Analysis of lateral displacements in large railway viaducts under traffic loads. Impact on ride safety and passenger comfort

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Abstract

The increasing design speed of the new high speed lines and the stringent requirements on track alignment parameters are leading to a sustained increase of the number of railway viaducts.

The relevant standards impose limiting values on lateral vibrations. Both the Spanish and European standards establish a minimum value for the first natural frequency of lateral vibration of a span, that should not be lower than f_{h0} = 1,2 Hz. This limit was originally proposed by ERRI committee D181 , which assessed the lateral forces in railway bridges. This limit was proposed in order to avoid lateral resonance in railway vehicles going across the structure, taking into account that the frequencies of lateral vibration of railway vehicles are, in general, not greater than 1,0 Hz.

In the case of large continuous viaducts with high piers, the lateral deformations occurring during a train pass-by can be significant and the natural frequencies of the first mode of vibration of the deck can be very low. In these cases it is not clear whether the required verifications must be applied to spans considered independently, to several successive spans or to the whole viaduct. There is currently no analysis methodology allowing to assess this situation and check the viaduct design against the requirements of ride safety and passenger comfort.

This paper analyzes the lateral deformations of a large continous viaduct and the infrastructure-vehicle interaction effects due to the circulation of freight trains and several types of high speed trains at different speeds.

The application of this methodology will allow an optimized design of viaducts with significant lateral deformations that cannot be justified only by using the simplified criteria of the current applicable standards.

In such cases, the compliance with standards may lead to overdimensioning or in other cases to neglect the limits without the adequate verification of the proper infrastructure behavior once it has been commissioned.

As it is the case for vertical deformations, for which the European standards require the assessment of dynamic effects, we stress the need for a dynamic analysis of the effects of lateral deformations in large railway viaducts.

Introduction

The first step will be a dynamic analysis of the viaduct behavior under railway loads. The lateral deformations of the viaduct are computed by means of a step-by-step process which takes into account the type of railway vehicle, its speed and the successive positions of the train on the viaduct. The lateral deformations are computed as a matrix of values depending on the points of the viaduct and the instants of time.

These deformations allow then to compute the virtual track alignment defects introduced by the presence of the viaduct. The "virtual path" is obtained for each train axle by considering the lateral deformation curve of the viaduct at each point and time as well as the position of each axle progressing along the viaduct at the operating speed being analyzed, i.e., the lateral displacement of the geometric point which coincides with each axle at each time.

The effect of these virtual paths is then analyzed as regards the lateral behavior of the vehicle, by means of dynamic models of the infrastructure – vehicle interaction that take into account the characteristics of the rolling stock.

The computation of the effects of the lateral deformations shall depend on both the different types of trains and the different running speeds. The results will allow to know at which speeds there are resonant effects, which are at least two: on one hand the increase of lateral deformations when railway loads excite lateral vibration modes of the viaduct and on the other hand, when the deformations of the viaduct create resonant effects due to the oscillating movement of the vehicle body.

Therefore, the maximum values of the guiding forces (ride safety) can be assessed, as well as the values of maximum lateral accelerations in the vehicle body (passenger comfort). These maximum values shall be compared with the admissible values from the point of view of ride safety and passenger comfort, thus confirming that viaduct design is adequate as regards lateral deformations.

This methodology has been applied in Spain for the analysis of the railway viaduct of the ‘Arroyo de las Piedras’ , on the ‘Córdoba-Málaga’ HSL, which is an exceptional viaduct, considering both its length and the height of its piers.

1.Viaduct dynamic computations

1.1. Viaduct description

Figure 1: "Arroyo de las Piedras" viaduct.

This viaduct has a continuous concrete-steel deck, with 20 spans in all, a 50.5 m span at one end, central spans 63,5 m long, and two spans 44 m and 35 m long at the other end, with an overall length of 1209 m. Its piers are quite high with two of them higher than 90 m.

The viaduct belongs to the new Spanish High Speed Line connecting Cordoba and Malaga. The "Arroyo de las Piedras" viaduct is the first composite steel-concrete high speed railway bridge in Spain and represents an innovative solution for high speed railway bridges. It translates to railway lines the strict box girder concept developed in Spain for highway bridges over the last few years. The new design focuses on typical twin plate girder solutions, frequently used in Europe, although optimized with strict box girder capabilities. This characteristic is very important in order to provide the structure with the torsional stiffness required for proper control of the dynamic response when railway vehicles run eccentrically along a single track.

The viaduct has a curvature radius greater than 7000 m and will be considered as a straight viaduct for analysis purposes. The cross section of the deck is made up of two 3.85 m wide twin-plate girders under a top slab 14 m wide, with a variable thickness from 0.41 m in the deck longitudinal axis to 0.22 m at the edge of the overhangs.

The resulting composite steel-concrete cross-section has a constant total height close to 4.2 m, as shown in Figure 2.

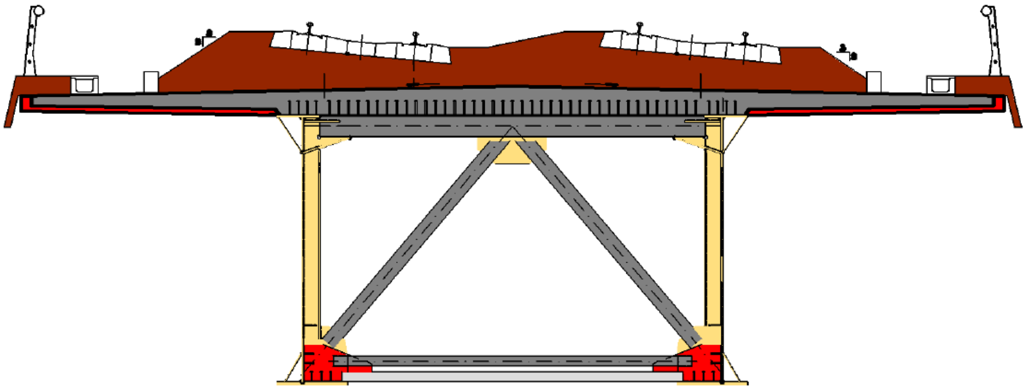


Figure 2: Viaduct cross section.

1.2. Viaduct model

The dynamic analysis has been computed with a finite element model of the viaduct (implemented with ANSYS) with twenty spans with the actual dimensions of the structure: one end-span 50.5 m long, seventeen spans 63.5 m long and two end-spans 44 m and 35 m long, with an overall length of 1209 m, as shown in Figure 3.

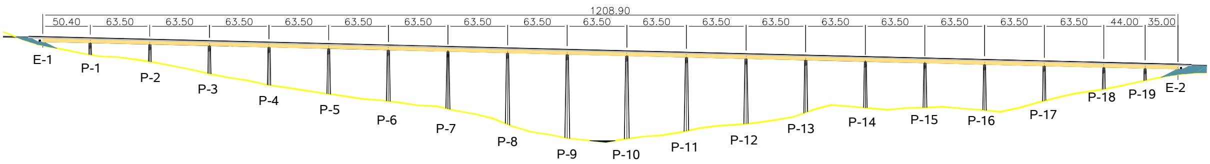


Figure 3: Lateral view of the viaduct model with its twenty spans.

The model has been implemented with 3D beam-type elements with six degrees of freedom per node that idealize the piers and deck and thus can fully represent the deformation behavior of the viaduct, i.e. vertical, transverse and longitudinal, and particularly, the transverse deformation which is mainly influenced by the lateral bending of piers and the deck torsion.

In railway bridges with double track, the eccentric vertical loads due to railraod traffic are responsible for torsional effects on the deck. These lead to lateral displacements at the top of piers with consequent lateral displacement of the deck, as represented in Figure 4, δ_1 represents the lateral displacement of the deck due to lateral bending of piers, which depends on the flexibility of the piers. However, the torsion of the deck within spans is also responsable for lateral displacements, being represented in Figure 4 as δ_2.

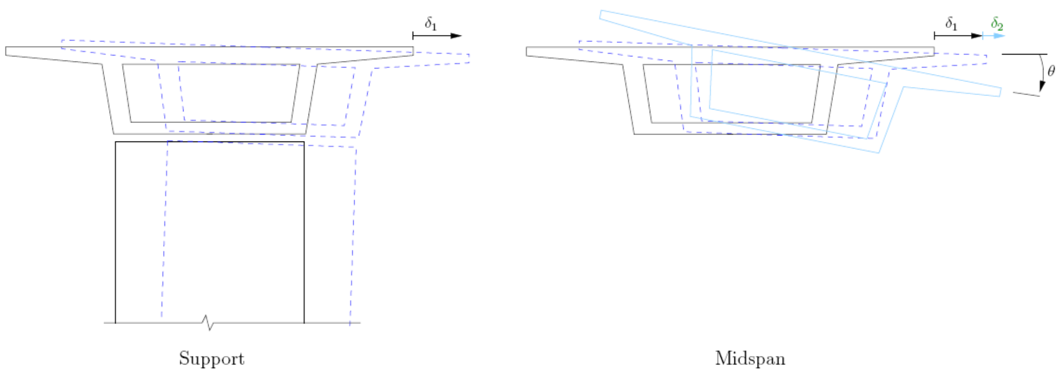


Figure 4: Lateral displacements of the deck due to torsional effects.

The dynamic computation also considers the translational mass of deck and piers as well as the torsional inertia of the deck . The masses include the own weight and permanent loads of the deck (ballast, rail, ties, etc.).

The dynamic computation is step-by-step with time integration.

1.3. Vertical traffic loads

Three types of trains have been considered:
- High speed trains: ICE2 and AVE;
- Freight train: wagon train for V=120 km/h, real train with UIC 71 load model (R1) .

1.4. Running speeds

A velocity sweep has been applied for each of the three trains:
- ICE2 and AVE: 50, 100, 150, 200, 250, 300, 350 and 400 km/h
- Freight R1: 10, 54, 75, 100, 125 and 150 km/h.

1.5. Virtual paths on the deformed viaduct

In each case study the deformation time curve of a representative point of the viaduct has been computed, as well as the virtual path followed by a group of bogies.

The virtual path is obtained by first considering the deformation curve of the viaduct at each time and computing the displacements in space or time of an axle going across the viaduct at a given speed. In each case study five axles are being considered (distributed between train head and train tail). The virtual paths have been computed by processing the results of the step-by-step computation of the structure.

1.6. Results of viaduct dynamic computations

Figures 5 to 7 depict the results of the computation for several simulation speeds.

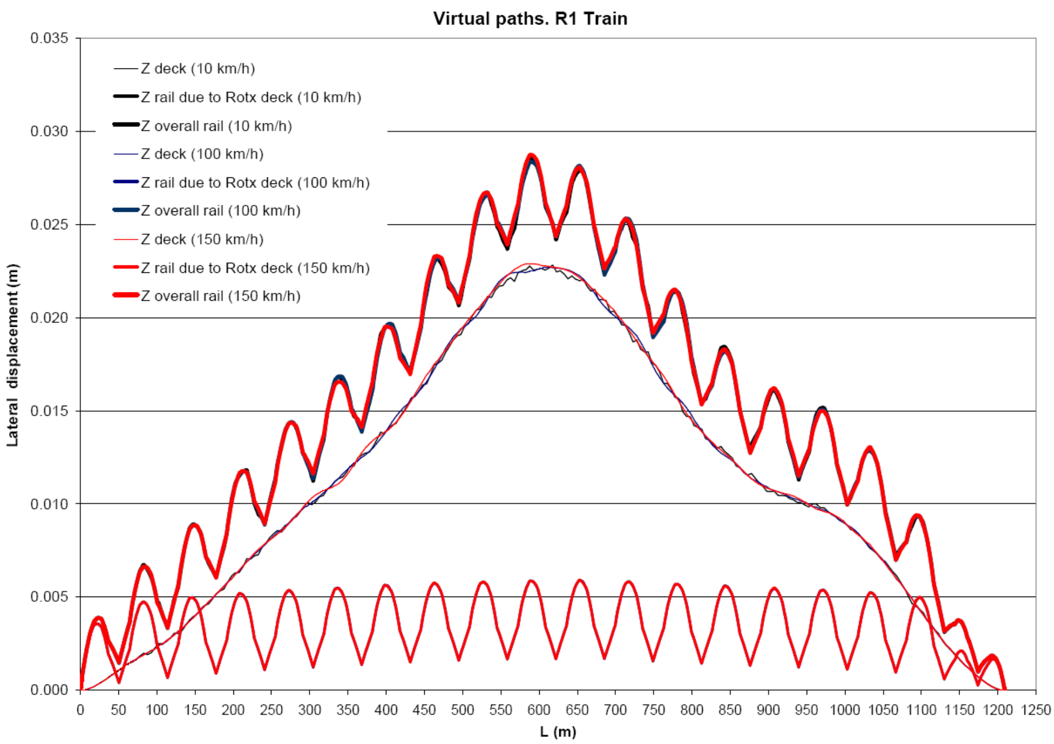


Figure 5 – Virtual path. R1 train

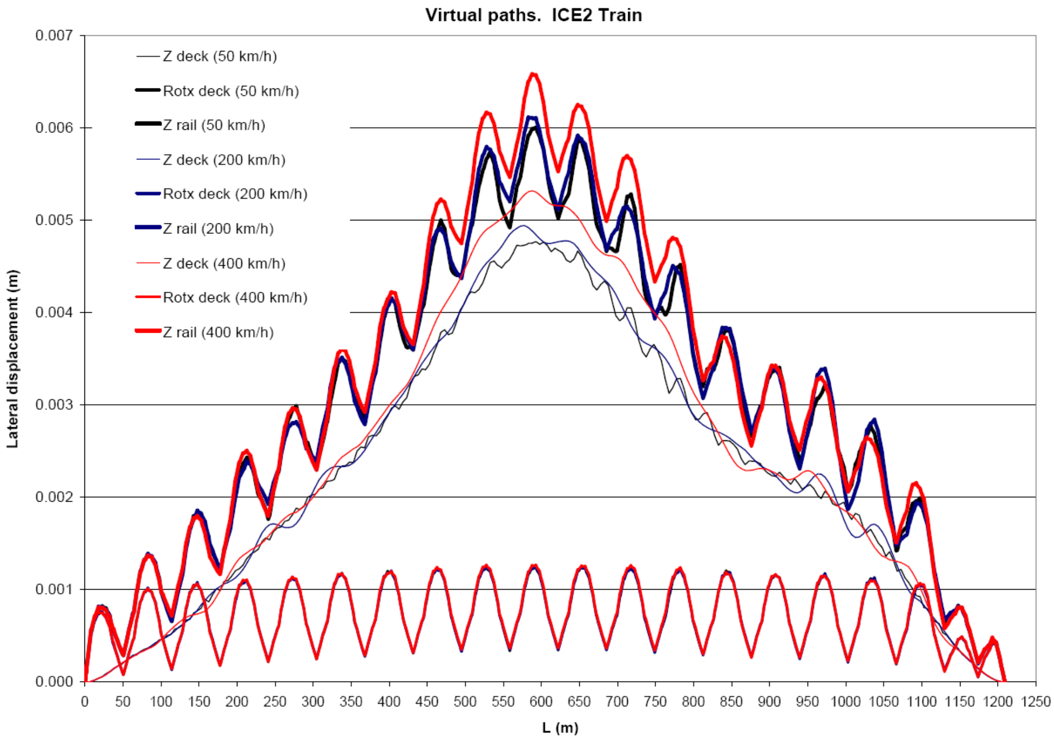


Figure 6 Virtual path. ICE2 train

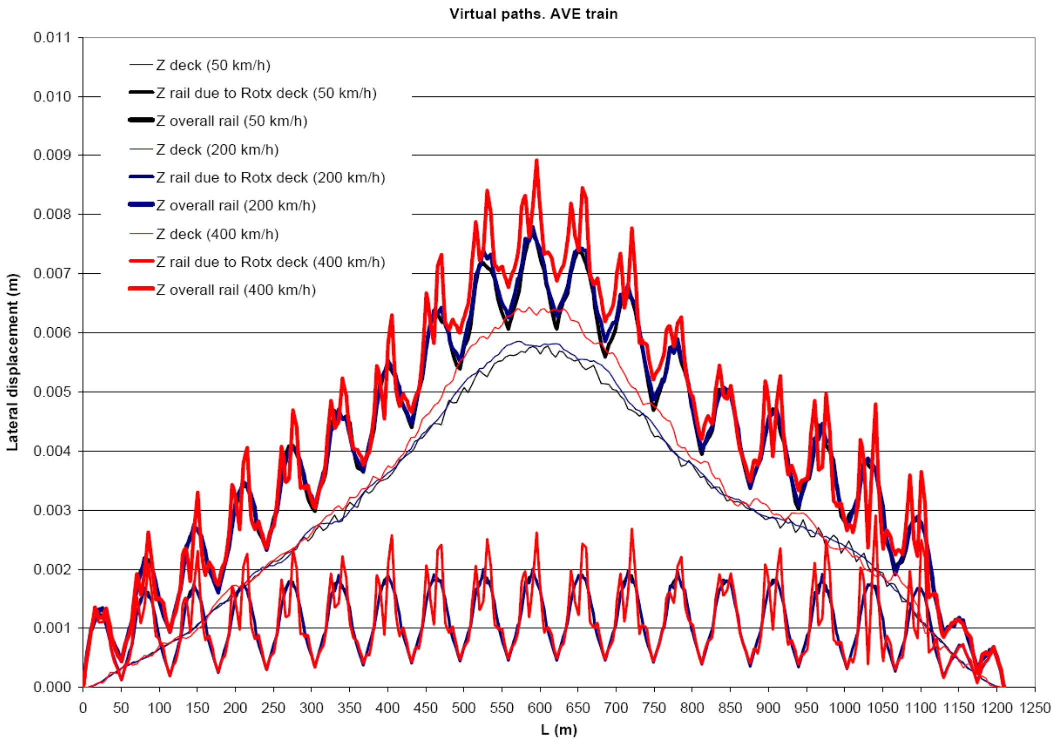


Figure 7 Virtual path. AVE train

As can be seen the lateral displacement of deck does not show significant dynamic oscillations but only a single half wavelength, almost quasi-static, when the train goes across the viaduct, where the half wavelength coincides with viaduct length.

Besides the lateral displacement of deck, the lateral displacement of rail will depend on deck torsion, in which oscillations with different wavelenghts appear clearly:

- An evident oscillation with maxima corresponding to the passage of an axle or bogie through the center of each viaduct span that may be considered as quasi-static;

- Oscillations of shorter wavelenght, due to resonant effects between the passage of an axle or bogie through the center of each span and the oscillation due to deck torsion; this effect is negligible for R1 and ICE2 trains, but can be clearly seen for the critical speed of AVE[1].

2.Vehicle dynamic computations

2.1. Introduction

The analysis of the dynamic lateral interaction between viaduct and vehicle is based upon the results previously obtained for lateral displacement and deck torsion of the viaduct due to eccentric loads.

On the other hand, simplified models of the railway vehicles have been developed. The dynamic analysis of lateral displacement and rolling of the vehicle can then be computed according to different approach:

- Effects on vehicle dynamics due only to virtual path
- Combination of the above effects with track irregularities

2.2. Effects of the virtual path on vehicle dynamics

2.2.1. Vehicle model

This first analysis is based upon two parametric models : one adapted to freight wagons and the other for passenger cars. These are simplified FE models where the lateral dynamic behavior of a single axle is analysed, and they combine 2D beam-type elements with very high stiffness, mass-type elements with torsional inertia and spring-type linear elements with viscous damping. Table 1 shows the main parameters used (values per axle) and figure 8 depicts a model schematic.

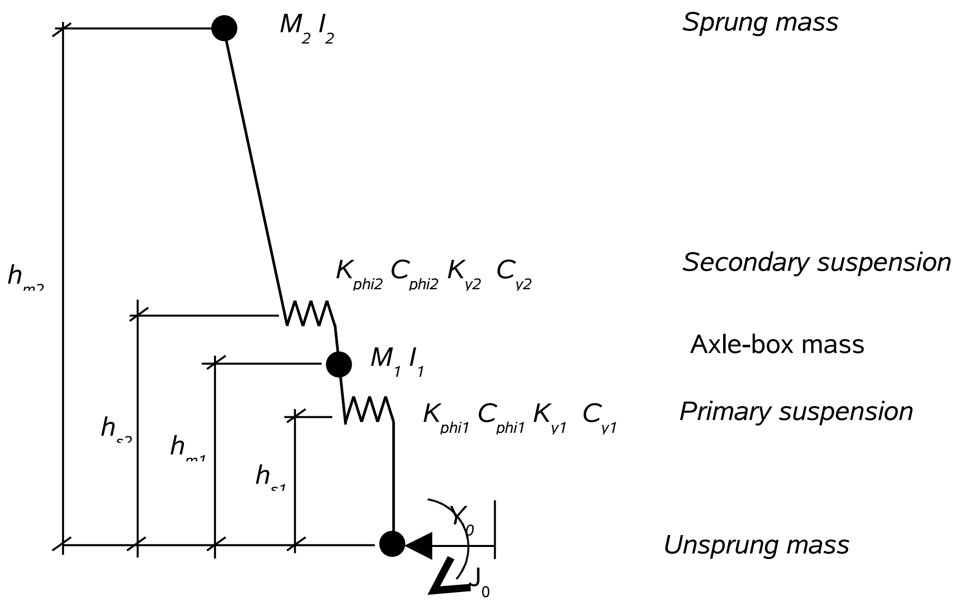
Parameter	AVE	ICE2	Freight R1
Unsprung mass	1580 kg	1580 kg	2000 Kg
Axle-box mass[2] (M_1)	1780 kg	1780 kg	
Sprung mass (M_2)	14369 Kg	8457 Kg	23000 Kg
Bogie roll inertia[2] (I_1)	1017 Kg m^2	1017 Kg·m^2	
Stiffness of lateral primary suspension (K_{y1})	4,35e6 N/m	4,35e6 N/m	1,5e6 N/m
Damping of lateral primary suspension (C_{y1})	0 N·s/m	0 N·s/m	34e3 N·s/m
Torsional Stiffness of lateral primary suspension (K_{phi1})	1,61e6 Nm/rad	1,61e6 N·m/rad	2,6e6 N·m/rad
Torsional damping of lateral primary suspension (C_{phi1})	15e3 Nms/rad	15e3 Nm·s/rad	0 Nm·s/rad[3]
Height of axle-box mass (h_{m1})	0,68 m	0,68 m	
Height of primary suspension (h_{s1})	0,68 m	0,68 m	
Car body roll inertia (I_2)	27315 Kgm^2	13657 Kg·m^2	8750 Kg·m^2
Stiffness of lateral secondary suspension[2] (K_{y2})	0,128e6 N/m	0,128e6 N/m	
Damping of lateral secondary suspension[2] (C_{y2})	20e3 Ns/m	20e3 Ns/m	
Torsional Stiffness of lateral secondary suspension[2] (K_{phi2})	0,333e6 Nm/rad	0,333e6 N·m/rad	
Torsional damping of lateral secondary suspension[2] (C_{phi2})	29,95e3 Nms/rad	29,95e3 Nms/rad	
Height of sprung mass (h_{m2})	1,5 m	1,5 m	1,5 m
Height of secondary suspension (h_{s2})	0,916 m	0,916 m	1,0 m

Table 1. Parameters of vehicle models

[1] The frequency of the first torsion mode of the deck for 63,5 m spans is close to 6 Hz. The AVE wheel-base being 18,7 m, the resonance speed will then be: $V = l{\cdot}f = 18{,}7m \cdot 6Hz = 112m/s = 403km/h$. The resonance peaks can be seen in Figure 6 for a computation speed of 400 km/h.

[2] For freight wagon: there is no axle box mass nor bogie and a single suspension

[3] For freight wagon: damping (due to friction) of vertical suspensions (equivalent to damping of rolling torsion) has been disregarded. This assumption is conservative.



Y_0 = transverse trajectory of track or virtual deformation curve of deck
J_0 = track torsion asociated with virtual path

Figure 8. Parametric model of passenger car

2.2.2. Dynamic computations

Dynamic computations have been run both in time and frequency domains.

In the frequency domain the computations have been used to analyse the response of vehicles to harmonic excitations, in order to assess resonance critical running speeds on the viaduct. This analysis has resulted in the transfer functions of the lateral displacement of the sprung mass for the different vehicles , shown in Figure 9.

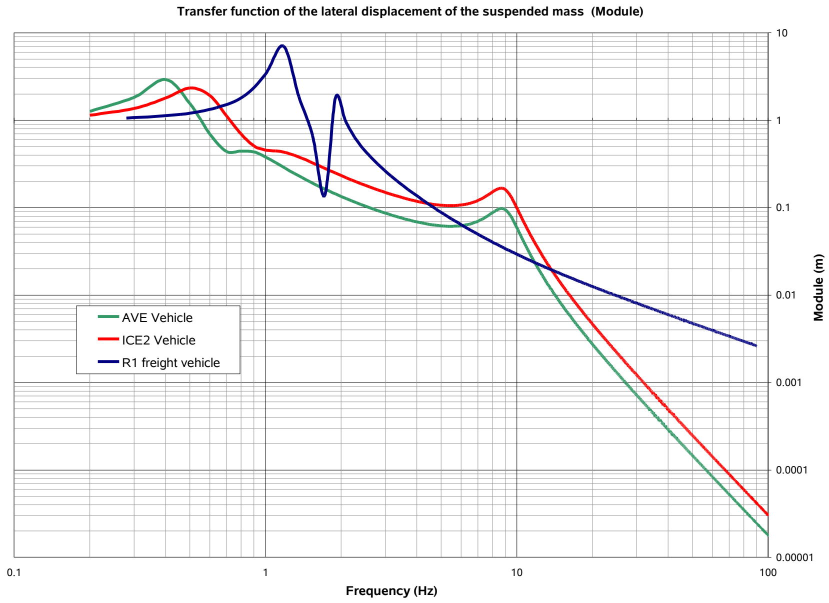


Figure 9. Transfer functions of the lateral displacement of the sprung mass (module)

For passenger vehicles, resonance effects in the car body can be expected below 0,7 Hz, with a maximum at 0,4 Hz, in the case of ICE2, and below 0,55 Hz, with a maximum at 0,3 Hz, in the case of AVE. In both cases a resonance peak can be observed at higher frequencies (around 10 Hz), corresponding to the excitation of the axlebox mass although it does not affect the computations due to its high value.

On the other hand, the main frequency of the excitation, as seen during the viaduct dynamic computation, corresponds to span passage, with a preponderant lenght of 63,5 m. Therefore the resonance effects on sprung masses will happen at relatively low speeds, lower than 160 km/h in the case of ICE2 and lower than 125 km/h in the case of AVE.

In the case of a freight wagon, significant dynamic phenomena will occur at frequencies close to the maximum resonance frequency of 1,17 Hz.

For the time domain computations, the input excitations applied to the vehicle model were precisely the virtual paths obtained from the dynamic computations of the viaduct (lateral displacement and rolling torsion). The results were the displacements of the different masses of the vehicle as functions of time and additionally the speeds, accelerations and guiding forces (reactions on unsprung masses).

Figures 10 and 11 show the dynamic response of the car body as regards lateral displacements and aceleractions for an AVE car running at 400 km/h. The vehicle response is quasi-static and there are no significant vibrations (the maximum relative displacement between car body and track is around 2 mm).

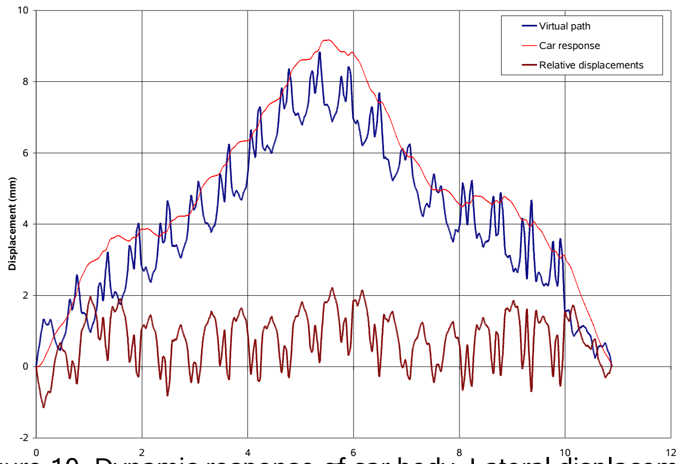


Figure 10. Dynamic response of car body. Lateral displacement

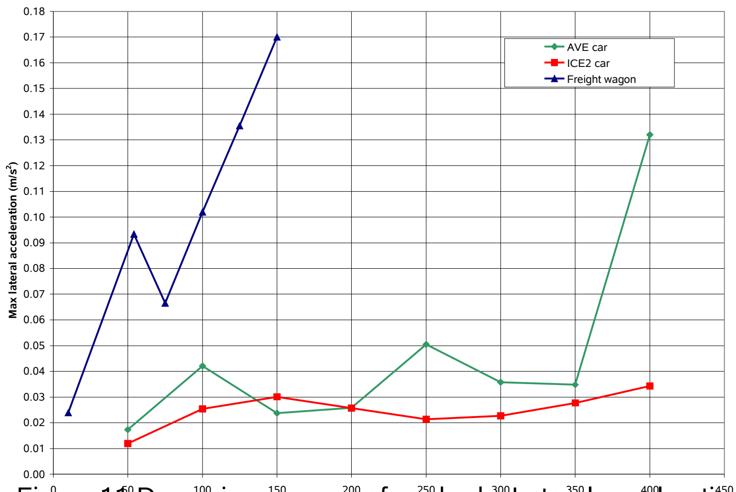


Figure 11 Dynamic response of car body. Lateral acceleration

Figure 11 shows the maximum values of car body acceleration as a function of speed, for the three types of vehicles. For cars of AVE and ICE2, the acceleration values are moderate and increase slightly with speed, showing a peak in the case of AVE at the critical speed of 400 km/h. Nevertheless this maximum value is lower than 0,15 m/s^2. For the freight wagon, the acceleration increase with speed is greater and the accelerations are greater than those coresponding to passenger cars for lower speeds, as there is no secondary suspension, and the maximum computed value has been 0,17 m/s^2 for 150 km/h.

 recommends limit values for lateral acceleration (0,65 m/s^2 for traffic category III, mixed traffic lines). As seen in Figure 11 the computed acceleration values are much lower than this limit .

The criteria for assessing ride comfort in railway vehicles proposed in and based upon comfort indexes for conventional alignments have been also examined. This standard describes a methodology for assessing ride comfort as a function of longitudinal, vertical and transverse accelerations. In this case only the lateral accelerations have been computed and thus have been the only component used. This method is based upon the computation of a *Comfort Index*, which indicates the percentage of passengers experimenting discomfort in a specific situation, These indexes can be computed via empiric formulae given in the standard, which depend on variables such as lateral acceleration, rate of change of acceleration and rolling velocity. All these values are filtered with a moving average filter that eliminates small wavelenght components. Using this methodology for the computed worst-case situations, the comfort indexes have been found excellent, therefore no passenger should feel incomfortable.

Ride safety must be assessed by considering the guiding forces. Figure 12 shows the maximum values of the guiding forces for the three type of vehicles as a function of speed.

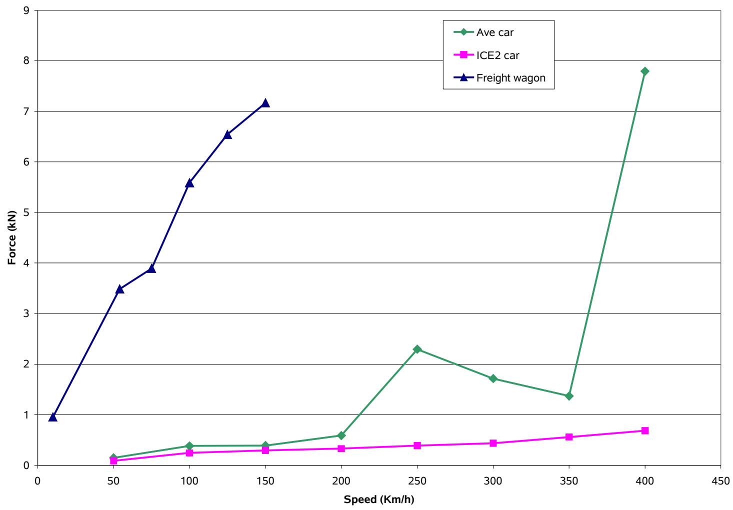


Figure 12. Guiding forces

 and propose safety limitations against railway vehicle overturning. From the maximum guiding force for a vehicle with a load per axle of 170 kN (AVE) is 66 kN per axle and 48 kN per axle for a vehicle with a load per axle of 112 kN (ICE2). For the R1 freight wagon (load per axle of 245 kN), the maximum guiding force per axle is 78 kN. These values are far greater than those obtained for the simulation.

2.3. Combination of previous effects with track irregularities

The objective here is the comparison of the dynamic effects caused on the vehicle by the lateral deformations of the viaduct with those caused by track alignment irregularities.

In order to study vehicle-track interactions and to predict vehicle response, some form of analytical description of track geometry and track irregularities is required. Track geometry models based on PSDs are very useful in determining the type of vehicle response. They can be used to calculate mean square values of rail deviations. PSD track definition discussed in references , and were reviewed.

Measurements of track irregularities made in German railway lines (DB) have shown that the power spectral densities can be standardised with functions as the one proposed in , as F_V and F_A, for vertical or lateral alignment irregularities, as seen in equation (1):

$$\Phi_{V,A} = A \frac{\Omega_c^2}{\left(\Omega_r^2 + \Omega^2\right)\left(\Omega_c^2 + \Omega^2\right)} \tag{1}$$

The values of the constant factors W_r and W_c defined in , are:

W_r = 0,0206 rad/m and W_c = 0,8246 rad/m.

The value A defines the level of track irregularities, being A_{low} and A_{high} used to define a track with low or high level of track irregularities, given in as:

A_{low} = 0, 59233·10^{-6} rad·m and A_{high} = 1, 58610·10^{-6} rad·m.

Figure 13 shows an example of lateral track alignment irregularities generated for the viaduct under study, adopting a profile with low irregularities where A = A_{low}.

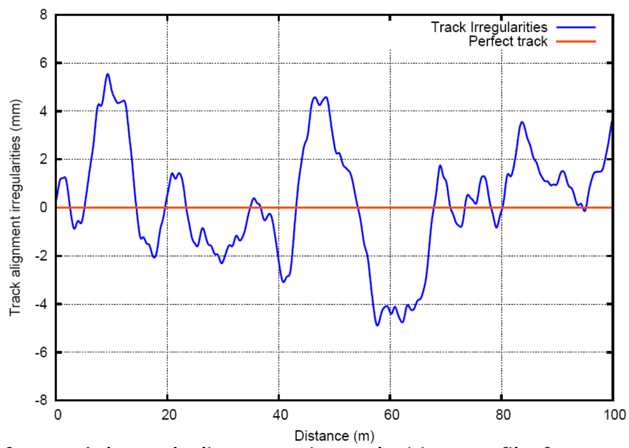


Figure 13: Example of a track lateral alignment irregularities profile for a track with low irregularities. Representation for a length of 100 m.

This analysis was performed with a three-dimensional model (See figure 14) with the geometry and the mechanical characteristics of a typical high speed train vehicle, defined in a finite element program. The selected vehicle was ETR500 defined in .

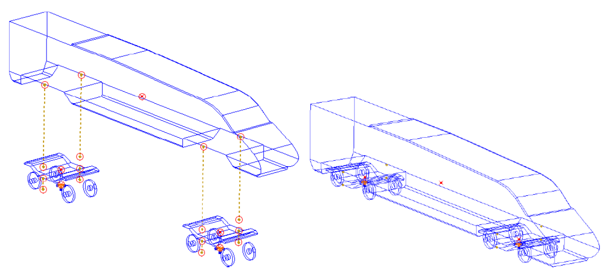


Figure 14: 3D railway vehicle model with the mechanical properties of the ETR-500 vehicle

The acelerations obtained show that bridge lateral displacements, considered through the virtual path, represent only 26% of the total response.

Conclusions

As regards viaduct dynamic computation:

- vertical loads will not induce resonance effects that may increase significantly the lateral displacements of the deck due to oscillations with respect to quasi-static displacement;

- there will be no resonance effect betwen the vehicle and the lateral displacement of the deck.

As regards vehicle dynamic computation:

- the frequency domain results show that resonance phenomena should be expected in passenger cars at frequencies around s 0,3-0,4 Hz, and around 1,1-1,2 Hz for freight wagons;

- considering only the excitation of bridge lateral displacements, considered through the virtual path, the values of maximum lateral accelerations computed for passenger cars and freight wagons are well below the normative limits;

- with the excitation of bridge lateral displacements the comfort indexes computed for passenger cars have been found excellent, therefore no passenger should feel incomfortable;

- the bridge lateral displacements, considered through the virtual path, represent 26% of the total response combined with the track alignment irregularities; thus, it is concluded that the lateral displacements of the bridge do not have a significant influence on the total dynamic lateral behaviour of vehicles.

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