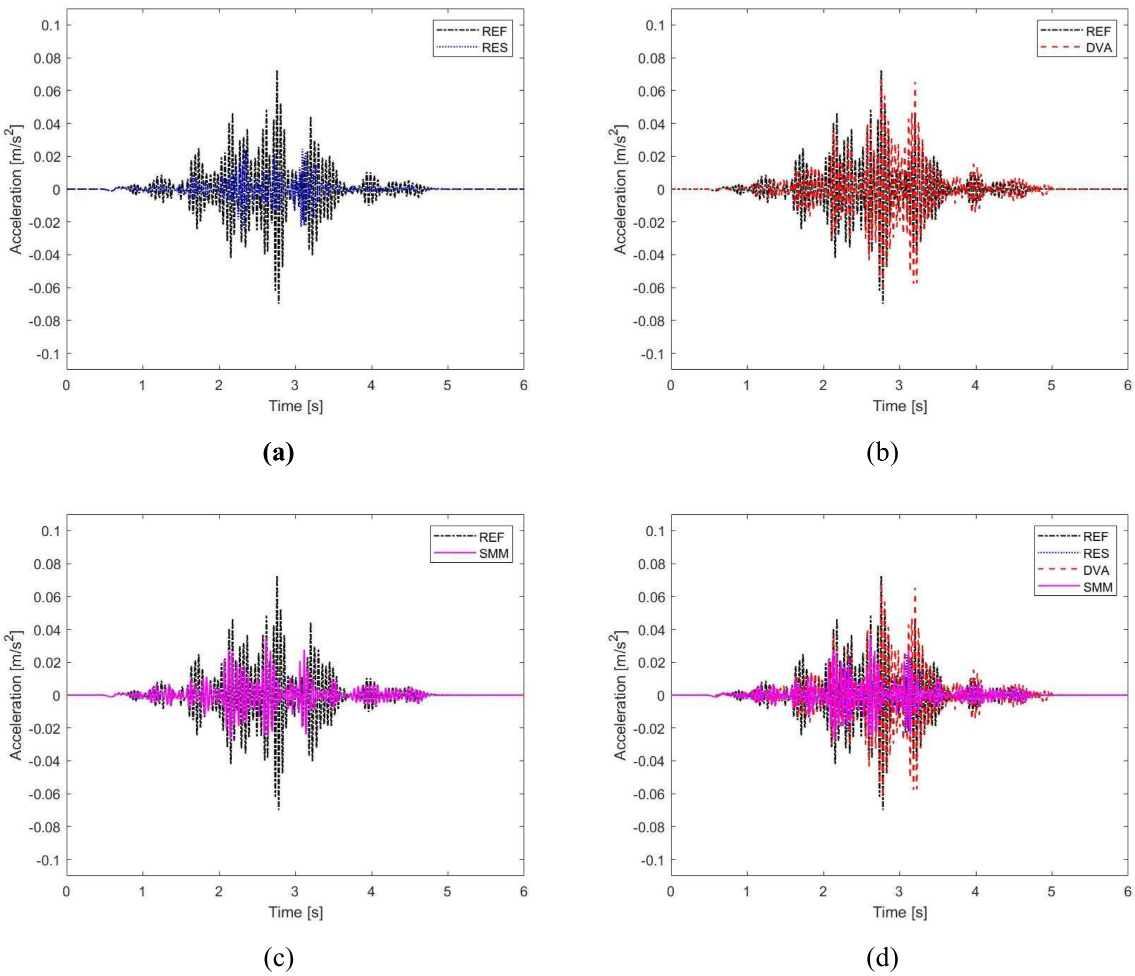

Figure 11. *Time history of vibration accelerations among the different mitigation measures at 18 m with tram velocity of 60 km/h.*

CONCLUSIONS

The design carried out in this research for the three mitigation measures each at one of the three levels for the validated model of the T2000 tram, shows the improvement in terms of vibration attenuation. The following reductions in terms of maximum acceleration are obtained:

- RES reduction of ~ 64 %
- DVA reduction of ~ 5 %
- GP reduction of ~ 52 %

The case of resilient wheels in this configuration has shown the best attenuation level, however, due to the maintenance cost of this technology the introduction of SMM that has shown as well good reduction might be the right answer of the induced vibration in railway, also considering the fact metamaterial behaviour can be improved by rearrangement of their unit cells and the enhancement of the material proprieties.

Further parametric investigations are worth understanding the capability of these mitigation measures, considering additional proprieties and the case of DVA applied at the vehicle instead of the track as in this paper.

Although in the current study has been presented an application of these three mitigation measures applied to urban tram due to its representative role. Their concept can be extended to other different types of vehicles starting from the underground train up to the high-speed train.

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