360.revista de alta velocidad
número 5 - junio - 2018. Pág 191 - 217

Testing railway tracks at 1:1 scale at CEDEX Track Box

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Abstract

The paper describes the experimental facility built at CEDEX to bridge the gap between simple laboratory tests and in-situ measurements to study the mechanical behaviour of railways tracks. The texting facility, called CEDEX Track Box (CTB), is a 21 m long, 5 m wide and 4 m deep device whose main objective is to test, at 1:1 scale, complete railway track sections of conventional and high speed lines for passenger, freight and mixed traffics, at speeds up to 450 km/h. The railway track response, in terms of displacements, velocities and accelerations, is collected from a great number of linear variable differential transformers (LVDTs), geophones, accelerometers and pressure cells installed both inside the embankment and the bed layers (ballast, sub-ballast and form layer) of the track. On the other hand, the railway superstructure response is recorded with a number of mechanical displacement transducers, laser sensors, geophones and accelerometers installed on the different track superstructure components: rail, sleeper and railpad.

After checking the results obtained in CTB with in-situ measurements carried out at different points in the Spanish high speed line network, CTB has been used to research on different matters: measurement of track vertical stiffness under different track conditions by imposing static loads step by step through a set of servo-hydraulic actuators and measuring the rail deflection as a function of the load applied; calibration of 3-D numerical models under static conditions to show the crucial role played by the non-linear behaviour of the different materials constituting the track bed layers and the embankment or the trench supporting ground on the behaviour of ballasted and slab tracks; use of a commercially available machine to determine the effect of repeating tamping operations in ballast degradation; assessment of track lateral stability in CTB with the aid of a special tool that pushes away the sleeper while its horizontal movement is recorded; study of the short and the long term behaviour of railway track sections through the obtainment of ballast, subballast and form layer permanent settlement curves in fatigue tests in which, at least, one million axles were applied, under different test conditions; determination of rail deflections under the pass-by of trains at very high speeds, up to 450 km/h; optimization of bituminous subballast thickness for high speed lines under mixed traffic conditions; abatement of noise by the use of sleepers with USP.

Furthermore, CTB can be also used to: study the influence of track or ground irregularities in the behaviour of slab tracks and the corrective actions to be taken; optimize the maintenance works in slab-ballast transition zones; analyse the behaviour of curved sections; and to assess the ballast degradation in switches and crossings.Recent developments already made, such as the deployment of a 3Hz natural frequency spring system at the CTB base, will allow in the future analysing experimentally the behaviour of ballast and slab tracks founded on soft soils. A summary of some of the results obtained during the first working years are shown in this paper.

Keywords: railway infrastructure, testing facility, track stiffness, lateral resistance, ballast degradation, critical speed.

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1. Introduction

The experimental research of any track component or configuration usually begins with the performance of simple laboratory tests, being the last step to perform tests with real traffic in a real railway track. However this last activity is a quite complicated task due to the difficulties to have access to the track and the complications derived of the in-situ instrumentation installation.

To bridge the gap between simple laboratory tests and in-situ measurements in railways tracks, CEDEX built the CEDEX Track Box 12 years ago, as part of Supertrack project (2001-05) in the frame of European Union Fifth Framework Program (Manzanas et al, 2007).

Since that, this testing facility has been extensively used in the following European Union projects: Innotrack (2005-09), Rivas (2009-13) and Capacity for Rails (2013-17) (Cuéllar, 2016).

2. General description of CEDEX Track Box

CEDEX Track Box (CTB) is a 21 m long, 5 m wide and 4 m deep facility whose main objective is to test, at 1:1 scale, complete railway track sections of conventional and high speed lines for passenger and freight trains, at speeds up to 450 km/h. Figure1 shows a general view of the testing facility.

Figure 1. General view of the testing facility

The testing facility was designed, built and developed as part of SUPERTRACK ("Sustained Performance of Railway Tracks", 2001-05) and INNOTRACK ("Innovative Track Systems", 2005-2009) projects funded by the European Union Fifth and Sixth Framework Programs, respectively.

Its principal advantage is the possibility of performing fatigue tests in a fast way as in one working week, the effect of the passing-by of trains during a year in a real section can be modelled.

The reproduction of the effect of an approaching, passing-by and departing train in a test cross-section, as it occurs in a real track section, is performed by application of loads, adequately unphased as a function of the velocity of the train which is being simulated, produced by three pairs of servo-hydraulic actuators (that can apply a maximum load of 250 kN at a frequency of 50 Hz), placed on each rail and 1.5 m longitudinally separated, as seen in Figure 2.

Figure 2. Detail of the hydraulic actuators

Furthermore, the reproduction of wheel and track imperfection effects that produces low amplitude high frequency dynamic loads can also be carried out by the use of two piezoelectric actuators that can apply loads up to 20 kN at 300 Hz.

The railway track response, in terms of displacements, velocities, accelerations and pressures, is collected from a great number of linear variable differential transformers (LVDTs), geophones, accelerometers and pressure cells installed inside both the embankment and the bed layers (ballast, sub-ballast and form layer) of the track.

On the other hand, the railway superstructure response is recorded with mechanical displacement transducers, laser sensors, geophones and accelerometers installed on the different track components (rail, sleeper and railpad), as seen in Figure 3. The acquisition data unit can receive information from 150 sensors at the same time.

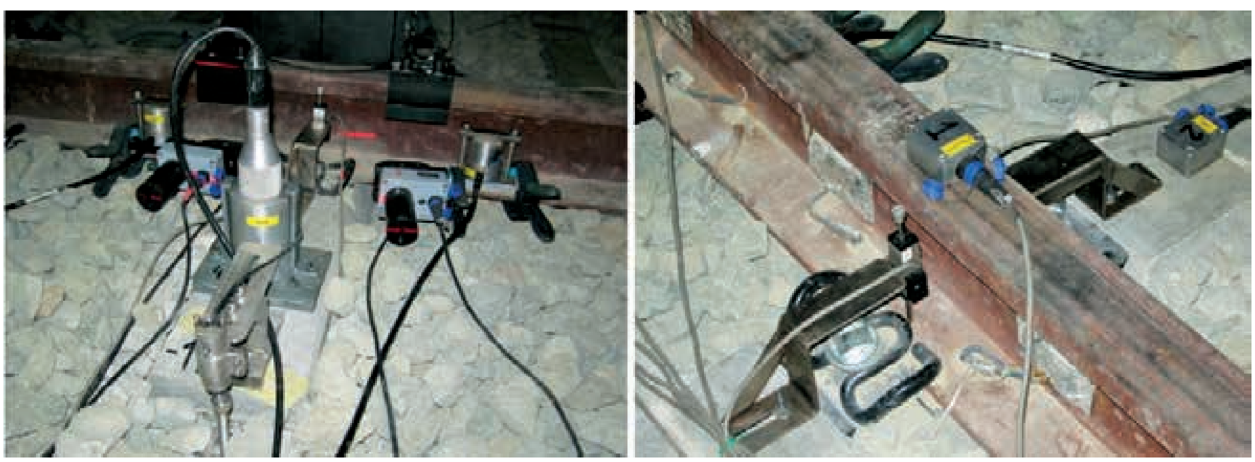


Figure 3. View of some of the instrumentation installed in the superstructure

Lastly, CTB is equipped with a little commercially available tamping machine, shown in Figure 4, to tamp the ballast if it is required in some of the tests.

Figure 4. General view of the tamping machine used in CTB

The 1:1 scale models that can be built in CTB can reproduce the following track conditions:

- Ballasted or slab tracks.
- Sections in straight line or in curve.
- Switches and crossings.
- Transitions zones.
- Sections with different kinds of ballast, sub-ballast, form layer or embankment.
- Sections with standard, polyvalent and three-rail sleepers.
- Sections equipped with new materials: sleepers with USP, under ballast mats, artificial ballast, bituminous sub-ballast, geotextiles and soils treated with lime or cement.

With these 1:1 scale models, a set of different tests can be performed having the following characteristics:

- Tests with passenger, freight trains and mixed traffic.
- Tests with static loads to determine track stiffness.
- Tests with quasi -static loads to simulate the pass-by of trains at different speeds up to 450 km/h.
- Tests with dynamic loads to simulate the effects induced by track and wheel irregularities.
- Tests to determine the fatigue behaviour of any track component (mainly, the fastening system, the ballast, sub-ballast layer) by the simulation of pass-by of millions of axle trains.
- Tests on vibration propagation and abatement solutions.
- Tests to determine the lateral and longitudinal track resistance.

The results obtained in the tests can be used mainly to analyse the short and long term behaviour of railway track sections submitted to any kind of train traffic and to calibrate 3D numerical models to be used in other type of studies or to widen the aim of the tests.

CTB has been used in the past to research on different matters, which are described in the following sections.

- Measurement of track vertical stiffness under different track conditions.
- Determination of track lateral stability.
- Study of short and long term behaviour of railway track sections by obtaining ballast, subballast and form layer permanent settlement curves in fatigue tests and under tamping operations.
- Measuring of track mechanic behaviour under the pass-by of trains at very high speeds, up to 450 km/h.
- Behaviour of sleepers with USP.
- Optimization of bituminous sub-ballast thickness.
- Behaviour of High Speed Lines subjected to mixed traffic.
- Calibration of 3D numerical models.

3. Static tests

3.1 Measurement of track vertical stiffness

The measurement of track vertical stiffness in any track condition is made imposing static loads by a pair of servohydraulic actuators that are installed in each of the cross-sections (A, B or C in Figure 5) on each of the rails (see Figure 2).

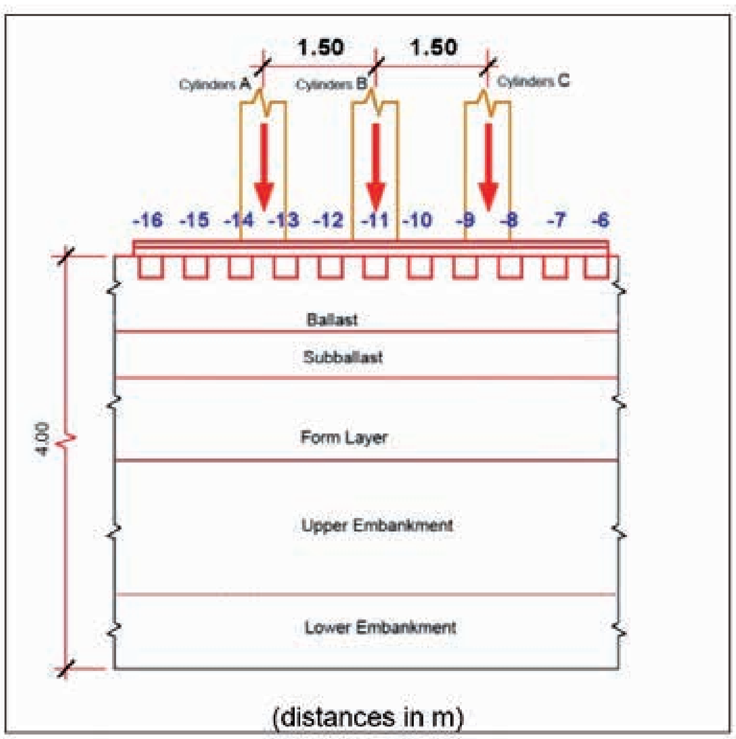


Figure 5. Cross section of the 1:1 scale model used in the tests with the position of the servo-hydraulic actuators

Each pair of actuators is activated simultaneously with the same time-load history. The static tests consist usually on two loading–unloading cycles. In the case shown in Figure 6 a maximum load level of 92.5 kN was reached, step by step, and a minimum load of 2.5 kN was applied to avoid a loss of contact between the actuators and the rail. Once a load level of 82.5 kN was attained in each loading cycle, two small excursions of ±10 kN were programmed to determine the dynamic track stiffness. The duration of each static test was 12 minutes. A total of four static test were performed, one with each actuator independently and another with the three pairs of actuators acting together.

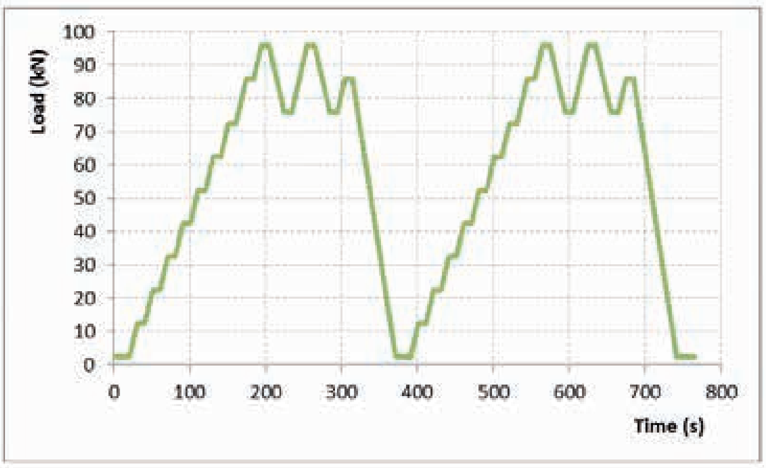


Figure 6. Time-load history used in the static tests

The rail vertical displacements were recorded with eight laser systems distributed in the three test sections. Figure 7 shows the distribution of the laser systems installed (blue labels) and the location of the three pairs of actuators (yellow squares).

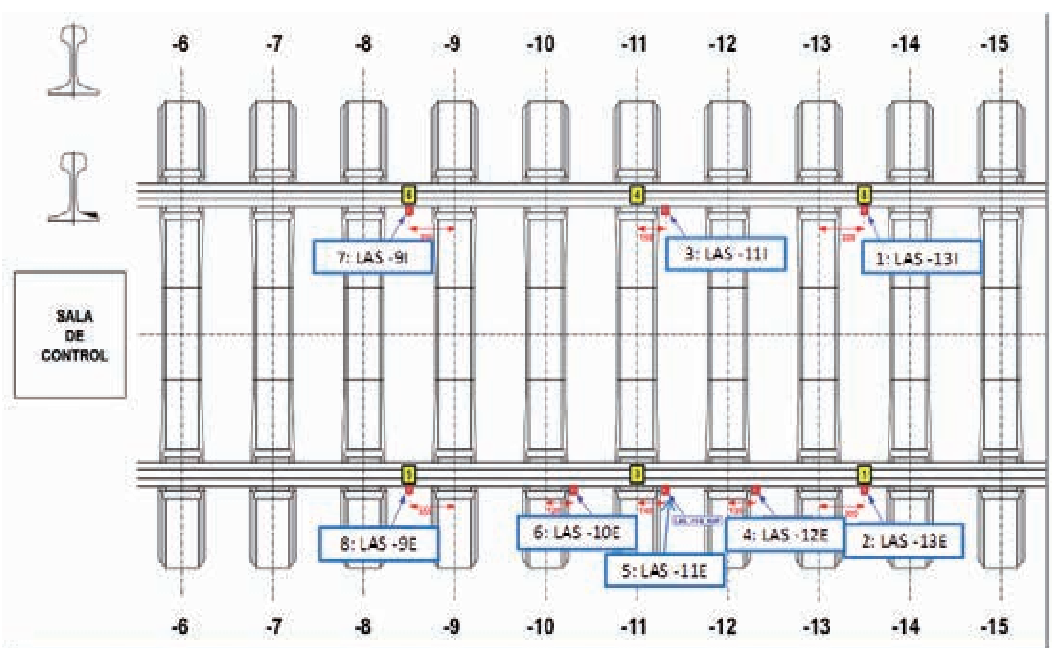


Figure 7. Location of eight laser systems (blue labels) and location of the three pairs of actuators (yellow squares)

Figure 8 shows the evolution with time of the rail displacement, measured with all the laser systems installed for the four static tests performed. These data can be used to analyse the rail deflection, as a function of the load applied, as shown in Figure 9. It can be seen that, in the case of a hard embankment combined with hard bed layers, the deflection curves are clearly non-linear so railway stiffness deduced from them should always be referred to the load in which it is being calculated. It is important to notice that this non-linear effect can even increase in the case of hard track bed layers on a soft soil foundation.

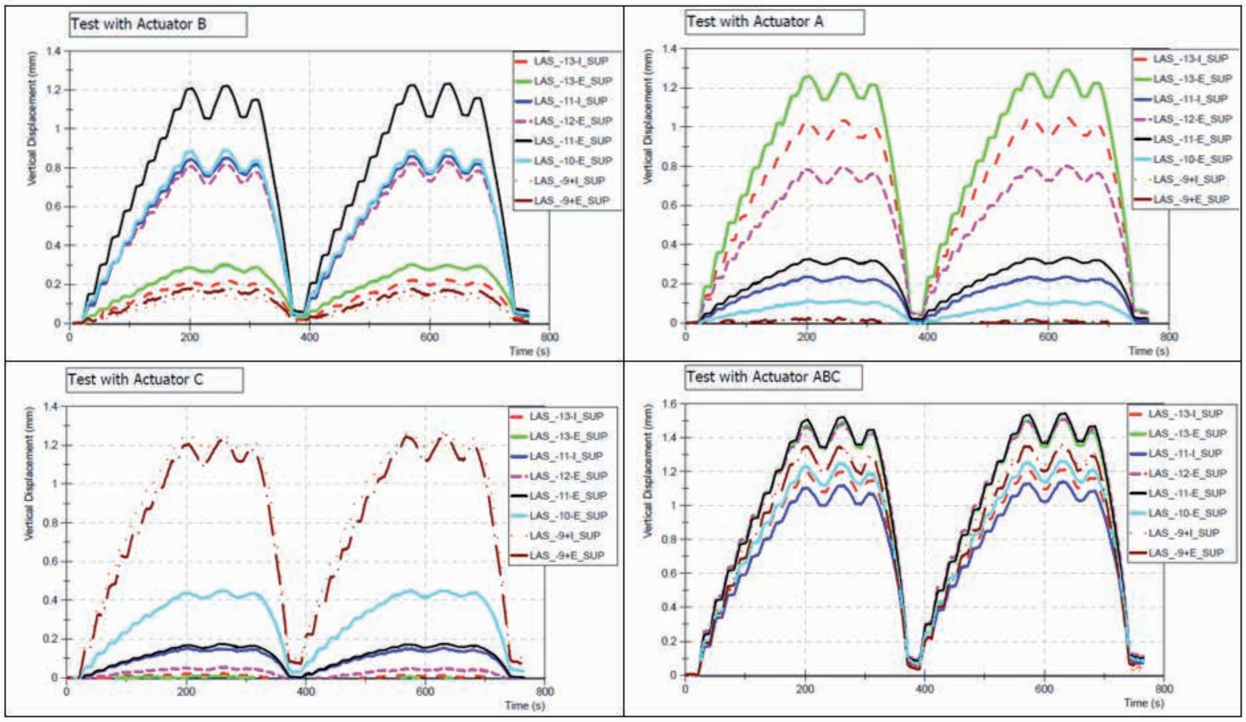


Figure 8. Rail displacement evolution with time for all the static tests

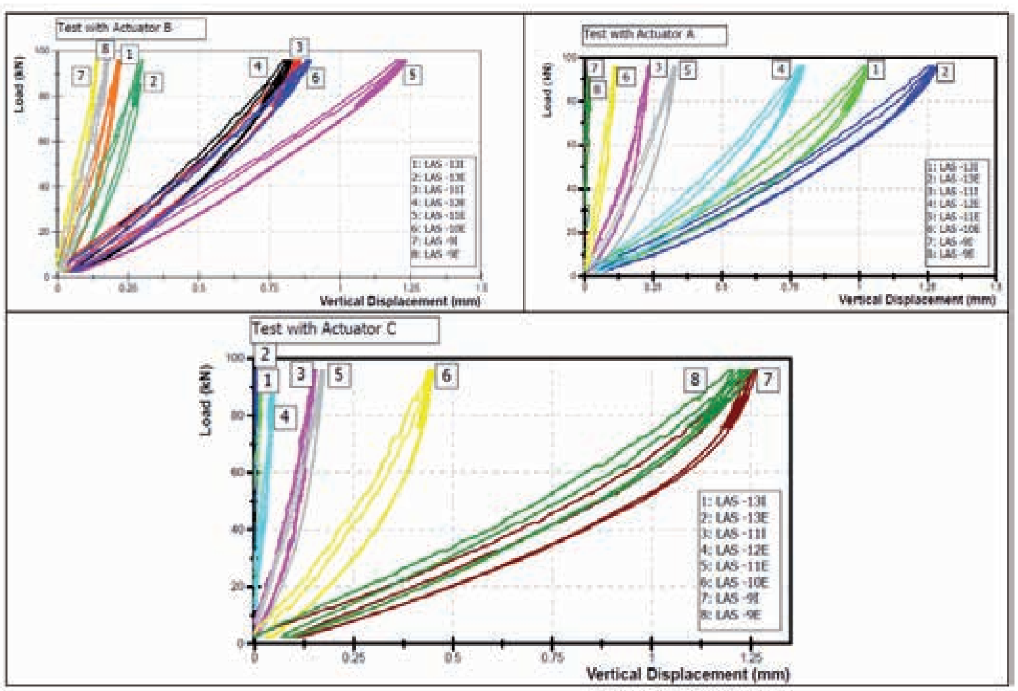


Figure 9. Deflection curves obtained in the static tests for hard embankment and hard bed layers

The next step is to analyze the rail deflections, for a certain load level, along the rail as a function of the distance from the load application point, as seen in Figure 10 for the static tests in which the three actuators were acting independently.

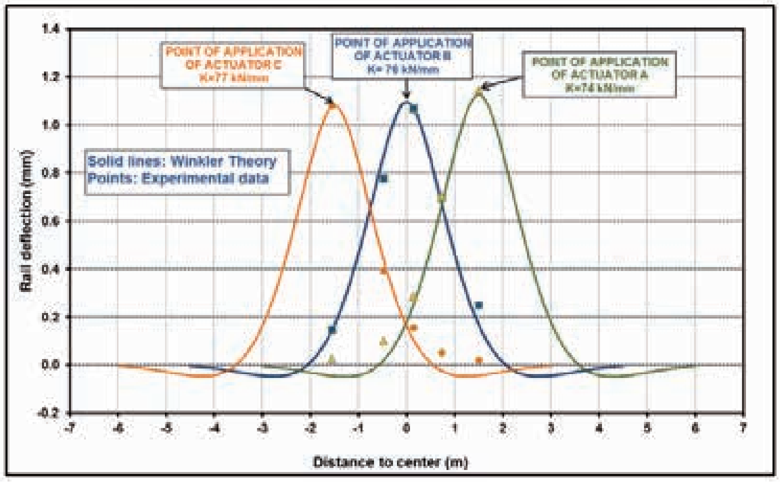


Figure 10. Rail deflection at different points during a set of static tests, including rail stiffness values obtained for a load of 83.34 kN per wheel

The good fitting between the measures and the theory, seen in Figure 10 and in a great number of other static tests, proves that the rail deflections due to a vertical single load can be predicted with high accuracy assuming the rail track has a Winkler-type behaviour quantified by Equation 1.

$$\delta(x,t) = \frac{Q}{K}\, e^{-\frac{|x-vt|}{L}} \left[cos\left(\frac{|x-vt|}{L}\right) + sin\left(\frac{|x-vt|}{L}\right)\right] \qquad (1)$$

As mentioned previously, the rail deflection-load curves were non-linear so track stiffness must be referred to the load imposed. Figure 11 shows the variation of the track stiffness for the load application point of the central actuator (B) in the two cycles. It can be seen that, for the second cycle, track stiffness increases logarithmically from 0 to 75 kN/mm when the load applied is in the range between 2 and 95 kN, while for the first cycle the valid values form a straight line beginning at a load of 12 kN. Below that load, the values cannot be considered valid due to the concavity of the results. These anomalous results can have been produced by a rearrangement of ballast particles during the first load cycle which indicated ballast was not enough stabilized at the beginning of the test.

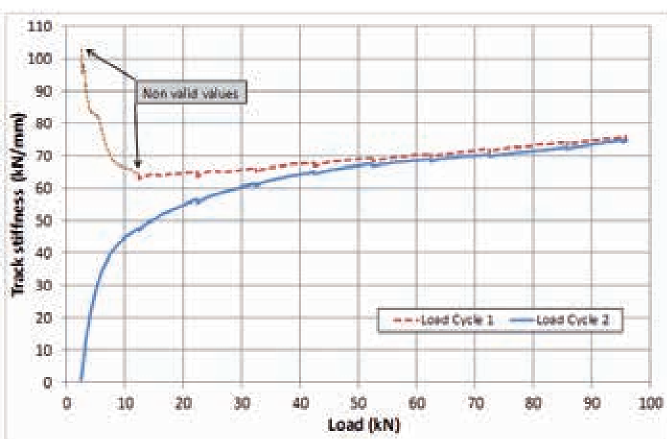


Figure 11. Track stiffness as a function of the load applied

3.2 Contribution of the track layers to the total rail deflection

In many of the static tests performed in CTB, besides the rail deflection recorded with laser systems, the track movements of other track elements can be measured:

- rail-pad vertical displacements, measured as rail-sleeper relative displacements, recorded with resistivemeters.
- ballast layer settlements, measured by LVDT inductive sensors, mounted attaching their heads to the sleepers and fixing their base to the top of the sub-ballast layer.

Figure 12 shows some photographs of the instrumentation used in the static tests.

Figure 12. Instrumentation used in the static tests

With the data recorded in the different elements previously listed, the contribution of each railway track layer to the total rail deflection was possible to be determined, as Table 1 reflects.

Table 1. Summary of results of the static tests performed

Train	Type	Passenger				Freight	
	Speed (km/h)	300				120	
	Load (kN/axle)	165				220 - 245	
Physical model (1)		1	2	3	4	2	3
Track stiffness K (kN/mm)		100	120	125	118	130	140
Contribution (%)	Pad	25	35	32	34	40	39
	Ballast	45	43	45	41	38	43
	Subballast	15	2	3	4	2	3
	Form layer	15	7	20	21	5	15
	Embankment		13			15	
(1) Subballast layers in the physical models: Model 1: 30 cm granular; Model 2: 8 cm bituminous; Model 3: 12 cm granular; Model 4: 16 cm bituminous							

Physical models 1 to 4, referred in Table 1, only differ in the sub-ballast layer, as collected in the table, while the other elements are common: 100 kN/mm stiff pad, 35 cm thick ballast layer, 60 cm thick form layer and 2.5 m high embankment with a shear wave velocity higher than 200 m/s. Figure 13 (left) is the section type of Model 1, while Figure 13 (right) shows a schematic drawing of physical Models 2, 3 and 4.

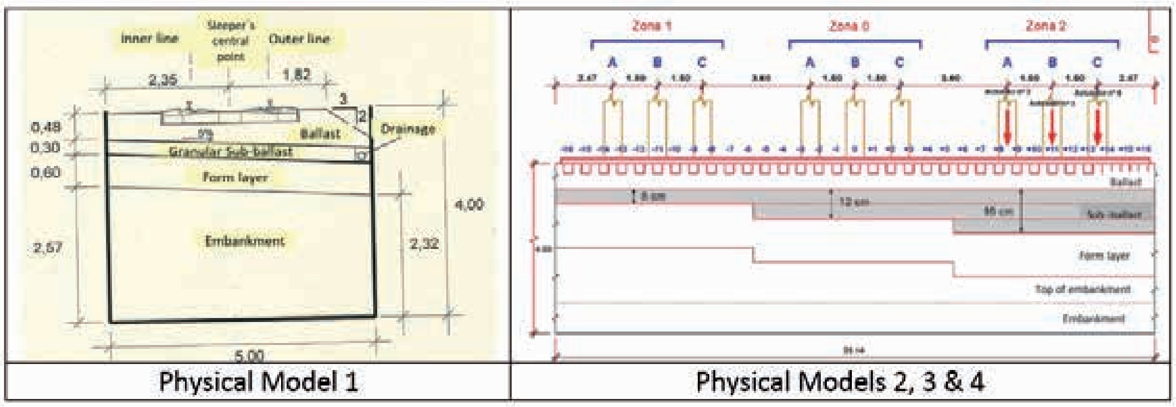


Figure 13. Section type of physical Model 1 (left) and schematic drawing of physical Models 2, 3 and 4 (right)

It must be highlighted, from Table 1, the track consolidation observed after the pass-by of 4 million axles of passenger trains at 300 km/h, thanks to the increase in track stiffness, in the Physical models 2 (from 120 to 130 kN/mm) and 3 (from 125 to 140 kN/mm). On other hand, it can be stated that the ballast layer settlement represents about 40-45% of the total rail deflection, the pad contributes between 25 and 40% and the rest of the rail deflection is due to subballast, form layer and embankment (Table 1).

3.3 Determination of track lateral stability

The study of the track lateral stability can also be carried out in CEDEX Track Box with the aid of a special tool, shown in Figure 14, which pushes away the sleeper while its horizontal movement is recorded.

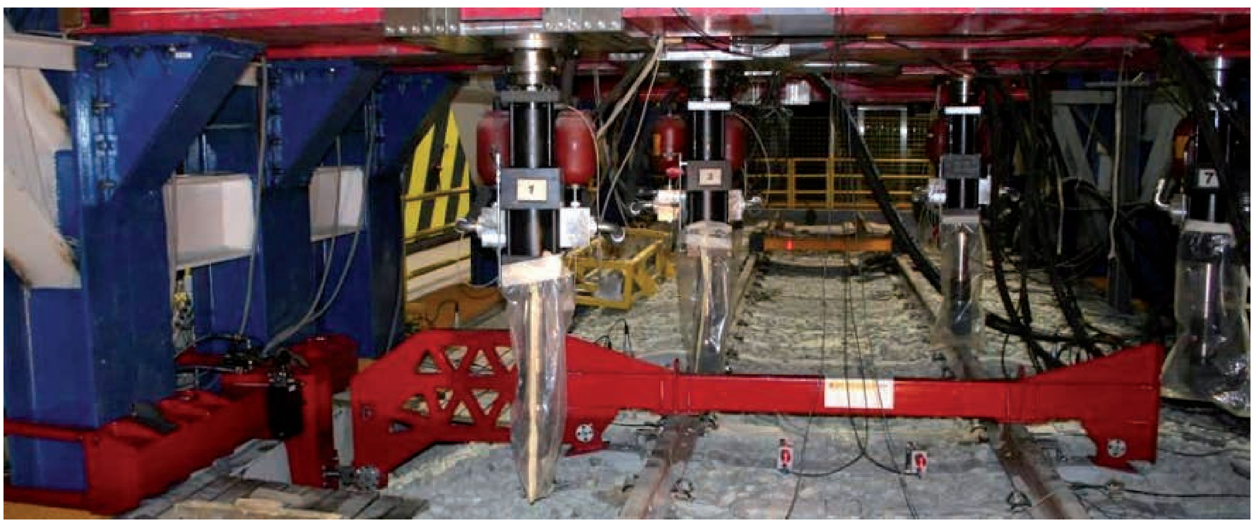


Figure 14. Tool designed to perform track lateral stability tests

The measurement equipment installed consisted on a load cell, two laser systems (to record the sleeper horizontal movement) and two potentiometers (to control the relative displacement between the sleeper and the rail).

Two different track lateral stability tests have been performed: in one of them the sleeper rested in a clean ballast layer while in the other one, the ballast layer was completely fouled with dry desert sand (Estaire et al. 2017). Test results showed a peak horizontal load of 12.5 and 16 kN in the tests performed with clean and fouled ballast, respectively, as shown in Figure 15. In both tests, peak load was reached when horizontal sleeper displacement was quite small (out 2.5 and 1.2 mm.

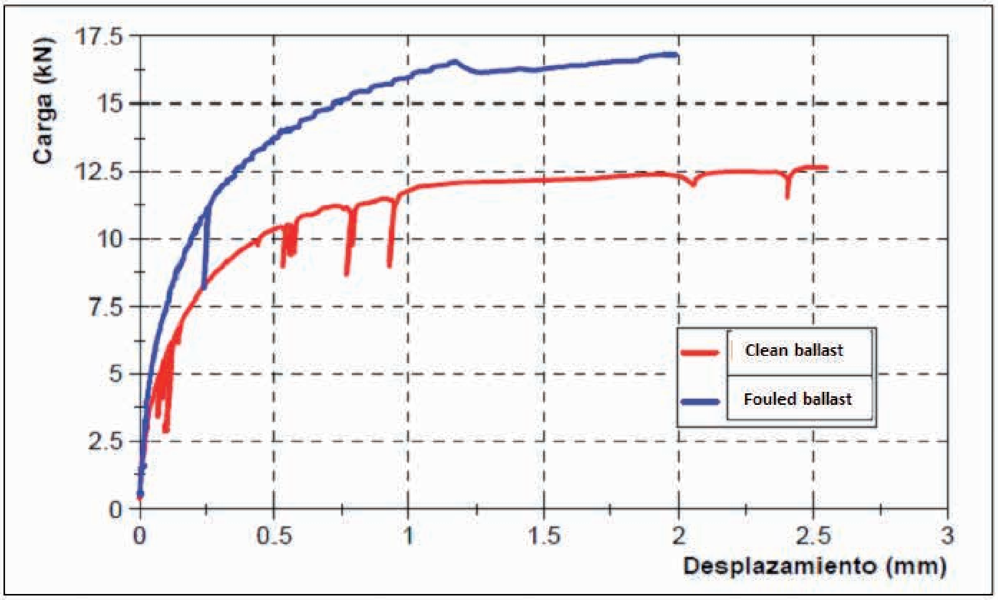


Figure 15. Result of the test performed with the sleeper on clean ballast

The results obtained in these tests show similar shapes and results than Single Tie Push Tests (STPT) performed in real railways in similar track conditions (Samavedam et al. 1999).

The track lateral stability tests were numerically modelled taking into account the following three mechanisms: the friction in the sleeper base with the ballast, the friction in the sleeper lateral faces with the ballast and the passive and active resistances of ballast in the sleeper shoulders (Kish, 2011).

The results of such modelling make it possible to draw the following conclusions:

- The main contributing components of the track lateral stability, when there is no vertical load applied, are the sleeper bottom friction (contribution between 25 and 45%, according to the cases analysed), the shoulder restraint in the frontal sleeper end (contribution between 25 and 60%), while the friction in the lateral faces accounts for the resting 15-30% (Estaire et al. 2017).
- When the sleeper is vertically loaded, the most important factor is the sleeper bottom friction, with a contribution higher than 80% and even increasing with the vertical load up to 95%, while the rest is shared between the passive resistance of ballast in the sleeper shoulder and the friction in the sleeper lateral faces, in a 1.5:1 proportion.
- Ballast friction angles used in the numerical modelling were in the range between 60 and 75° that can be considered quite high, although they are in accordance with the direct shear test results obtained in the very large shear box (1x1 m) belonging to CEDEX (Estaire and Santana, 2017).
- This similarity between the friction angles obtained in direct shear tests performed in

laboratory with the angles deduced from track lateral resistance tests makes it possible to give a great consistency and verisimilitude to both group of tests performed.

4. Quasi-static tests

4.1 Determination of ballast settlement curves

Since its beginning of work, 26 fatigue tests have been performed in CEDEX Track Box (CTB) in which, at least, one million axles were applied, under different test conditions:

- Two types of trains: passenger trains (with speeds between 300 and 320 km/h and axle loads mainly between 165 and 190 kN) and freight trains (running at a speed of 120 km/h and axle loads in the range between 220 and 245 kN).
- Two different types of sub-ballast layer: granular, with a thickness of 20 and 30 cm, and bituminous, with thickness of 8, 12 and 16 cm.
- Two different types of track systems: a) GIF AI-99 sleepers with a weight of 3.44 kN and rail pads with a stiffness of 100 kN/mm and b) B90.2 sleepers with a weight of 6.10 kN, equipped with an G04 (SLN 1010) type USP with 0.1 N/mm3 of static bedding modulus and rail pads with a stiffness of 450 kN/mm.
- Two different situations in the ballast layer: clean and fouled with desert sand in different proportions between 0 and 100%.
- The thickness of the ballast layer was 35 cm in all the tests, being formed by andesite particles.

In these tests, permanent settlement curves for the ballast, sub-ballast and form layers were obtained.

The set of the settlement curves obtained for the ballast layer in the tests performed, such as the ones shown in Figure 16, were analysed to discriminate the main factors that have influence in the track settlement and to obtain a mathematical expression to fit the results (Estaire et al. 2017).

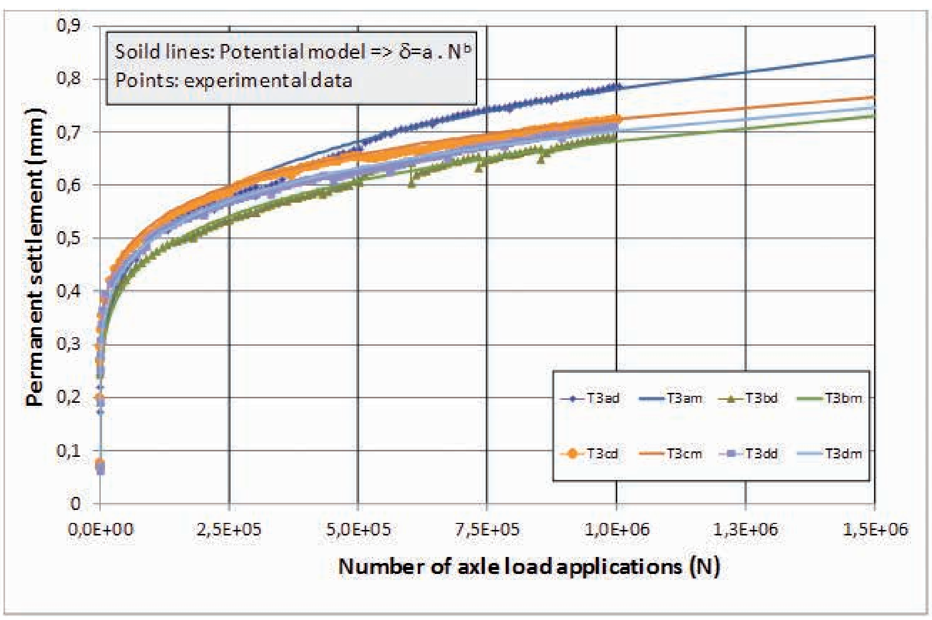


Figure 16. Some ballast settlement curves and their modelling with a potential model

The principal aspects that can be highlighted from the analysis of the experimental curves and their numerical modelling are:

- The values of the permanent settlement obtained in the tests are, in average, around 1 mm in the ballast layers, 0.03 mm in the bituminous sub-ballast layers and 0.02 mm in the form layers for 1 million of load axles, regardless the speed of the trains and the axle loads applied.
- The ballast settlement curves were modelled using a potential expression (δ = a . Nb), in which "a" represents theoretically the permanent settlement in the first cycle and "b" the rate of settlement growth with the number of axles applied. From a conceptual point of view, parameter "a" can be related with the axle load and parameter "b" with train speed, although in the final expression (Eq.2) train speed does not appear as external parameter.
- This model is different of the settlement models existing in literature, as shown with the review performed.
- A remarkable good adjustment of the test curves was obtained that confirms the validity of the potential model.
- The summary of the analysis performed for train speeds between 120 and 320 km/h leads to the following general expression of the ballast settlement law, as a function of the number of axle load applications (N), which is considered valid for axle loads (Q) between 110 and 250 kN:

$$\delta \text{ (mm)} = 0.0004 \cdot Q \text{ (kN)} \cdot N^{0.155} \qquad (2)$$

4.2 Kynematic behaviour of the different track elements

During the fatigue tests described before, the kinematic behaviour of the track elements could be determined.

On one hand, it has been shown that the track stiffness obtained in the quasi-static tests practically coincide with the ones shown in Table 1, for static tests, being the differences found in all the cases around 2-4%.

On other hand, the installation of geophones and accelerometers made it possible to measure velocities and accelerations in different track elements, as shown in Table 2, for trains travelling at about 300 km/h.

Table 2.Velocities and acceleration peaks obtained in the fatigue tests

	Velocity peaks (mm/s)		Acceleration peaks (g)	
Train	**Passenger**	**Freight**	**Passenger**	**Freight**
Rail	40 – 45	15 – 20	1.0 – 1.5	0.50 – 0.80
Sleeper	20 - 30	10 – 15	0.5 – 1.0	0.15 - 0.30
Ballast	15 – 20	7 - 10	< 0.5	< 0.15
Form layer	10 – 15	7 - 10	---	---
Embankment	2 - 6	< 4	---	---

These values must be considered as reference values when track is in good mechanical conditions, so they can be used to indicate the need to perform maintenance or repair works.

4.3 Determination of track behaviour for different speeds

4.3.1 Introduction

Some tests were performed in CTB modelling the pass-by of trains at different speeds (50/ 100/ 150/ 200/ 250/ 300/ 350/ 400 km/h) to analyse the effect of speed in the global response of the track. To do that, a Siemens S-100 train (a train with 13 bogies, with a separation between bogies of a wagon of 18.7 m and almost 200 m long) was modelled, supposing a constant wheel load of 71 kN instead of the real loads, that are in the range between 63 and 76 kN, as shown in Figure 17.

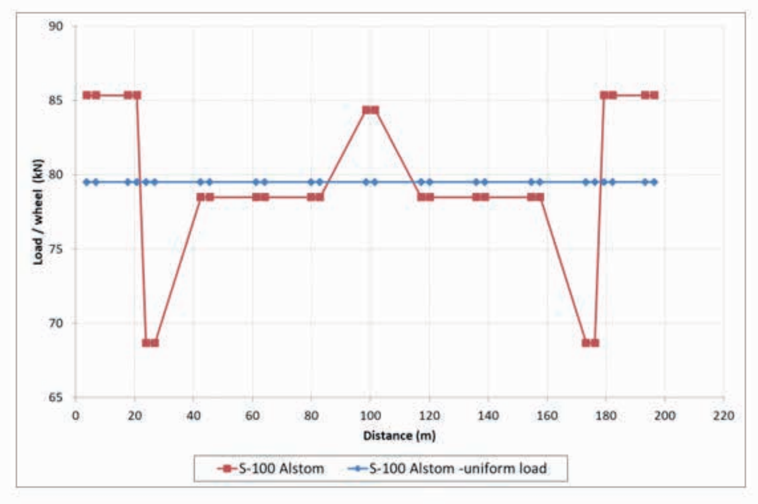


Figure 17. Loads per wheel in the modelled train used in CTB tests

Figures 18 and 19 show, as examples, the load-time history of the loads imposed by the modelled train and their frequency content, respectively, when the train speed is 150 km/h. It can be seen that, for that speed (v), the fundamental frequency is about 2.25 Hz which corresponds to the frequency (f) derived from the distance between bogies (d) in the same wagon (f=v/d).

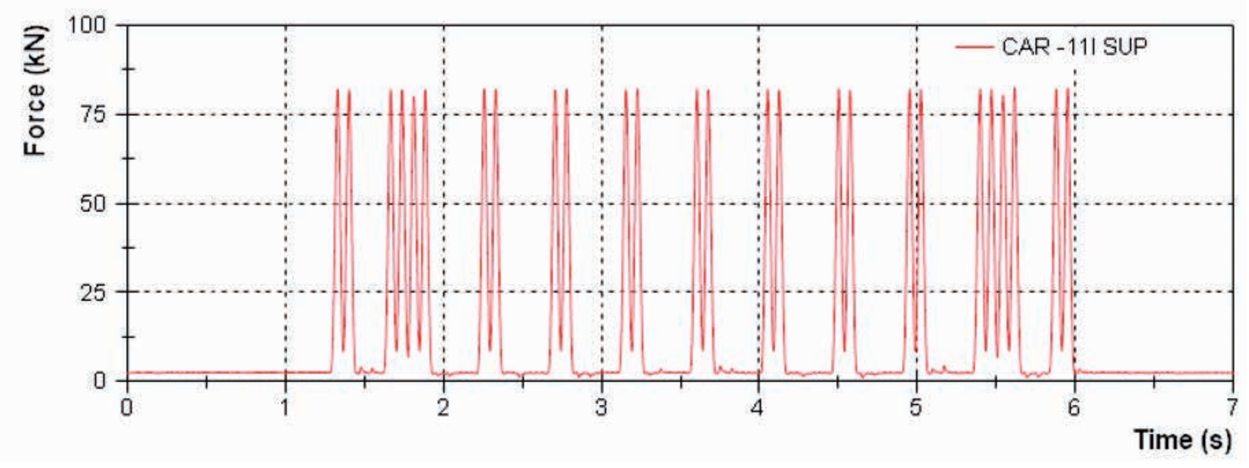


Figure 18. Time-load history in the modelled train used in CTB tests, running at 150 km/h

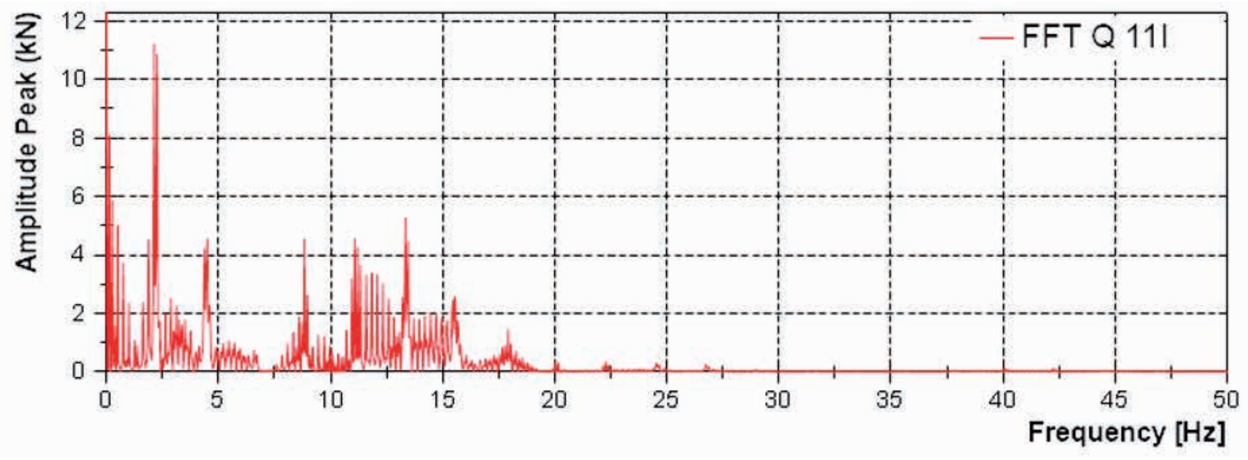


Figure 19. Frequency content of the load history in the modelled train used in CTB tests, running at 150 km/h

4.3.2 Rail deflection

Some of the test results performed with different speeds, in terms of rail deflections, are shown in Figure 20. The numerical results are collected in Table 3 that includes the result of a static test performed previously at the beginning of the tests.

Table 3. Test results for a S-100 train passing by at different speeds		
Train speed (km/h)	**Rail deflection (mm)**	**Relative rail deflection (1)**
0	0.931	1.00
50	0.943	1.01
100	0.928	1.00
150	1.013	1.09
200	1.007	1.08
250	1.006	1.08
300	1.023	1.10
350	1.113	1.20
400	1.152	1.24

(1): Relative rail deflect (speed): Rail deflect (speed) / Rail deflect (v=0 km/h)

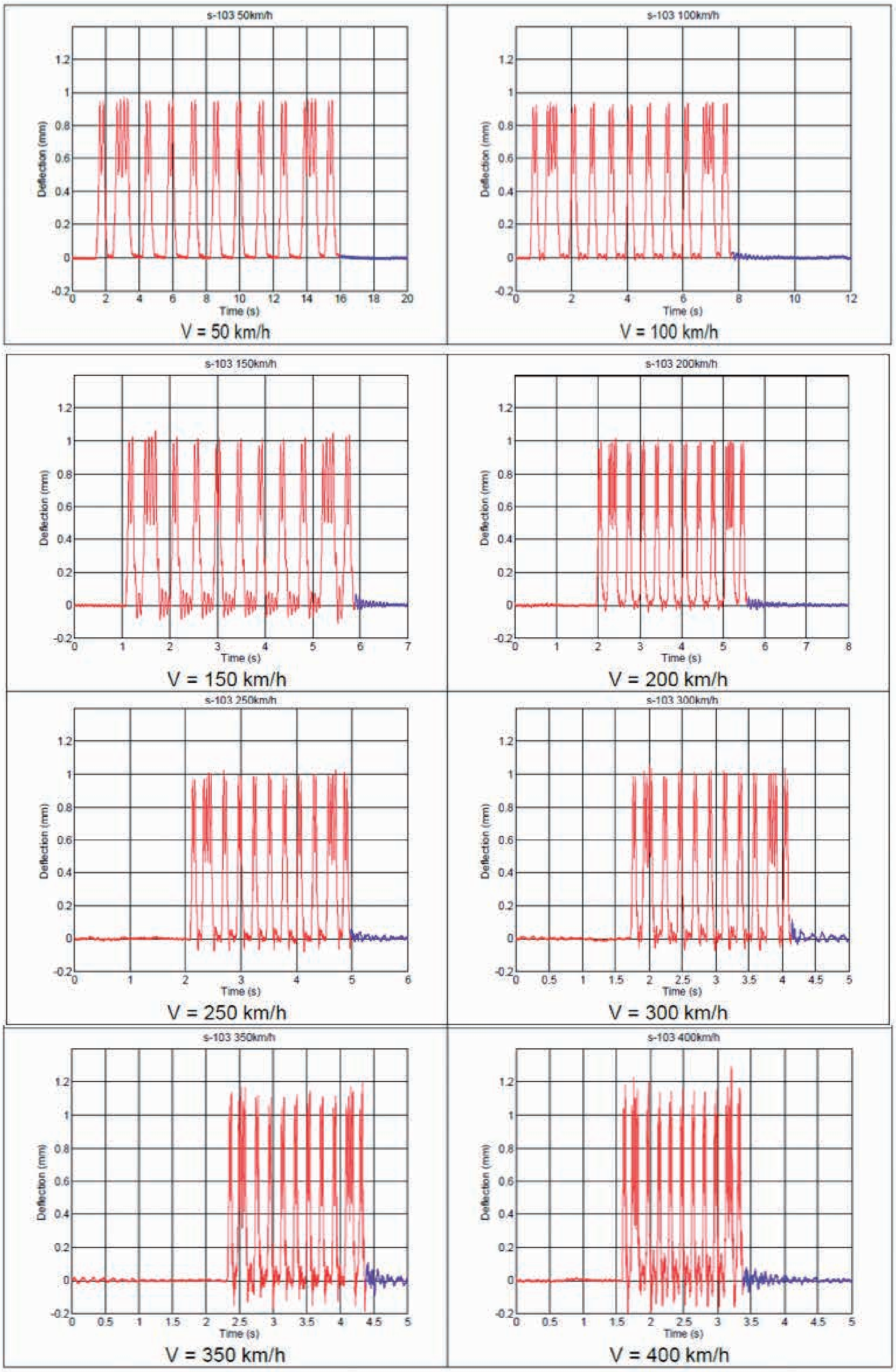


Figure 20. Rail deflection curves obtained for different train speeds in CTB tests

The analysis of the test results shown above makes it possible to highlight the following aspects:

- The tests can be divided in three groups according with the rail deflection obtained, as it can be seen in Figure 21:
  - For tests with speeds below 100 km/h, the rail deflection is below 1 mm.
  - For tests with speeds between 150 and 300 km/h, rail deflection is a bit above 1 mm.
  - For tests with speeds above 300 km/h, rail deflection increases steadily up to 1.15 mm.

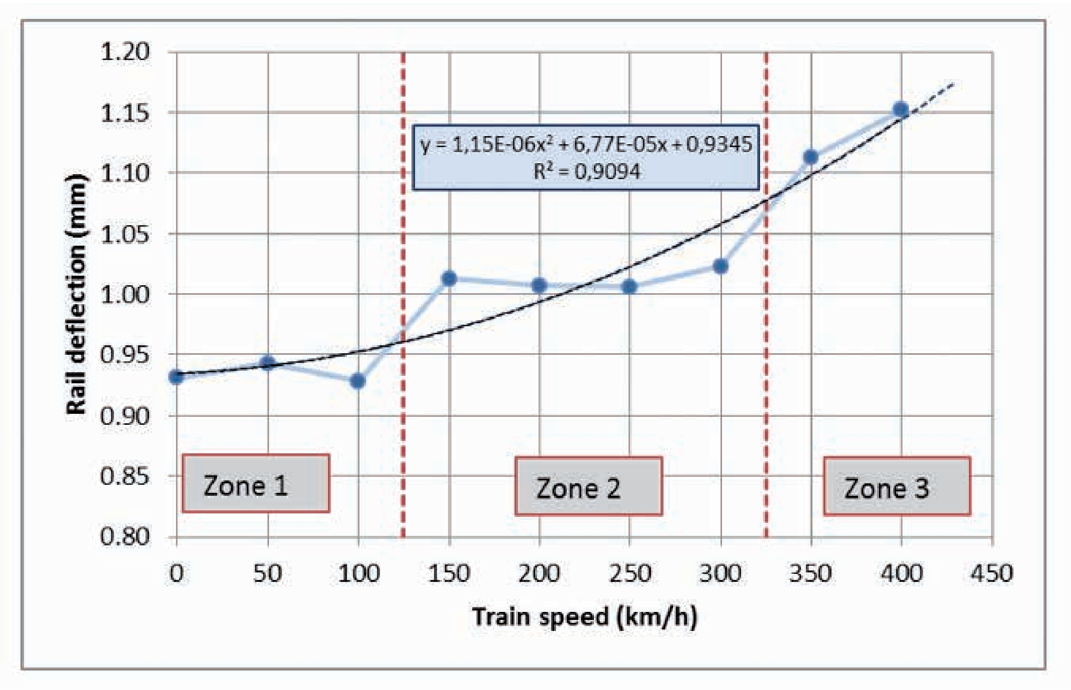


Figure 21. Rail deflection obtained in CTB tests as a function of the train speed

- The increase in rail deflection was from 0.93 to 1.15 mm when train speed varied from 0 to 400 km/h. That supposes an increase of 25%.
- The rail deflections obtained for speeds between 150 and 300 km/h can be considered quite steady, while for 350 and 400 km/h the peak rail deflections are more irregular and oscillate much more than the ones obtained for smaller speeds.
- It can be also observed that the free rail oscillation during the bogie pass-by significantly increases with the speed.

The results can be used to deduce the critical velocity of the 1:1 scale model built in CTB, with the aid of the graph in Figure 22 that relates the increase of rail deflections with the increase of train speed. The curves in Figure 22, for different damping ratios, appear as the solution of the differential equation that gives the vertical deflection of an infinite beam on an elastic foundation when a load is moving on it (Fryba, 1999).

The best fitting of the results is obtained, in this case, for a critical speed of 640 km/h which can be considered accurate enough for a very good railway track, with a hard embankment and hard track bed layers.

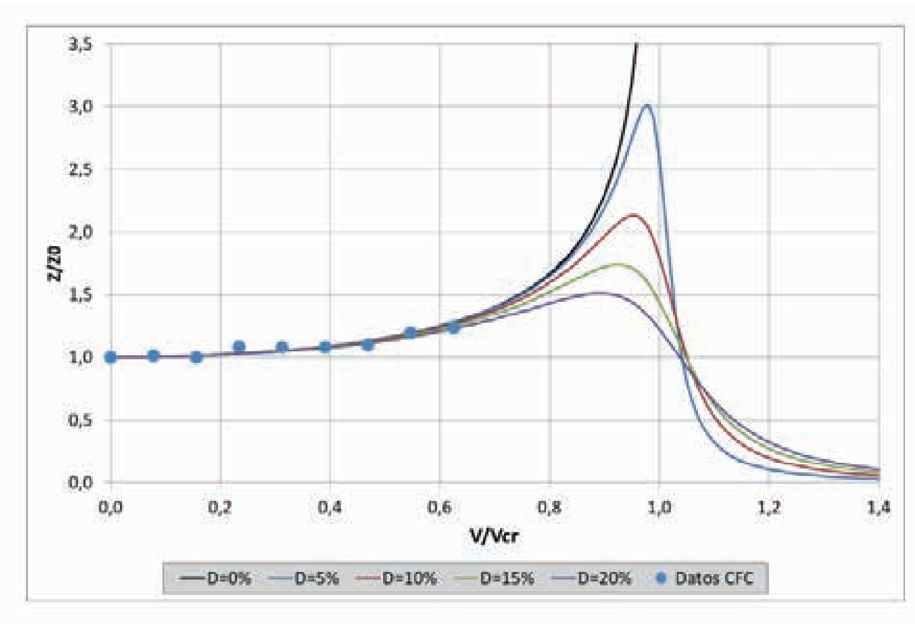


Figure 22. Analysis of the displacements obtained for different train speeds to deduce the critical speed of the 1:1 scale model built in CTB with a hard embankment and hard track bed layers

4.3.3 Rail and sleeper velocities

The tests performed at different speeds also made it possible to record velocities in the rail and in some sleepers by the use of geophones. The values obtained are collected in Table 4 and represented in Figure 23.

Table 4. Velocities obtained in rail and sleepers for different train speeds.

Train speed (km/h)	Outer Rail Amplitude (cm/s)	Inner Rail Amplitude (cm/s)	Outer Sleeper Amplitude (cm/s)	Inner Sleeper Amplitude (cm/s)
50	0.83	0.66	0.36	0.57
100	2.00	1.16	1.11	0.83
150	3.50	2.20	2.00	1.10
200	5.90	5.40	4.40	3.50
250	7.50	7.10	4.50	3.90
300	9.70	11.10	5.60	5.20
350	12.60	12.01	7.50	6.40
400	16.00	14.50	10.40	8.00

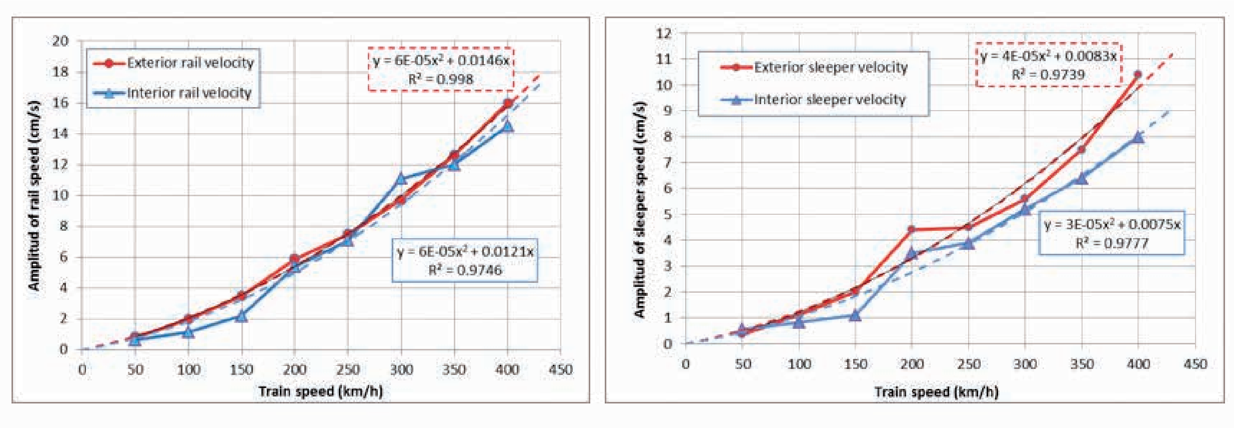


Figure 23. Amplitude of rail (left) and sleeper (right) speed

As it can be seen in Figure 23, the amplitude of velocities obtained in the rail and in the central sleeper increase with the train speed, showing a similar pattern than the increase of rail deflections. Note that the best fitting curves are, in all cases, second degree polynomials.

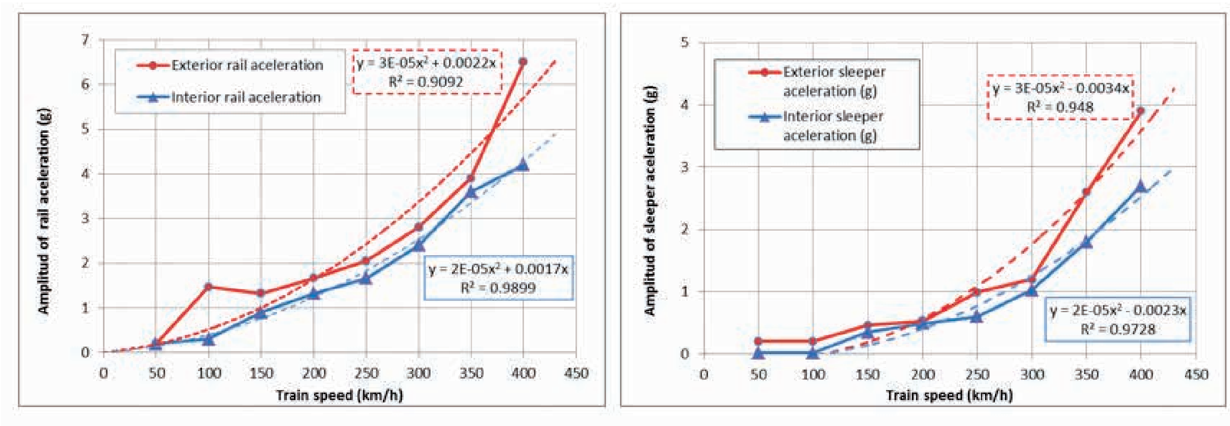
4.3.4 Rail and sleeper accelerations

In the tests performed at different speeds, the accelerations in the rail and in the central sleeper were also recorded with some accelerometers. The values obtained are tabulated in Table 5 and represented in Figure 24.

Table 5. Accelerations obtained in the rail and the central sleeper for different train speeds

Train speed (km/h)	Outer Rail Amplitude (g)	Inner Rail Amplitude (g)	Outer Sleeper Amplitude (g)	Inner Sleeper Amplitude (g)
50	0.20	0.20	0.20	0.02
100	1.47	0.30	0.20	0.02
150	1.32	0.90	0.46	0.35
200	1.66	1.32	0.53	0.49
250	2.05	1.66	0.99	0.60
300	2.80	2.40	1.20	1.03
350	3.90	3.60	2.60	1.80
400	6.50	4.20	3.90	2.70

Figure 24. Amplitude of rail (left) and sleeper (right) acceleration



As shown in Figure 24, the rail and sleeper accelerations have the same trend as deflections and velocities: an increase of the values recorded with an increment of train speed, following a second degree polynomial.

4.4 Tests with new materials: sleepers equipped with USP

The aim of this work was to analyze the behavior of a prototype of sleepers equipped with Under Sleeper Pad (USP) by the performance of both static and quasi – static tests. These tests were carried out as part of RIVAS project (Railway Induced Vibration Abatement Solutions) in the frame of European Union Seventh Framework Program.

4.4.1 Sleeper characteristics

The sleepers used in the tests were 13 mono-bloc concrete pre-stressed units of the B90.2 type. Their average weight was 6.10 kN and they had a length of 2.80 m, while the rest of the dimensions can be seen in Figure 25. The sleepers were provided with 0.1 N/mm3 static bedding modulus under-sleeper pads of the G04 (SLN 1010) type, glued along all the sleeper bottom, as can be seen in Figure 26.

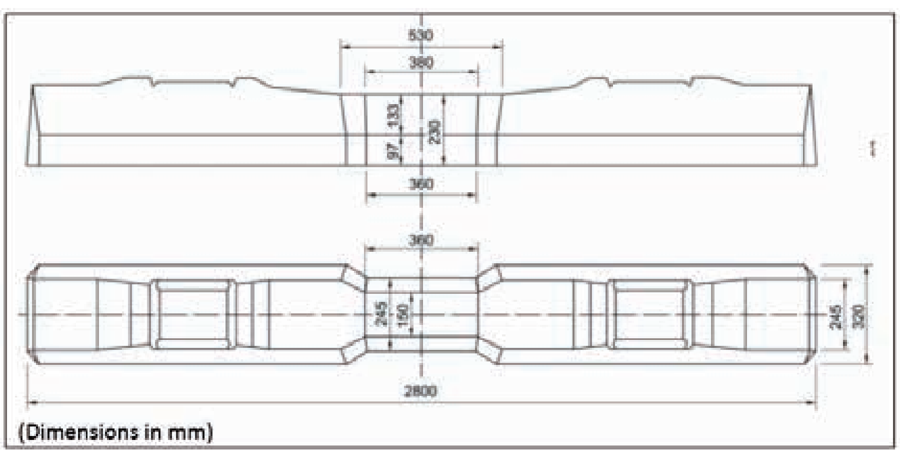


Figure 25. Schematic drawings of the sleeper used in the tests

Figure 26. General aspect of USP installed in the sleepers

4.4.2 Static tests

Four series of three step by step static tests, up to a maximum axle load of 225 kN each, were carried out loading the track subsequently in cross sections A, B and C, as shown in Figure 27 (left). For each cross section, two hydraulic actuators were used simultaneously to load both rails. The time-load history used in the static tests is indicated in Figure 27 (right).

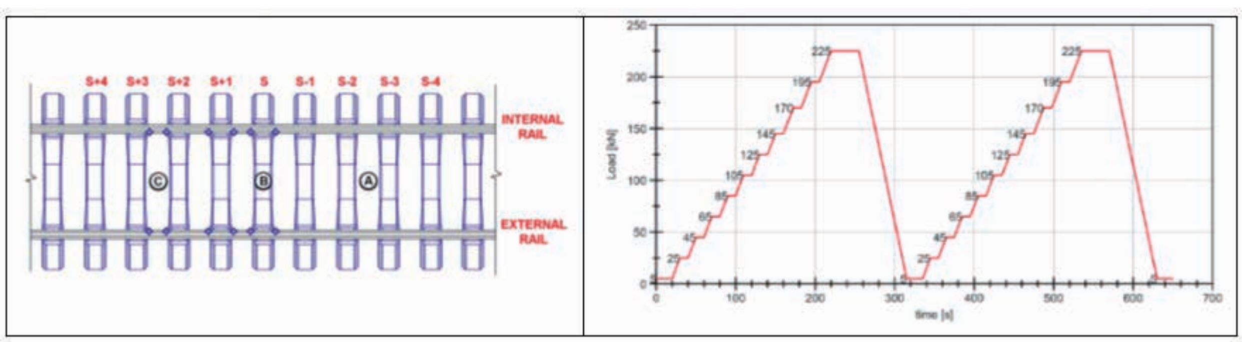


Figure 27. CTB static test cross sections (left) and load time history used in the tests (right)

The static tests were performed to determine the mechanical behavior of the track system with the ballast in the following states:

- BT state: after extended and compacted.
- BTS state: after tamped and stabilized with 70,000 freight vehicle tones.
- B1M state: after consolidated under the pass by of 1M freight vehicle axle loads.
- B2M state: after consolidated under the pass by of 2M freight vehicle axle loads.

The following sets of sensors were used for each static test set:

- 8 laser beam systems: 4 for cross section B and 2 in each cross sections A and C.
- 16 inductive rail-pad displacement sensors: 8 for each rail.
- 3 inductive sleeper displacement sensors: 1 for each cross section.

The rail load-deflection curves obtained in the static tests carried out in the central cross section (cross section B) are given in Figure 28. On other hand, Figure 29 shows the supporting load/ballast + under sleeper pad compression curves obtained in the static tests carried out. From both set of curves it can be noticed the non-linear behaviour of the track components.

The variations of the track stiffness, along the rails, obtained in the four series of static tests are illustrated in Figure 30, for the different ballast state. In each one of them three values are given for each rail representing the global stiffness values obtained in cross sections A, B and C. Also one single value, corresponding to the average of the three global values, is given for each rail in those figures.

It can be seen that there are significant differences between the different points that reflects the heterogeneities produced during the construction operations in spite of the laboratory conditions and the careful control under those activities were performed in CTB.

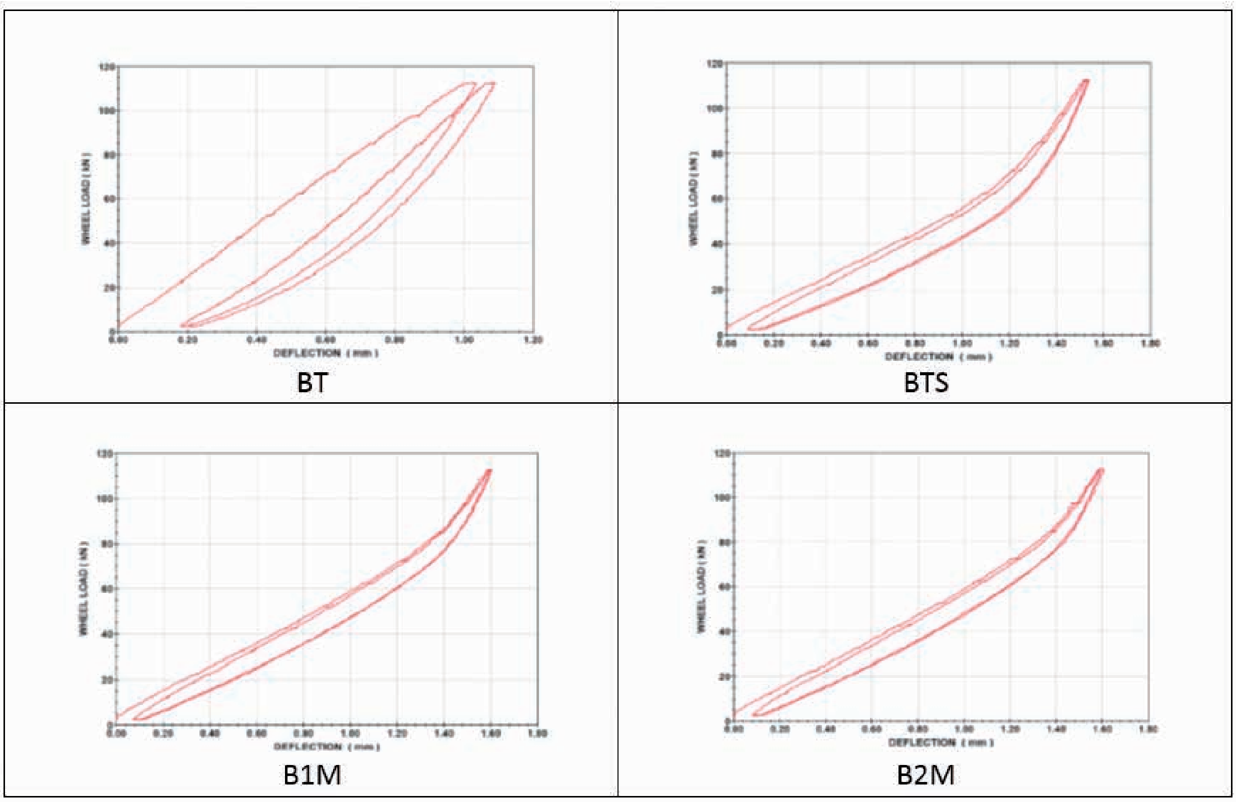


Figure 28. Rail load-deflection curves obtained in the static tests

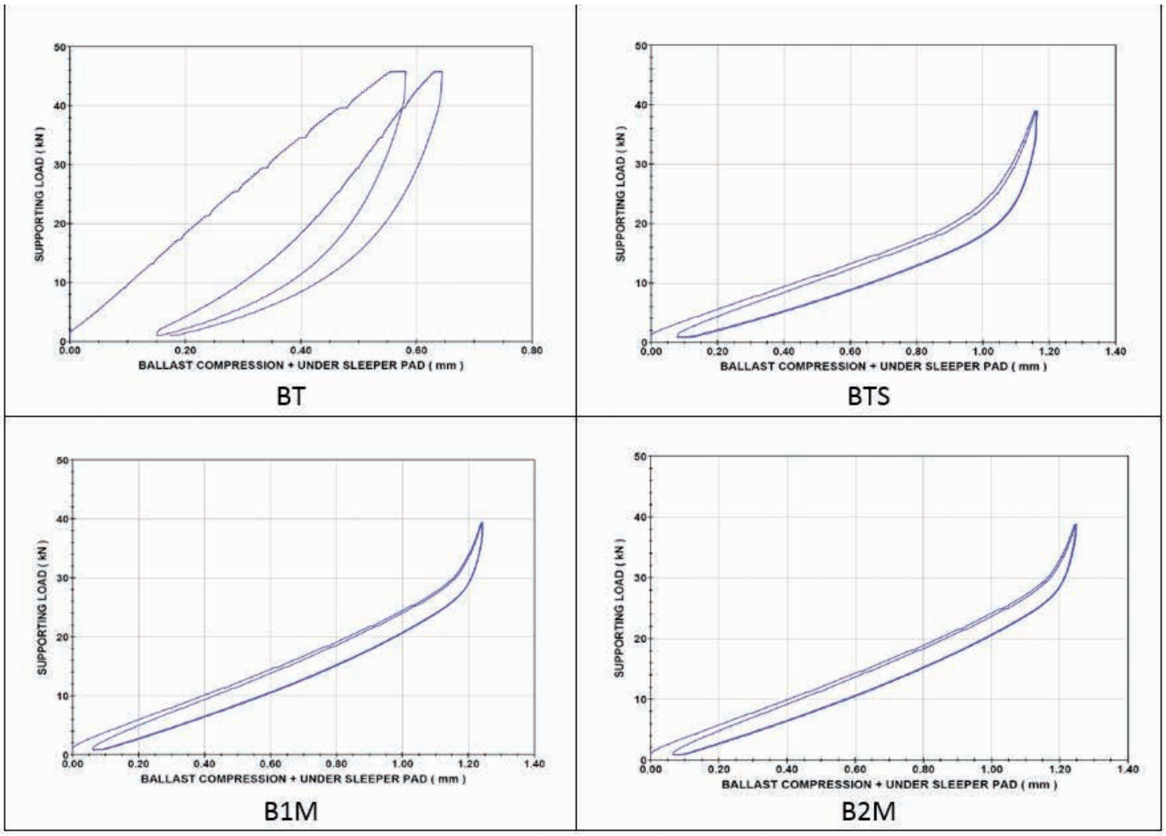


Figure 29. Supporting load/ballast + under sleeper pad compression curves obtained in the static tests

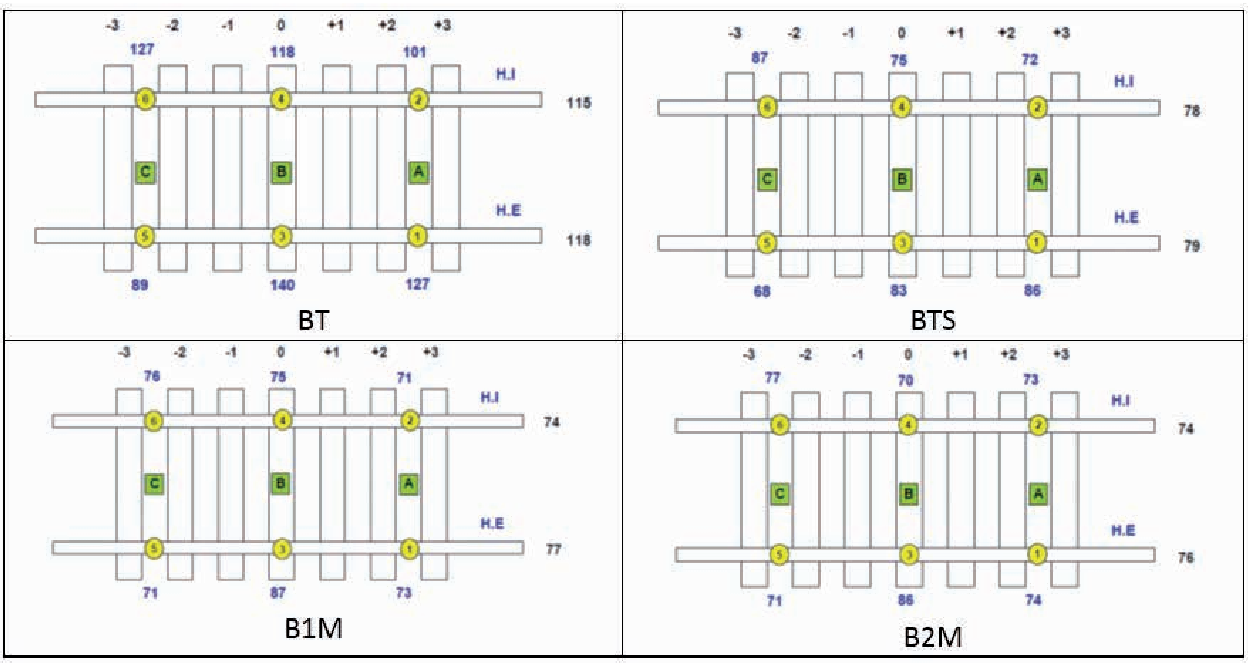


Figure 30. Track stiffness deduced from the static tests for different ballast states

The non-linear behaviour exhibited by both the rail load/deflection curves and the ballast load/compression curves have been quantified through the lower, global and higher load range stiffness values presented in Table 6.

Table 6: Track stiffness values obtained in the second loading cycle at the central cross section

Ballast State	Lower range value 2.5 - 42.5 kN	Global range value 2.5 - 112.5 kN	Higher range value 82.5 - 112.5 kN
BT	104	128	136
BTS	56	78	145
B1M	58	81	123
B2M	60	78	133

On other hand, the vertical displacement measured in the different potentiometers installed in both rails to measure the pad vertical compression are tabulated in Table 7 and represented in Figure 31. Additionally, the rail pad spring constant (kp) is aslo collected in Table 7.

Ballast state	Rail	Rail pad compression (x 10^{-3}mm)									Rail pad spring kp (kN/mm)
		Sleeper									Sleeper
		-4	-3	-2	-1	0	1	2	3	4	*0*
BT	Inner	1	2	8	18	56	26	8	1	1	795
	Outer	2	1	8	33	42	26	8	1	1	1121
BTS	Inner	3	4	5	5	50	17	10	28	2	767
	Outer	3	4	8	32	63	1	11	2	2	628
B1M	Inner	2	16	8	12	64	6	15	10	0	599
	Outer	2	16	9	19	74	17	4	2	0	543
B2M	Inner	4	12	18	17	61	3	22	14	0	617
	Outer	4	12	13	16	74	19	5	2	0	541

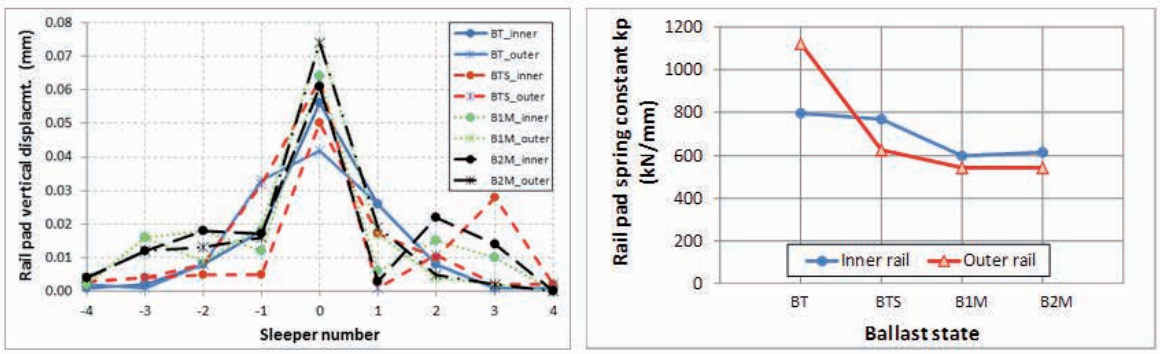


Figure 31. Rail pad vertical settlements measured in the static test performed at the central section for different ballast states (left) and rail pad spring constant (kp) deduced for the central section

The most significant feature of the results is that, for each section, the rail pad settlements, and consequently its spring constant, change during the test although the most apparently affected track component should be the ballast, since it was tamped, stabilized and loaded with 2 M load cycles.

4.4.3 Long lasting quasi - static tests

For the long lasting tests, the three couples of hydraulic cylinders situated at cross sections A, B and C (see Figure 27) were used simultaneously but with a time lag of 45 ms between each couple to simulate the pass by of freight vehicles having 164 axles that apply a load of 225 kN, at 120 km/h, until fulfilling the 2M axle loads.

The evolution of the vertical deflection amplitudes of the rail, the rail-pad and the sleeper, measured at the central cross section along the first million of axle loads is illustrated in Figure 32. It can be seen that those amplitudes have a light decrease once the first 100,000 cycles have been applied, while during the rest of the test they are quite constant.

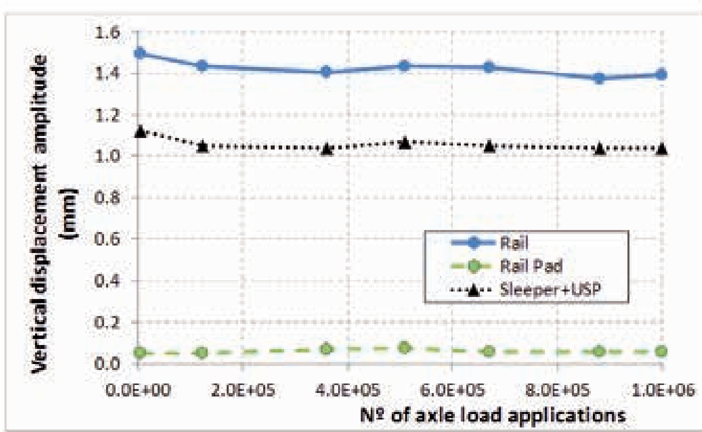


Figure 32. Track, rail pad and sleeper deflection amplitudes at central cross section

Figure 33 shows the track stiffness determined during the test, besides the values obtained in the static tests corresponding to the initial (BTS state) and final (B1M state) stages. It can be seen that the track stiffness is quite constant during all the test although there is a little increase in the outer rail values. On other hand, the static values are quite similar to those obtained in the quasi-static tests.

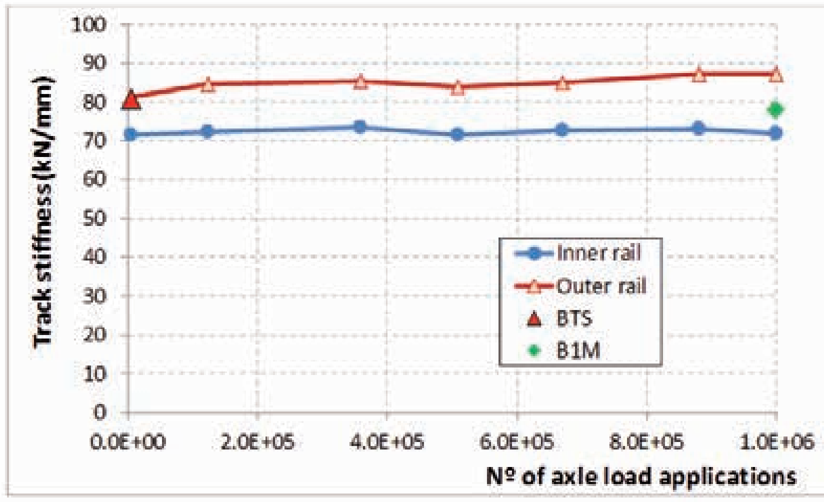


Figure 33. Quasi-static track stiffness values at central cross section obtained along the first million of axle loads

Finally, the evolution of the irreversible settlement experienced by the ballast is shown in Figure 34. This curve can be interpreted as the ballast fatigue curve. It can be seen that there is a great initial settlement around 0.6 mm which roughly represents the half of the total and that, from 250,000 cycles there is a linear increase with a rate of settlement of about 0.22 mm/ 1M axle loads.

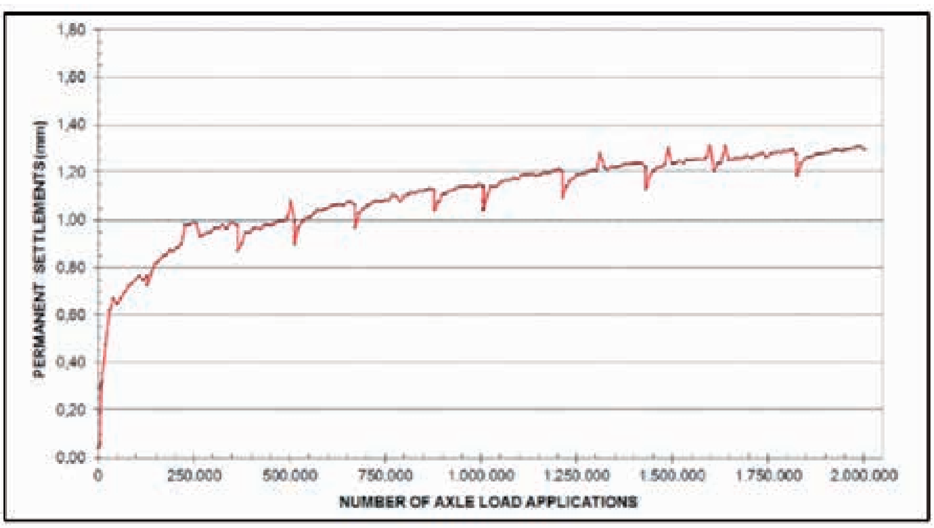


Figure 34. Ballast permanent settlement curve

5. Summary

CEDEX Track Box (CTB) is a 21 m long, 5 m wide and 4 m deep facility whose main objective is to test, at 1:1 scale, complete railway track sections of conventional and high speed lines for passenger, freight and mixed traffics, at speeds up to 450 km/h.

CTB has been used since its construction, 12 years ago to research on different matters of rail way tracks founded on hard soils such as: measurement of track vertical stiffness under different track conditions, determination of track lateral stability, determination and interpretation of ballast permanent settlement curves in fatigue tests, calculation of rail deflections under the pass-by of trains at very high speeds, up to 450 km/h, behaviour of sleepers with USP, optimization of bituminous sub ballast thickness, , behaviour of High Speed Lines subjected to mixed traffic and calibration of 3D numerical models.

Furthermore, it can be also used to study the influence of ground irregularities in the behaviour of slab tracks, to optimize the maintenance works in slab-ballast transition zones or to analyse the ballast degradation in switches or crossings.

The recent deployment of a 3 Hz natural frequency spring system at the base of CTB will allow in the future to assess experimentally the behaviour of ballasted and slab tracks founded on soft soils.

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7. Acknowledgements

The authors of the paper want to acknowledge all the people who have worked in CTB during all its working life: Francisco Navarro, Miguel A. Andreu, Juan L. Cámara, Ricardo Fernández, Francisco González, Inés Crespo, Raul Reinoso, Ángel Carballo, Gema Villar. Pedro León, Antonio García, José M. Cerezo y José L. F. Rocha.