

**NUMERICAL SIMULATION OF TRAIN-TRACK INTERACTION FOR
THE DYNAMIC PERFORMANCE ESTIMATION OF AN INNOVATIVE
METRO EMBEDDED-RAIL TRACK SYSTEM**

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ABSTRACT

Vibrations and structure borne noise due to train transit in underground railways is still one of the major technical issues for both network operators and companies involved in track engineering and construction. Various kind of ballastless track systems are often installed in tunnels of urban mass transit systems to reduce vibrations and structure borne noise. This paper deals with an innovative embedded-rail track system which is designed for combining the advantages of improved vibration attenuation with those of reduced maintenance costs and of a smooth and obstacle-free surface in case of emergency evacuation.

1. INTRODUCTION

The need of vibration attenuation and quick maintenance operations is greatly felt by underground operators since lines usually run below densely populated areas and traffic may be stopped only few hours during the night. To achieve better vibration isolation, slab track systems (figure 1) have been developed. However, such systems require big tunnels due to the use of an additional suspended mass. Moreover, in case of malfunctioning, slab track systems require long and difficult maintenance operations.

For such reasons, embedded track systems have been developed (figure 2). The main feature of such systems is that the rail is almost completely wrapped by rubber. Thus, through a correct choice of the adopted rubber compound and of the rubber jacket dimensions, it is possible to achieve isolation characteristics that are comparable with those of slab track systems but the necessary space below the rails is significantly less. In fact, it is possible to directly fix the rubber jacket to the inverse arch of the gallery since no additional suspension

layer is required. To be able to quickly and cheaply change the rails and/or the rubber jacket, a special design of the embedded track system is necessary, i.e. the track system has to be dismountable. Another advantage of embedded track systems is that the concrete can be poured so to achieve a flat road at the same level of the top of the rails thus facilitating the evacuation of passengers and/or the arrival of rescue vehicles in case of an emergency. The main drawback of such systems, instead, is their high deformability that does not guarantee the correct positioning of the rails during vehicle transit.

In this paper, the dynamic performance of a removable embedded track system (REMS) is investigated through numerical simulation of train – track interaction in order to assess its isolation characteristics as well as alignment and gauge variations due to train transit. The implemented numerical algorithm is based on a multi-body model of the metro train and on a finite element schematisation of the track. The differential equations of the two subsystems are coupled by the wheel-rail contact forces which are a function of both vehicle and track coordinates. Train and track equations of motion are simultaneously integrated in the time domain using Newmark integration algorithm. An output of the train – track interaction model are the vibrations transmitted to the ground as well as the displacement of the rails. A comparison with a conventional slab track with direct fixation is also presented.

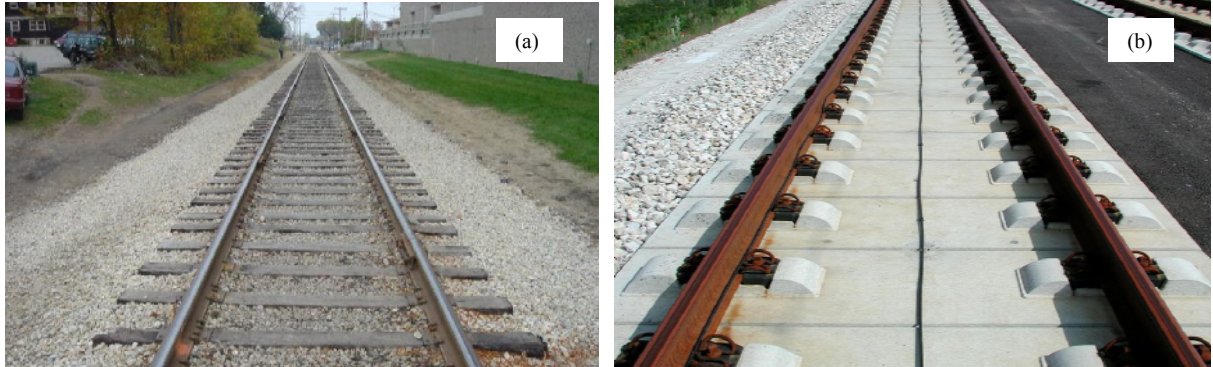


Figure 1. Traditional track systems for train and metro lines: ballast track (a) and slab track (b)



Figure 2. Embedded track systems for metro lines

2. THE EMBEDDED RAIL TRACK SYSTEM

The cross-section of the considered removable embedded track system is shown in figure 3. It can be clearly seen that the rail the rail is surrounded by three different layers of rubbers in lateral direction and by two different layer of rubber in vertical direction. The different layers allow to control and tune the level of vibration attenuation as well as of the rail displacements during train transit and to easily dismount the REMS.

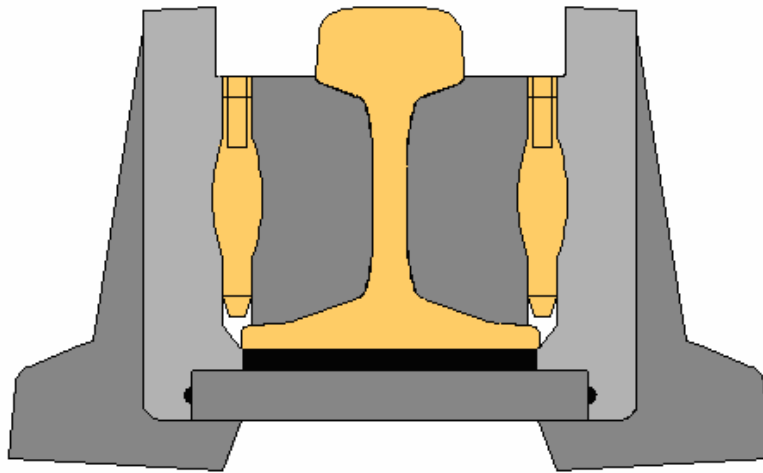


Figure 3. Schematic drawing of the removable embedded track system (courtesy of CDM®)

In the shown configuration, the rail is an UNI 60 rail. The adjacent rubber supports, called “inner jacket”, are mainly responsible of the attenuation of lateral vibrations induced by train transit and of gauge maintenance. Then, two “keys” (shown in orange in figure 3) are used to symmetrically pre-compress the track system in order to avoid rubber elements’ openings due to the application of lateral loads, to increase the lateral stiffness of the REMS and to allow the mounting/dismounting of the track. Note that keys can be made of any material. During installation of the REMS or during its dismounting, keys are the last/first elements that are inserted/removed by applying a vertical force.

Two more rubber elements (shown in light grey in figure 3, and from now on called “outer jacket”) are necessary to allow the use of the key system. In fact, without the outer jacket, one side of the keys would be in contact with the rough concrete surface thus making it very hard to inset and pull out the keys. Around the outer jacket there are two L-shaped rubber elements that, once the REMS is installed, become irremovable and represent the support of the whole system.

Below the rail there is a soft rubber layer (in black in figure 3) that is responsible for the attenuation of most of the vertical vibrations induced by train transit. In fact, according to the requirements of the metro stake holders, this layer can be easily changed to increase damping or stiffness. Below this pad, a second irremovable rubber layer, usually harder and from now on called “substrate” (in dark grey in figure 3), separates the REMS from the concrete thus allowing an easy dismounting of the system.

Note that all elements of the considered REMS can be considered as continuous in longitudinal direction. Cables for signalling can be easily fitted below the keys.

3. IDENTIFICATION OF STIFFNESS AND DAMPING CHARACTERISTICS

The model used to simulate train – track interaction schematized the vehicle using a multibody approach and the track using a FEA approach. However, to be able to carry out simulations in a reasonable time, it is necessary to dynamically condensate the rubber elements into one single rubber element, eventually having non-linear visco-elastic characteristics. Thus a refined FEA model of the REMS is used.

The first step is to determine the non-linear characteristic curve of the track system, i.e. the applied vertical load on the rail top vs. vertical rail displacement curve. For this purpose a 2D FEA model of the REMS is developed.

Once this non-linear curve has been determined, Winkler’s model is used to determine the equivalent force to be applied to the rail top of a finite track sample that allows to achieve the same vertical rail displacement that would be obtained with an infinite track sample. Usually, the finite track sample is 300mm long.

Finally, the determined vertical force is applied to a 3D FEA model of the REMS having a length of 300mm and the equivalent vertical stiffness and damping characteristics of the track are determined. In order to determine both equivalent lateral stiffness and damping, a lateral force pointing outwards is applied to rail top so that the resultant applied force has an inclination of 26deg with respect to the vertical direction as prescribed by the standards.

3.1 2D FEA model

Figure 4 shows the 2D FEA model used to determine the non-linear vertical stiffness characteristic curve of the REMS. The rubber surfaces in contact with the surrounding concrete are supposed to be tied to the ground while the inner surfaces can slide one with respect to the other. Coulomb friction model is considered: the static/sliding friction coefficient in rubber-rubber contacts is assumed to be equal to 0.87 while in rubber-steel contacts it is supposed to be equal to 0.67.

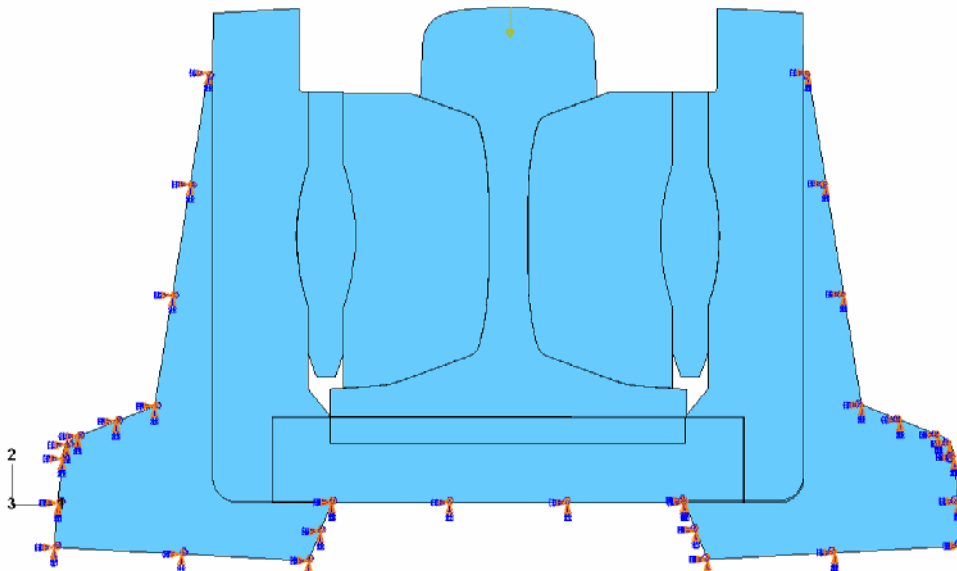


Figure 4. 2D FEA model of the removable embedded track system

The model is fully non-linear in the sense that both the hyperelastic characteristic of the rubber material, the large displacements/rotations (non-linear geometry) of the various components of the REMS and the finite sliding between adjacent elements are accounted for.

The adopted mesh has a mean size of 2mm x 2mm and 4-node bilinear plane stress quadrilateral elements are used. Pre-compression is obtained by inserting keys that are 20% more wide than their place. To facilitate key insertion, contact friction between keys and adjacent rubber elements (inner and outer jackets) is reduced to 0.3. This is equivalent to use some lubricant during key insertion.

By applying an increasing vertical load to the rail top and by calculating the corresponding reaction force, it is possible to determine the non-linear vertical characteristic curve of the REMS (figure 5) that is the input of Winkler’s model. Note that the applied force is measured in N/mm, i.e. it is a force per unit sample length.

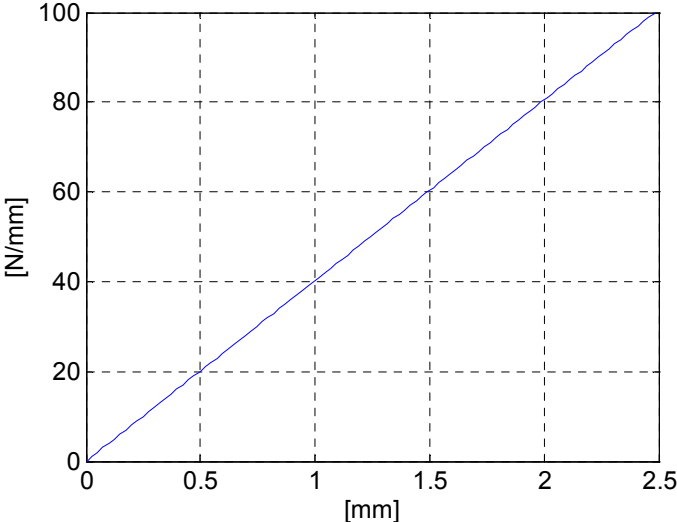


Figure 5. Vertical characteristic curve of the removable embedded track system determined through the 2D FEA model

3.2 Winkler’s model

Winkler’s model ([1]) considers an infinite rail and a continuous rail support (figure 6). Through a simple analytical formula, the rail vertical displacement w is determined as a function of the applied vertical loads Q_i (axle loads). In fact, due to the linearity of the model, force superposition can be used. Thus, in the following equations, a single vertical load Q is taken into account.

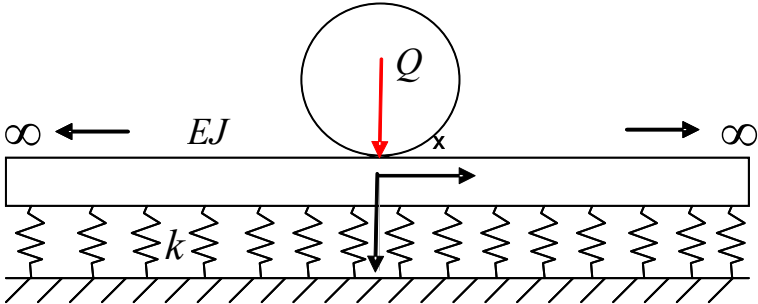


Figure 6. Track scheme on which Winkler’s model is based

The differential equation that governs the rail vertical deformation is

$$EJ \frac{d^4 w}{dx^4} + kw = 0 \quad (1)$$

EJ being the flexural stiffness of the rails and k being the stiffness of the elastic bed, i.e. the gradient of the curve shown in figure 5. The closed form solution of this differential equation is

$$w(x) = \frac{Q}{2kL} e^{-\frac{x}{L}} \left[\cos \frac{x}{L} + \sin \frac{x}{L} \right] \quad (2)$$

where

$$L = \sqrt[4]{\frac{4EJ}{k}} \quad (3)$$

Note that, in general, k is a function of w . Thus, w has to be determined iteratively: starting from a given value of k , e.g. from the value at zero deformation, the vertical deformation w of the rails is determined through equations (2) and (3); a different stiffness value k of the elastic bed corresponds to this value of vertical deformation; inserting this new stiffness value into equations (2) and (3) a new vertical deformation of the rails is found; and so on. Few iterations are sufficient to determine both w and k . Figure 7 shows the rail deformation determined using Winkler's model for the metro vehicle considered.

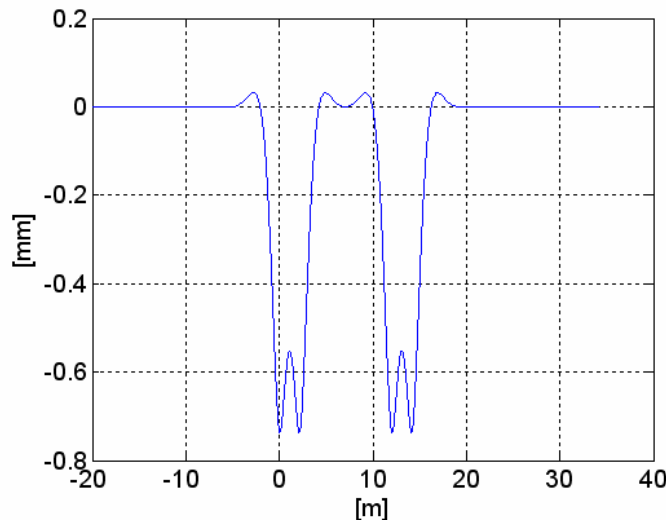


Figure 7. Rail deflection determine through Winkler's model

Knowing the maximum rail deformation (0.71mm in our case), it is possible to determine the load to be applied to a finite section of the removable embedded rail section from the non-linear vertical characteristic curve shown in figure 5 (32N/mm in our case). This load will be applied to the 3D FEA model of the REMS. Since the 3D track sample is 300mm long and a concentrated force will be applied, this force will be equal to 9.6kN.

3.3 3D FEA model

The 3D FEA model (figure 8) is identical to the 2D FEA model for what concerns material characteristics, interactions and boundary conditions. The only difference is that, being 3D

instead of 2D, the concentrated applied load is no longer a load per unit length and that the elements chosen are 8-node linear brick elements.

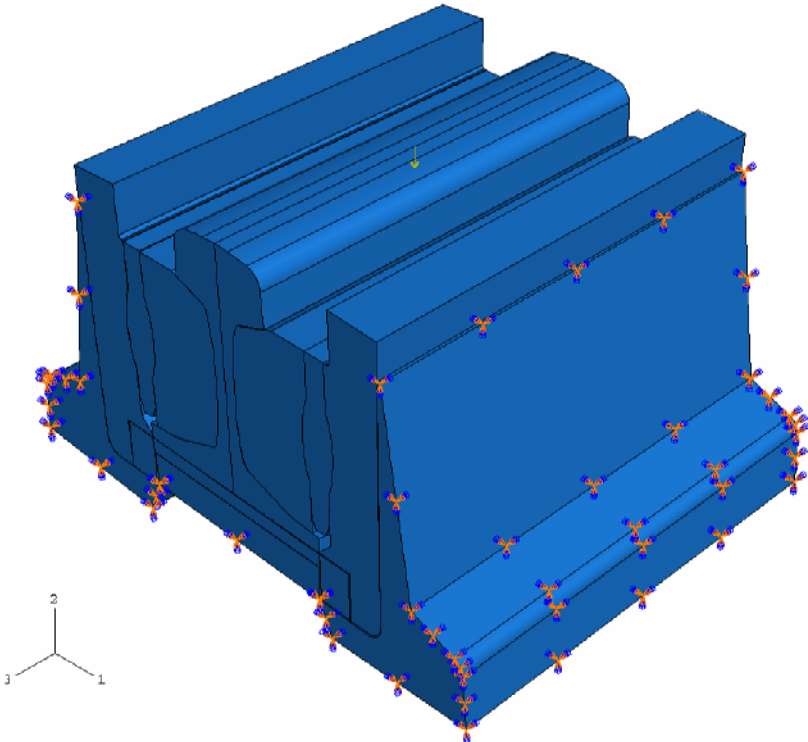


Figure 8. 3D FEA model of the removable embedded track system

The sample length of 300mm is usually chosen for carrying out laboratory tests to characterise the track system and in particular the rubber elements. Shorter samples would produce results that are too much affected by boundary conditions (longitudinal flow of rubber) while longer samples would give results in which the flexural bending of the rails is no more negligible.

The first FEA simulation is carried out by applying a vertical load equal to 9.6kN at rail top at midspan. This simulation has allowed to assess the strains and stresses (figure 9) in the rubber elements and in the rail, thus allowing to verify the correctness of the design and of the rubber material chosen. This simulation has also allowed to determine the equivalent vertical stiffness of the removable embedded rail system. As already pointed out, the stiffness varies as a function of the rail deformation. However, in such case, the dependency is weak. It was therefore chosen to consider a constant stiffness value equal to the mean stiffness during the rail deflection from 0 to 0.71mm.

For what concerns damping, the visco-elastic properties of the rubber elements should have been inserted (note that these properties are usually a function of the deformation amplitude). However, to simplify the identification of the equivalent vertical damping to be introduced into the train – track simulation model, it was decided to use an equivalent damping value that was experimentally determined on a similar embedded track system.

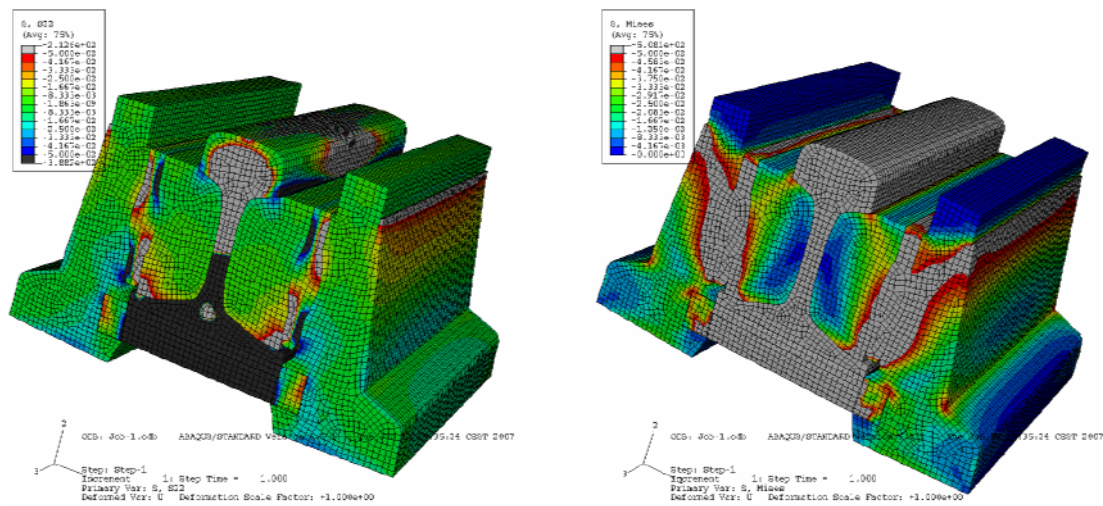


Figure 9. Strain along direction 2 (a) and Von Mises stresses (b) due to the application of a vertical load at rail top at midspan

Two more FEA simulations are carried out to determine the equivalent lateral and roll stiffness values of the REMS. At first, a lateral load equal to 9.6kN is applied to the rail top at midspan. In this simulation the rail translates laterally and rotates around its roll centre. Then, a lateral load equal to 9.6kN is applied to the roll centre of the rail at midspan. In this simulation the rail only translates laterally thus allowing to determine the equivalent lateral stiffness of the removable embedded rail system. Once this stiffness value is known, the previous simulation can be used to determine the REMS equivalent roll stiffness.

For what concerns equivalent lateral and roll damping values, the same consideration done for the vertical damping value holds: experimental valued determined on a similar embedded rail system were used.

Finally, as required by the standards, the REMS was virtually tested by applying a load inclined of 26deg with respect to the vertical direction. In order to achieve such load, both a vertical and a lateral load were applied to the rail top at midspan. While the applied vertical load was equal to 9.6kN, the lateral load was chosen equal to 4.7kN. This FEA simulation has allowed to verify the behaviour of the REMS in terms of contact openings that could determine a malfunctioning of the system. However, this part of the FEA simulations will not be included in the present paper.

4. TRAIN – TRACK INTERACTION MODEL

The train – track interaction model adopted has been developed at Politecnico di Milano in the past decades ([2], [3]). As already described in the previous paragraphs, the track is schematized using a FEA approach while the vehicle is described through a multibody approach.

In the present research, two types of tracks were considered, one embedded track system and one direct fixation system used as a reference (figure 10). To be able to determine the vibrations transmitted to the ground, the tunnel was also introduced as a beam element into the FEA models of these two track systems. In fact, such beam element is only used as a “vibration sensor”. The stiffness and damping characteristics of the elastic bed that connects the tunnel with the ground were determined through experimental tests in Metro of Milan ([4]). In the case of the embedded track system, the rails, schematized through beam elements, are connected to the tunnel through elastic beds having vertical, lateral and roll stiffness and

damping values determined as described above. For the direct fixation system, instead, the rails, again schematized through beam elements, are connected to discrete fasteners, schematized as lumped masses, through concentrated visco-elastic elements. These fasteners are then connected to the tunnel through concentrated visco-elastic elements. The longitudinal distance between discrete connection element is 0.6m. The identification of inertial, stiffness and damping parameters of the direct fixation track is exhaustively explained in [5].

A track length of 90m is considered. This length is chosen as the best compromise between computational cost and avoidance of boundary conditions (connection to the ground).

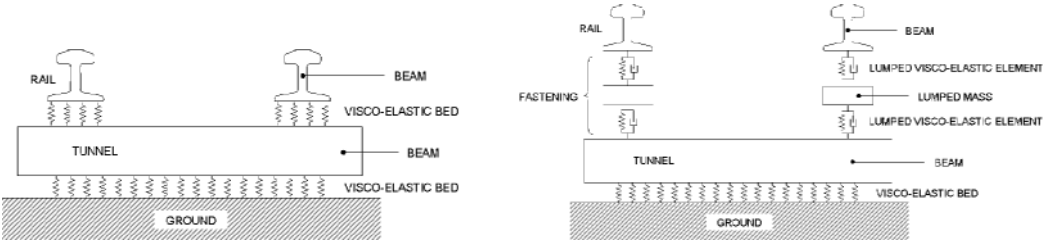


Figure 10. Scheme of the track systems considered: embedded rail track system (a) and direct fixation track system (b)

To assess the dynamic properties of the two considered track systems, the transfer functions at mid track length of the rails' and of the tunnel's vertical deformation speeds were determined using a vertical symmetric (in-phase on both rails) force excitation on the rails (figure 11). Two resonance peaks can clearly be seen on the rails' transfer function: a smaller one below 100Hz, associated to the tunnel vertical eigenmode, and a bigger one around 260Hz for the direct fixation track and around 170Hz for the embedded track, associated to the rails' vertical eigenmode. The difference in resonance frequency is associated to the much higher attenuation of the embedded track system that shifts the resonance peaks towards lower frequencies and significantly reduces the peak value (the first peak amplitude, instead, is almost the same for the two track systems since the visco-elastic bed between tunnel and ground is supposed to be identical).

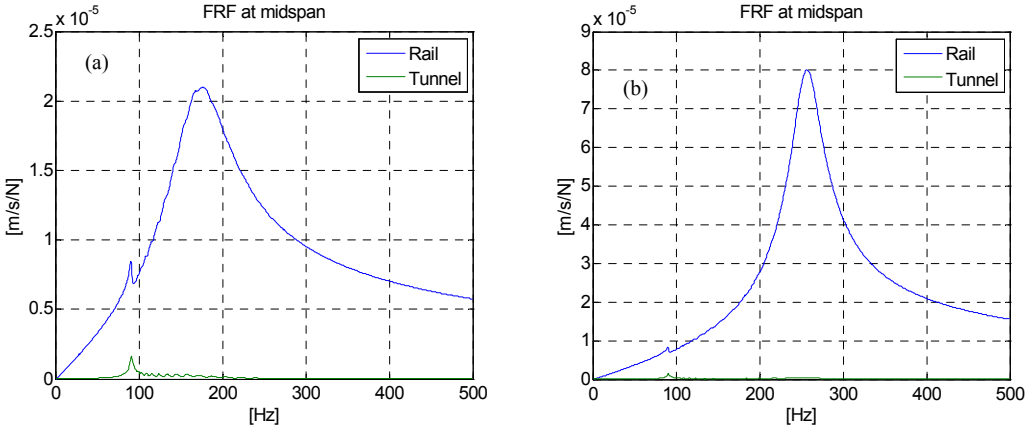


Figure 11. Frequency response function of the rails at midspan due to symmetric excitation on both rails: embedded rail track system (a) and direct fixation track system (b)

The multibody vehicle model assumes carbody, bogies and wheelsets as rigid bodies connected to each other through non-linear visco-elastic elements. Figure 12 show a scheme of the bodies and visco-elastic elements of the vehicle model considered in this analysis. Vehicle parameters are taken from Metro of Milan vehicles. It should be pointed out that the

vehicle's model accounts for both kinematical, contact and structural non-linearities. In fact, wheel – rail contact is modelled using a multi-hertzian contact model that accounts for multiple contacts and out-of-plane contacts ([6])

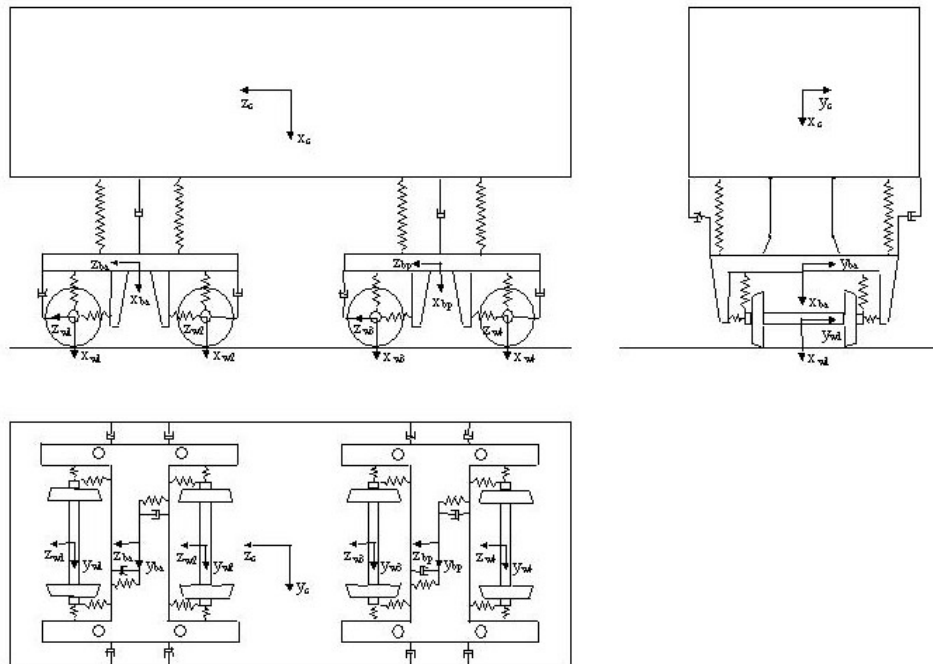


Figure 12. Scheme of the vehicle MB model

As already described in previous paragraphs, vehicle and track equations of motions are coupled by wheel – rail contact forces and have therefore to be integrated simultaneously in the time domain. This is done using an explicit Newmark integration algorithm:

$$\begin{cases} [M_v]\ddot{x}_v + [C_v]\dot{x}_v + [K_v]x_v = f_v(x_v, \dot{x}_v, x_s, \dot{x}_s, t) \\ [M_s]\ddot{x}_s + [C_s]\dot{x}_s + [K_s]x_s = f_s(x_v, \dot{x}_v, x_s, \dot{x}_s, t) \end{cases} \quad (4)$$

where the pedix v is associated to vehicle quantities and the pedix s is related to track quantities. Note that the contact forces f_v and f_s are not only a function of both the vehicle and track state but also explicitly of time due to the presence of track and wheel irregularity.

5. DYNAMIC PERFORMANCE ESTIMATION

Once both vehicle and track models have been setup, train – tack interaction simulations can be carried out. At first, straight track running with measured track irregularity (on Milan underground line) and measured wheel irregularity was simulated to assess the differences in dynamic behaviour of the two track types. Figure 13 shows the vertical left rail and tunnel accelerations at mid track during vehicle transit at 72km/h. It can be clearly seen that, for the embedded track system, almost no vibration reaches the tunnel and that the rails' peak accelerations are lower than those of a direct fixation track. Moreover, train passage is felt by the embedded track system almost only when the vehicle is passing over the considered section. This means that longitudinal vibrations are very effectively damped out.

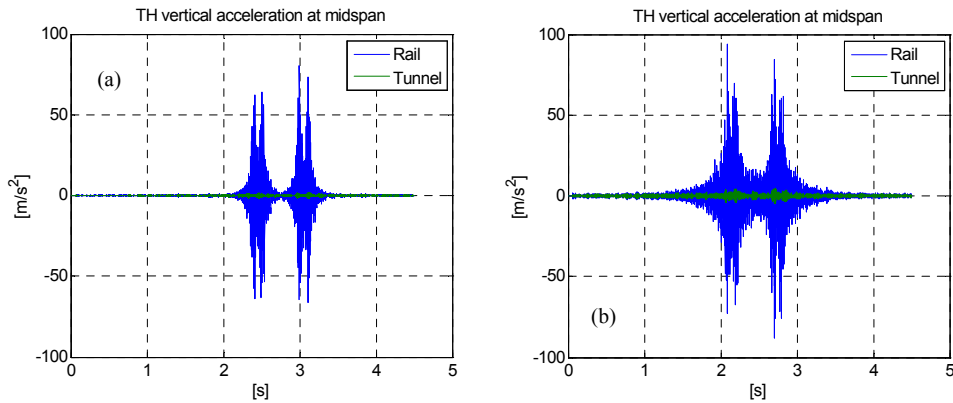


Figure 13. Vertical rail acceleration during straight track running at 72 km/h: embedded rail track system (a) and direct fixation track system (b)

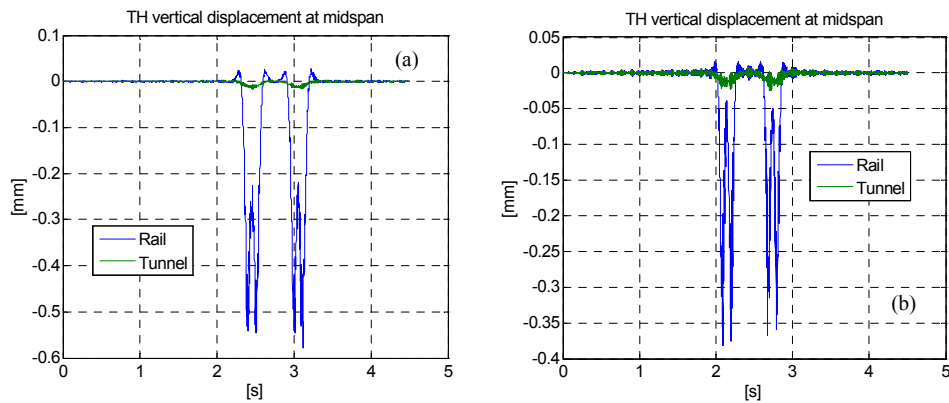


Figure 14. Vertical rail displacement during straight track running at 72 km/h: embedded rail track system (a) and direct fixation track system (b)

The drawback of the embedded track system is seen in figure 14: while the vertical deformation of the rails for the direct fixation track is less than 0.4mm, that of the embedded track reaches almost 0.6mm thus reducing the vehicle maximum speed. This limitation is however not significant for metro vehicles since their maximum speed is 80km/h.

More critical for the embedded track system is the deformation during curved track running: while running along a 500m radius curve at 72km/h, rails experience a vertical deformation (figure 15) almost identical to that shown during straight track running and a lateral rail deformation (figure 16) that reaches 3mm (almost 10 times that of a direct fixation track). This means that, also considering the rail roll rotation, gauge widening during curved track running reaches almost 4mm which is near the maximum value accepted by the standards.

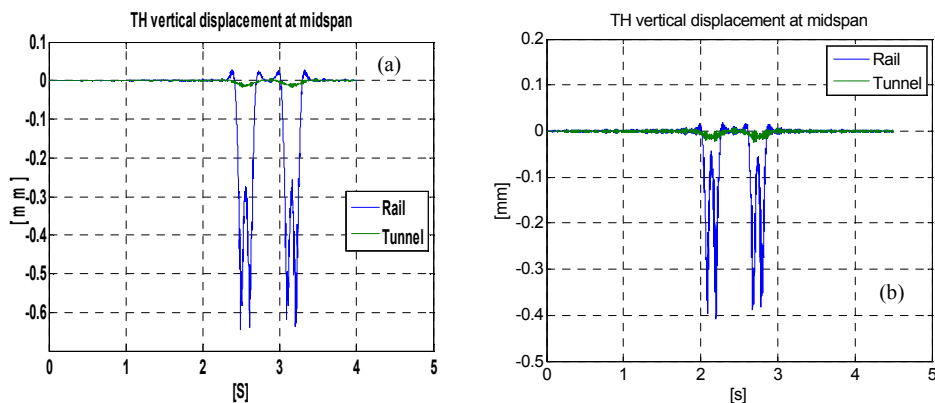


Figure 15. Vertical rail displacement during curved ($R = 500$ m) track running at 72 km/h: embedded rail track system (a) and direct fixation track system (b)

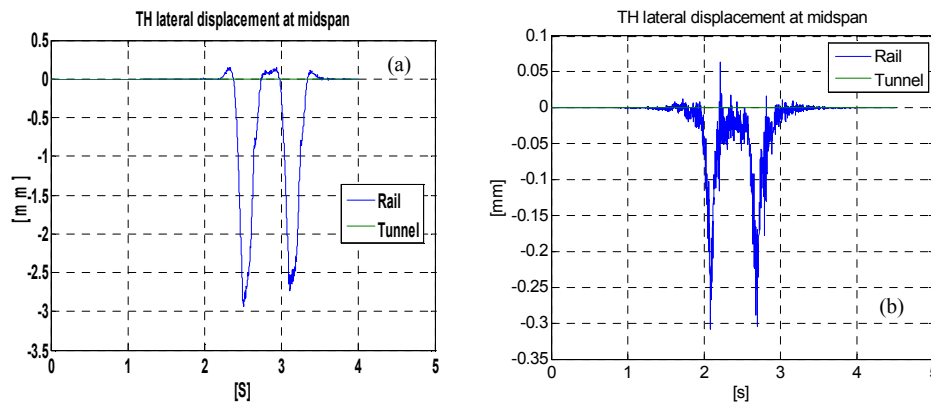


Figure 16. Lateral rail displacement during curved ($R = 500$ m) track running at 72 km/h: embedded rail track system (a) and direct fixation track system (b)

6. CONCLUSIONS

In this paper, an integrated approach to investigate the dynamic performances of a removable embedded track system (REMS) is presented. This approach is based on a detailed FEA description of the REMS system that allows to determine equivalent stiffness and damping parameters to be used within train – track interaction simulations. Note that, at the present stage of the research, only stiffness parameters were extracted while damping parameters were taken from experimental tests carried out on similar embedded track systems.

The proposed innovative removable embedded track system allows to significantly damp out vibrations transmitted to the ground but leads to gauge variations that, although within the limits imposed by the standards, are almost ten times bigger than those measured on traditional direct fixation tracks.

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