Integrated Project (IP)
Project No. TIP5-CT-2006-031415

Thematic Priority 6:
Sustainable Development,
Global Change and Ecosystems

Methods of track stiffness measurements

INNOTRACK GUIDELINE

Deliverable D2.1.11

Table of Contents

1. Executive Summary

Vertical track stiffness is an important parameter in railway track engineering, both from a design and maintenance point of view. This guideline presents important aspects of track stiffness as well as different measurement methods to gather stiffness information of the track.

Within Innotrack, three methods for global track stiffness measurement have been used and partially developed. The Portancemetre and the RSMV (Rolling Stiffness Measurement Vehicle) measures stiffness while rolling. Track instrumentation is capable of determining track stiffness at a site by ordinary traffic passing. Stiffness can be acquired at speeds up to 50 km/h with the vehicle devices.

Also a method called Panda, for determining local track stiffness has been used and developed. Panda is a lightweight penetrometer which determines the cone-resistance of the layers of the track substructure rapidly.

2. Introduction

Subproject 2 (SP2) in INNOTRACK is dedicated to the supporting structure of the railway track. In order to decide maintenance actions for the substructure, the condition of the substructure must be known. Historically, most attention has been paid to inspection techniques of the superstructure. Several such techniques are standard measurements used worldwide. The substructure has been given much less consideration, especially the subballast and subsoil components, even though it has a major influence on the cost of track maintenance. Most of the substructure investigation techniques are not standard measurements and are not performed regularly. This guideline focuses on condition monitoring techniques to assess the vertical stiffness of the track.

Track stiffness is the relation between force and displacement. The term global stiffness is used if the whole track structure is considered, often measured as applied force to rail divided by rail displacement. Global track stiffness varies both with frequency, dynamic amplitude, applied preload and position along the track. Global track stiffness is an important interaction parameter in the wheel-rail interaction, and variations of track stiffness as well as extreme values (both low and high) will affect the degradation of the track. Global track stiffness can be measured both at standstill and while rolling along the track. Few railway authorities have access to track stiffness measurement equipment at present date.

Local track stiffness here refers to the stiffness of different components or layers. Local track stiffness of components can often be quantified by the manufacturer from lab-tests and variability can be also be quantified. Local stiffness of different layers can be measured in laboratories if soil-samples are used, however there are also methods for onsite investigations by means of cone-penetration tests and similar.

Research within Innotrack has focused on developing measurement techniques as well as methodologies to use measured data.

3. Motive for track stiffness measurements

Several references point out vertical track stiffness as important for track maintenance. Esveld states [1]: “Track stiffness has been found to be very useful for the purpose of determining the cause of certain substructure problems. Unfortunately, in most of the cases railways do not possess the right equipment for this type of measurement and, thus, do not utilize the insight these measurements could have provided them with”. Sussmann et al. state [2]: “Track stiffness test provides a potentially useful technique for systemwide evaluation of track safety and performance. The data can be used to provide an additional indicator of track condition to inspectors and to guide maintenance planning and execution.” Fröhling states [3]: “Spatial variation of the track stiffness contributes significantly to track deterioration, both in terms of differential track settlement and increased dynamic vehicle loading. It is thus recommended that track maintenance procedures should be used to reduce the variation of the spatial track stiffness." Ebersöhn and Selig state [4]: "The continuous measurement of track deflection or stiffness and the correct interpretation of the results will be a tool for the track maintenance engineer to correctly direct the maintenance activities which will result in optimal use of the maintenance budget."

Selig and Li [5] performed a parametric study with the software GEOTRACK, to find out the potential effects different track components have on track modulus. This study clearly showed that the subgrade (soil) properties had most impact on the total track modulus. The authors summarize the parametric study: "The factor affecting the track modulus most is the character of the subgrade layers. The influence of subgrade condition on track modulus is further enhanced by the fact that the subgrade resilient modulus is the most variable quantity among all the track parameters, subject to change of soil type, environmental conditions, and stress state. Therefore, a change of track modulus in the field is primarily an indication of a change of subgrade condition. Since the subgrade condition is subject to weather, extremes of temperature and moisture, the track modulus may vary with seasonal changes."

There are several different areas where track stiffness measurements have potential for supporting track maintenance decisions: indicator of root cause at problem sites, upgrading of track for higher speed and/or axle load, verification of newly built track.

3.1. Indicator of root cause at problem sites

Measurement of track geometry quality is the most used automated condition assessment technique in railway maintenance. Most problems with the track (at least the ones concerning the ballast and substructure) will be visible as track geometry irregularities, but the root cause of the problem is not detected with the help of track geometry measurements. In these cases, track stiffness measurements can help finding the root cause of the problem [2], [4], [5]. However, it is also important to be aware of that track stiffness measurements can not indicate the root cause problem in all cases. Examples of common root causes detectable by stiffness measurement is transition zones, soft soil related causes and environmental vibration.

3.2. Upgrading of track for higher speed and axle load

The trend towards using faster trains and heavier axle loads than those originally considered in many cases compel upgrading of existing tracks. There are many aspects that have to be considered when upgrading a track, and among them are bearing capacity, stability, and future maintenance needs for the track. Civil engineering structures, for example bridges, are in some sense known structures in terms of materials and can be subjected to visual inspection. The substructure of the track is on the contrary often unknown and only limited visual inspection is possible. The possibility to measure the vertical track stiffness could be a help for determining which sites along the track that need some kind of substructure reinforcement or further investigation.

3.3. Verification of newly built track

During design of a new track, track stiffness is most often considered with questions like: What is the desired rail deflection? How long transition zones at bridges etc. shall be used? Different design aspects can be found in [6]. In the study by Lopez Pita et al. [7], changes of track stiffness through culverts and bridges was considered the main cause of track deterioration. There is a lack of recommendations for track stiffness variability; however the Eurobalt II project recommended that variations in the stiffness of the subgrade should be limited to less than 10% of the mean value [8]. With the help of continuous track stiffness measurements, it is possible to verify newly built tracks; both for stiffness magnitudes and variability.

4. Global track stiffness

4.1. Definitions

Vertical track stiffness (k) can be defined in a number of ways. The simplest form is the ratio between track load (F) and track deflection (z), where the force can be either axle load or wheel load:

$$k = \frac{F}{z} \tag{1}$$

Commonly the stiffness of the different components of the track structure, such as the rail pad and subgrade, can be nonlinear. Further, the sleepers may also have voids beneath them, which lead to large deflections for low load magnitudes as indicated in Figure 1. To take these factors into account other definitions of track stiffness may be used. For example, to eliminate the effect of voiding, stiffness may be calculated from a load-deflection point after the end of the seating stage as in the secant stiffness:

$$k_{x-ykN} = \frac{F_y - F_x}{z_y - z_x} \tag{2}$$

Where F_x and z_x are the seating load and resulting deflection respectively.

Alternatively the tangent stiffness can be used:

$$k_{tng,z} = \left|\frac{dF}{dz}\right|_{z_0} \tag{3}$$

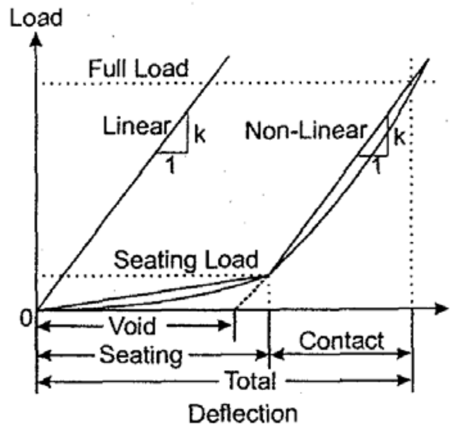


Figure 1. *Load – deflection diagram illustrating voids and non-linearities (after Sussmann et al. [2]).*

Examples of measured vertical track stiffness are shown in Figure 2. Figure 2a displays a force-deflection diagram where the rail is slowly (quasi-statically) loaded up to 150 kN while the corresponding deflection is measured. The curve is non-linear and also shows a hysteresis, which indicates a damping factor.

To facilitate the analysis of dynamic track stiffness using Fourier transforms and associated transfer functions, it is necessary to assume that the stiffness is linear about a certain reference preload. This presumption is approximately valid for a limited portion of the force-deflection diagram. The transfer function between force and displacement is called receptance (α) or dynamic flexibility, Eq. 4 which is the inverse of dynamic stiffness. The receptance is a complex-valued quantity and is often given with magnitude and phase.

$$\alpha(f) = \frac{z(f)}{F(f)} \tag{4}$$

An example of receptance magnitude, where the same track as in Figure 2a is loaded statically by 90 kN and dynamically by 10 kN, is shown in Figure 2b. This load is representative for the track behavior from an axle load of 180 kN when fully loaded. In this particular case we find a resonance around 5 - 8 Hz due to soft soil (clay). We also see that the track is stiffer (lower receptance) for higher frequencies, at least up to 50 Hz.

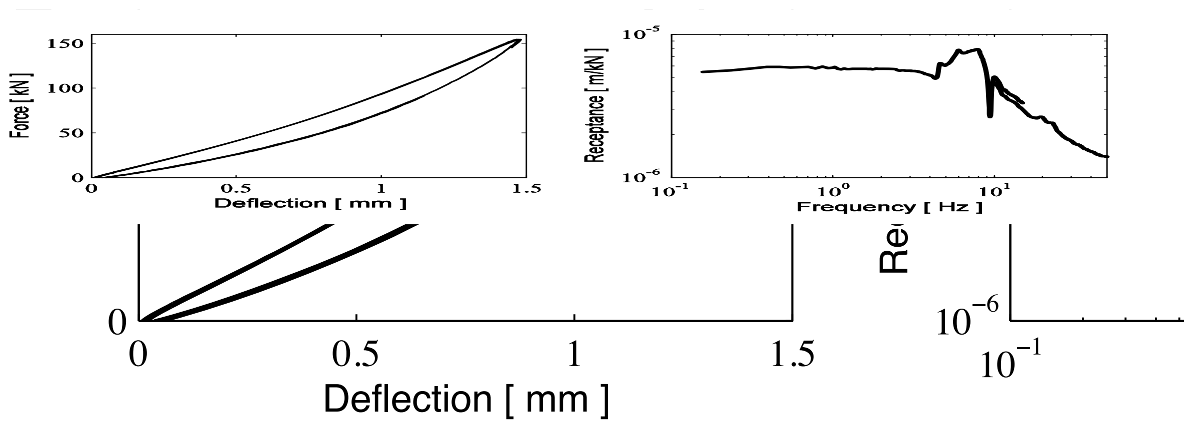


Figure 2. a*: Vertical force-deflection diagram of track with quasi-static excitation (measured on rail),* ***b:*** *Magnitude of vertical track receptance with subsoil of clay (measured on rail),* $F_{stat} = 90$ *kN,* $F_{dyn} = 10$ *kN. Measurements made by Banverket with standstill track-loading test vehicle at the Svealand line km 37+537.*

Depending of which part of the track that is considered, different definitions may be appropriate.

One common term used is track modulus where everything except the rail is considered. The track modulus, u, is defined as the applied force per unit length of rail per unit deflection (δ) (unit Pa) as in Eq. (5):

$$u = \frac{q}{\delta} \qquad (5)$$

where q is the vertical foundation supporting force per unit length. Using the theory of a beam on elastic foundation, a relationship between track modulus and track stiffness can be found as follows [5]:

$$u = \frac{k^{4/3}}{(64EI)^{1/3}} \qquad (6)$$

The difference between u and k is that k includes the rail bending stiffness EI, whereas u is related only to the remainder of the superstructure (i.e. fasteners and sleepers) and the substructure (ballast, subballast and subsoil).

4.2. Global stiffness measurement methods within Innotrack

4.2.1. RSMV

The Rolling Stiffness Measurement Vehicle is a rebuilt two-axle freight wagon equipped with loading and measurement equipment. The track is dynamically excited through two oscillating masses above an ordinary wheel axle of a as shown in Figure 3. The track stiffness is calculated from the measured axle box forces and accelerations as described thoroughly in [9]. Dynamic stiffness is a complex-valued quantity, represented by its magnitude and phase. While magnitude is the direct relation between applied load and deflection (kN/mm), phase is a measure of deflection-delay by comparison with force. The phase has a partial relationship with damping properties and ground vibration.

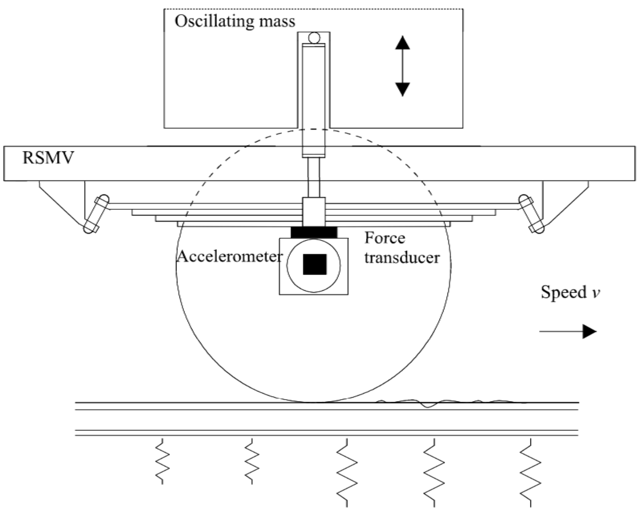


Figure 3. *Measurement principle (one side only) of RSMV.*

The static axle load is 180 kN and the maximum dynamic axle load amplitude is 60 kN. The RSMV can measure the dynamic track stiffness up to 50 Hz. Both overall measurements at higher speeds (up to 50 km/h) with 1 – 3 simultaneous sinusoidal excitation frequencies or detailed investigations at lower speeds (below 10 km/h) with noise excitation can be performed.

The RSMV has been in use since 2004 and several hundreds kilometers of tracks have been measured. The reasons for measurement have varied from research questions to investigations of specific issues, e. g. upgrading of a track for higher axle load.

Example from a repeatability test is shown in Figure 5, where the measurement speed was 40 km/h and the excitation frequency 11.4 Hz. The standard deviation uncertainty between the different runs was 3.3 kN/mm, which correspond to 1.5 % of actual values. Stiffness is given with reference to the axle load.

Figure 4. *Photo of excitation equipment of RSMV*

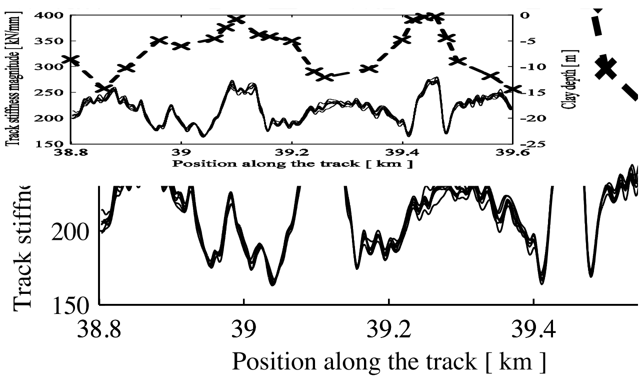


Figure 5. *Example of results; Repeatability test of stiffness magnitude – six measurements on the track v = 40 km/h, f = 11.4 Hz and F_{dyn} = 2x30 kN (solid lines). Standard deviation: 3.3 kN/mm. Depth of clay layer is also indicated in the figure (x-marked dashed line).*

4.2.2 Portancemetre

The Railway Portancemetre is a new apparatus with a vibrating wheel axle (wheel-set) to measure the dynamic stiffness of railway track. It includes unsprung mass (vibrating wheel axle) and suspension mass instrumented by accelerometers on both axle sides. The track is excited through dynamic force produced by two electric vibrators with adjustable eccentricity. Figure 6 shows the schematic view and on track photo of the Portancemetre. The total applied force is calculated by vector summation of all components as described in the Eq. 7. The vertical displacement is calculated by a double integration of the wheel acceleration, Eq. 8.

$$FTA = M_1.g + M_0.\Gamma_b + (M_1 - M_0).\Gamma_c + m.e.\omega^2.\cos\varphi \qquad (7)$$

Where, M_1 is the total mass, M_0 is the vibrating mass, *m.e* is the eccentric moment of unbalanced system, Γ_b is the vertical acceleration of the vibrating wheel, Γ_c is the vertical acceleration of the suspended mass, ω is the angularity velocity and φ is the angle of rotation (Figure 7).

$$z(t) = \int\int \Gamma_b(t)\,dt\,dt \qquad (8)$$

The total applied force, *FTA*, and the corresponding deflection, *z*, allow a determination of the stiffness, *k*, over an average time period which is typically 30 cycles. Both applied force and displacement are function of time and their time history depend on the sample rate of data recording.

Basically, there is always a phase between the maximum force and the displacement response of the structure. In our calculation we use the Fourier series to remove the noise and to smooth the time history of total applied force and displacement.

The static load of the Portancemetre may vary between 70 and 120 kN and the maximum dynamic load amplitude may increase up to 70 kN. The Portancemetre can measure the stiffness by exciting the track with a frequency up to 35 Hz.

The fabrication of the Portancemetre demonstrator was done on February 2009 and actually, we are testing the first series of the measurements are currently in progress. The maximum running speed for the demonstrator is about 15 km/h and the calculation of the stiffness is done on post treatment for both left and right rails. At the present, the irregularities of the rails in the stiffness calculation and the influence of the phase between force and displacement are ignored. These objectives will be attained during the next phase of the research. For the demonstrator of the Portancemetre the stiffness is calculated by a simple secant method, Eq. 9.

$$k_{xy} = \frac{\Delta F}{\Delta z} = \frac{F_b - F_a}{z_b - z_a} \qquad (9)$$

where, ΔF and Δz are the difference between two values of applied force and obtained displacement respectively. The "b" and "a" may be selected based on various definitions and here the maximum and minimum values are chosen.

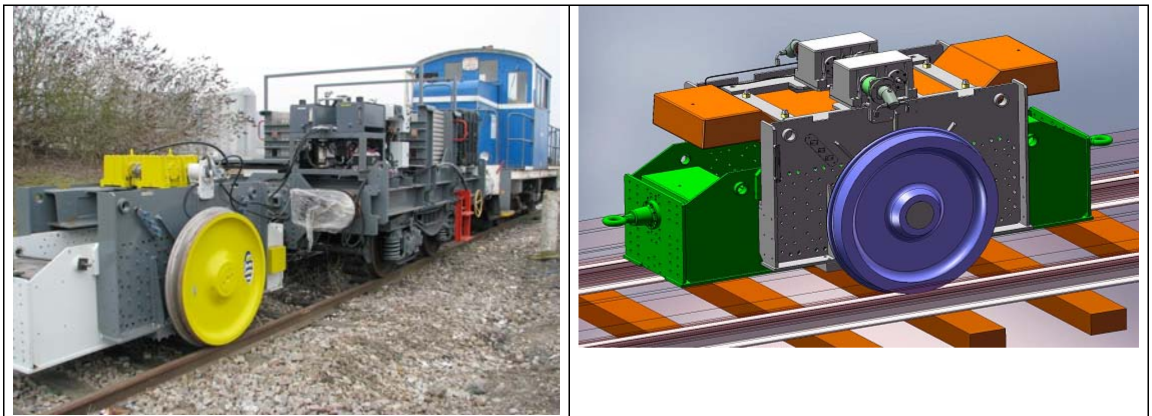


***Figure 6:** Schematic view (right) and operational demonstrator (left) of constructed Portancemetre*

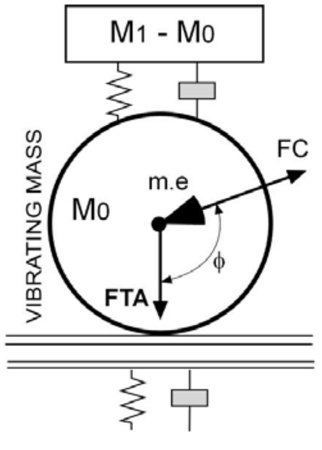
	M1 - M0 = suspension mass M0 = vibrating (unsprung) mass Fc = centrifugal force FTA = total applied force me = eccentric moment

Figure 7: *Main parameters of the vibrating wheel of the Portancemetre*

Examples of measured vertical track stiffness are shown in figures 8 and 9. Figure 8 illustrates the typical Force-Displacement curve with quasi-static excitation measured on "Des Jardins" track. The static and dynamic force per rail was about 50 kN and 20 kN respectively. The curve is non-linear and also has a hysteresis, which indicates a damping factor. By considering the stiffness as constant in time and place, the average value of the stiffness was calculated. This is of course not valid in the time domain nor in the frequency domain with a high degree of accuracy.

Figure 9 presents the typical result of continuous track stiffness by Railway Portancemetre. The running speed is 6 km/h and the excitation frequency is 30 Hz. At the present, the stiffness is calculated by the method mentioned above, which is adapted for a linear system and used as an approximation for non-linear system. Track stiffness values evaluated are per rail.

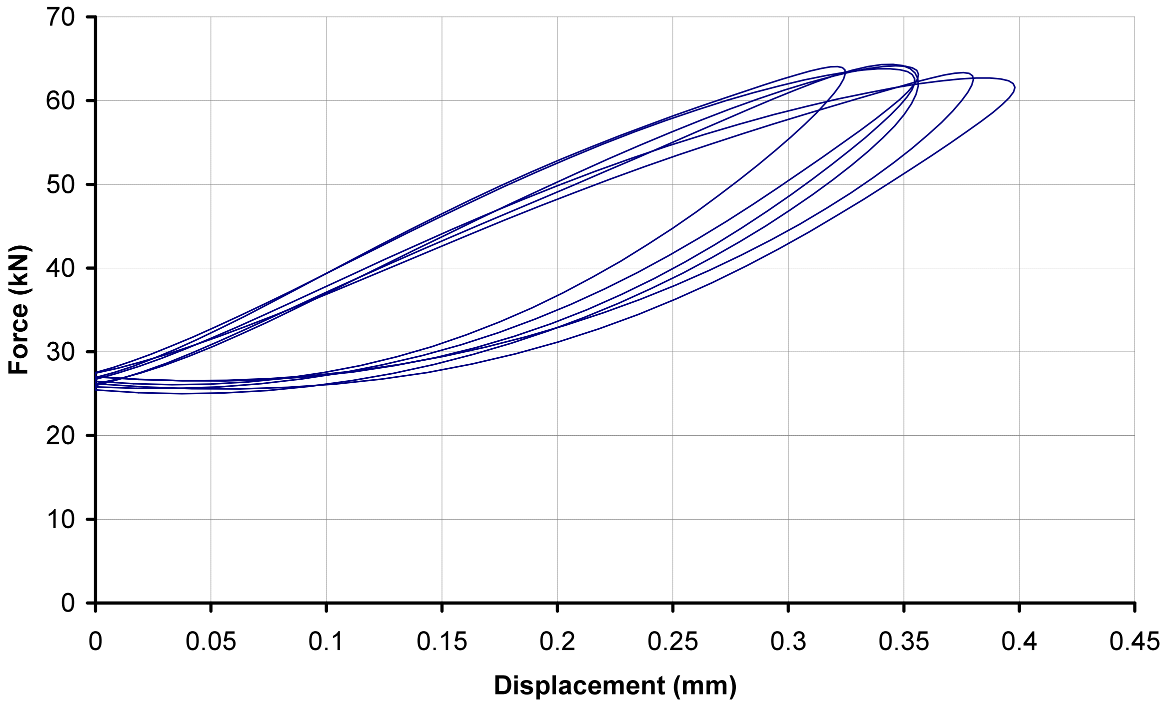


Figure 8: *Vertical Force-displacement curve for the "Des Jardins" track*

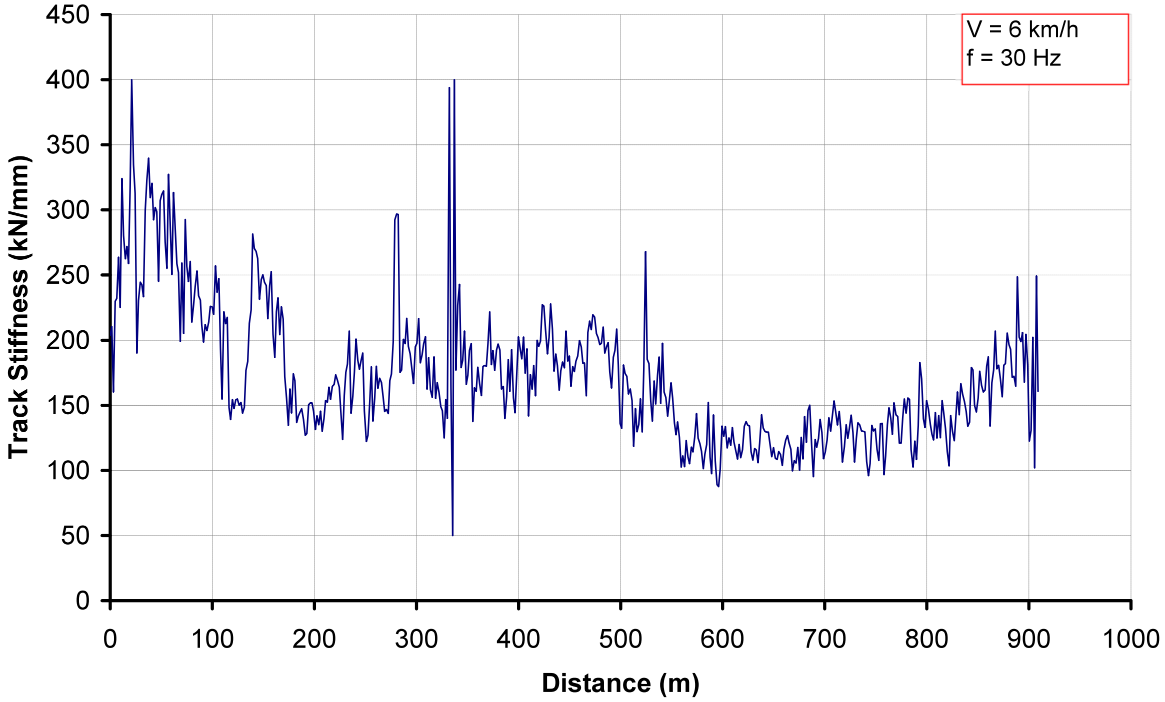


Figure 9: *Results from continuous track stiffness measurement by Railway Portancemetre (demonstrator version)*

4.2.2. Track instrumentation stiffness measurement

The procedures used by CEDEX as commissioned by ADIF are based on the use of sensors external to the track and mounted on the rails. They have been used to detect wheel loads and the rail movements induced in the track by operating trains.

As explained below, the wheel loads have been assessed by a method based on the determination of the maximum shear stress induced in the rail cross section during train passes, while both direct and indirect methods have been adopted for measuring rail deflections.

The measurements have been achieved with the following pieces of equipment:

- Extensometer shear bands
- Laser beam sensors
- 2 Hz geophones

The techniques and methodology employed with those sensors are described in the following.

Wheel load measurements

The measurement of wheel loads have been made by finding the difference between the two shearing forces induced in two cross sections of the rail, 0.30 m apart between two consecutive sleepers (see Figure 10), by a travelling wheel passing over them.

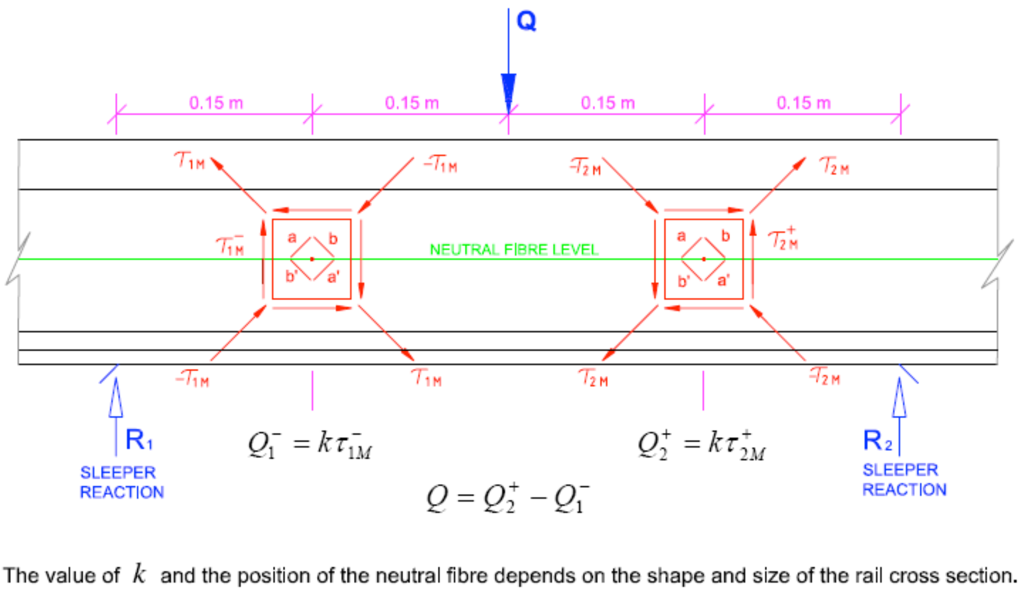


Figure 10: *Schematic arrangement of strain gage gridlines for measuring wheel loads*

For the determination of the shearing force in each of the two cross sections, a strength of materials standard procedure, based on the use of 4 strain gage gridlines connected in a full Wheatstone bridge has been used. For that purpose, two commercial strain gage bands, with two perpendicular strain gage gridlines each, were attached, at the level of the neutral fibre, to the rail web keeping the strain gage gridlines at 45 degrees to the rail axis.

The strain gages have been manufactured by VISHAY MICRO-MEASUREMENT. The bands used have been of the CEA 06 062 UV 350 type having the following characteristics:

- Active length: 1.57 mm
- Total length: 8.38 mm
- Supporting base length: 10.70 mm
- Grid width: 1.60 mm
- Total width:4.06 mm
- Supporting base width: 5.80 mm

The gage factor and the nominal resistance of the strain gage gridlines have been 2.12 and 350 Ohms respectively.

For interpretation purposes, the output signals provided by the Wheatstone circuit have been amplified 1000 times.

Direct rail deflection measurements

The laser beam system used is a 1D photo-voltage system constituted by a transmitter unit and a position sensing device (PSD). Once mounted in a fixed reference base, the transmitter emits a horizontal beam light, fixed in the space, susceptible to be used as a reference level for measuring the vertical displacements experienced by the support of the sensor (see diagram in Figure 11). Depending on the position of the light beam over the active area of the sensor, a voltage signal is generated that conveniently processed permits to identify the vertical movements experienced by the solid to which the sensor is attached.

The equipment employed has been manufactured by PROEL Inc. It has a resolution of 0.001 mm and an accuracy of ± 0.01 mm for a maximum distance of 6 m between the transmitter and the sensor. Both the transmitter and the sensor were delivered with the appropriate elements for attaching them to vertical steel bars 20 mm in diameter in the fixed reference bases and to the base of standard rails.

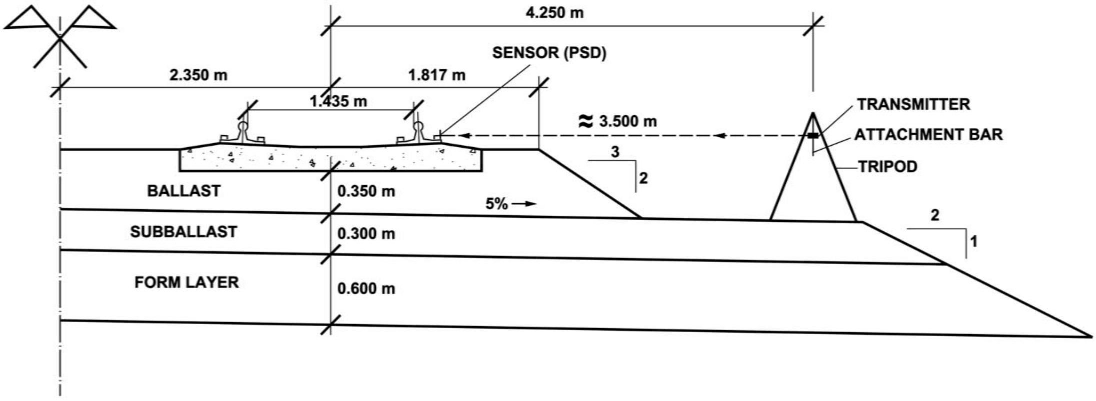


Figure 11: *Set-up of requirements for direct rail deflections measurements with 1D laser system*

The tripod sketched in Figure 11, conveniently dead weighted, has proved to be stable enough to complied with the requirements that could be demanded to a reference base for monitoring rail deflection in the track. When replacing the transmitter, in the tripod attachment bar, with a 2 Hz geophone, velocity time histories with a maximum amplitude of 1 mm/s were recorded at a distance of 3.5 m. from the outer rail under the passages of AVE S-103 trains operating at 300 km/h in the high speed line Madrid – Barcelona. When integrating those time histories, displacement maximum amplitudes of the same magnitude than the accuracy of the laser system were obtained.

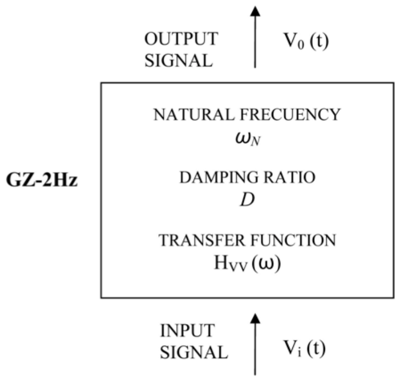
Indirect rail deflection measurements

To set up a procedure to get absolute rail displacements without needing to deploy firstly, at a certain distance of the track, a reference base for the direct measurement of movements, a tiny 2Hz L-22E MARK geophone manufactured by SERCEL Inc. has been selected. Its dimensions, 60.3 mm in diameter and 50.8 mm in length and its weight (425 g) makes it a portable instrument very adequate to be clamped in a very short time to the base of standard rails.

Compared to accelerometers with similar weight and dimensions, the 2Hz geophone offers the advantage of not needing to be fed with external electric signals and of allowing an easier base line correction of the integrated signals.

On the other hand, being that sensor a one degree of freedom system, it modifies the received signal according to its own characteristics. Analysing the response of the sensor to any type of excitation it can be shown that whereas the unit chosen does not modify significantly the amplitudes of the received signals for excitations frequencies above its resonance frequency (2.11 Hz), it affects substantially the phase of the frequencies in the range 0-20 Hz.

Accordingly, before integrating the signals captured by the sensor, to obtain, the absolute deflections of the rail, it has been deemed necessary to correct the signals as sketched in Figure 12. The phase correction of the signal is done in the frequency domain. Then, the Inverse Fourier Transform of the corrected signal provides a velocity time history suitable to be integrated directly to obtain the history of the absolute displacements of the rail. If it is found necessary, the base line of the resulting signal may be further corrected using high pass filters in the range 0 (roll off) – 0.5 Hz (cut off). The final signal can be expected to have amplitudes slightly less than the one searched for, since no amplitude signal correction has been incorporated to the procedure.



$$\begin{cases} H_{VV}(\omega) = |H_{VV}(\omega)| e^{i\theta_{vv}(\omega)} \\ \theta_{VV}(\omega) = arctg \dfrac{2D\dfrac{\omega}{\omega_N}}{1-\left(\dfrac{\omega}{\omega_N}\right)^2} \end{cases}$$

OUTPUT SIGNAL FOURIER TRANSFORM

$$V_0(t) \rightarrow F.T. \rightarrow V_0(\omega) = |V_0(\omega)| e^{i\theta_0(\omega)}$$

FREQUENCY DOMAIN

$$V_0(\omega) = H_{VV}(\omega) \cdot V_i(\omega)$$

FOR $\omega > \omega_N$

$$|H_{VV}(\omega)| = 1 \qquad |V_0(\omega)| = |V_i(\omega)|$$

THEN

$$V_i(\omega) = |V_i(\omega)| e^{i\theta_i(\omega)} = |V_i(\omega)| \frac{e^{i\theta_0(\omega)}}{e^{i\theta_{VV}(\omega)}}$$

$$e^{i\theta_i(\omega)} = e^{i[\theta_0(\omega) - \theta_{VV}(\omega)]}$$

$$\boxed{\theta_i(\omega) = \theta_0(\omega) - \theta_{VV}(\omega)}$$

Figure 12: *Instrumental correction recommended for signals captured with the 2Hz geophone chosen.*

Figure 13: *Geophone of 2 Hz and laser beam receiver clamped together to the rail base at the middle of a track span.*

To illustrate the results obtained when using this technique, the rail deflection and rail velocity time histories, induced in a cross section of the high speed line Madrid Barcelona by an AVE S-103 train operating at 300 km/h, have been plotted in Figure 14. The rail deflections were obtained directly with the laser technique described above and the rail velocities using the 2Hz geophone. The laser beam receiver and the geophone were clamped to the rail base, next to each other.

The two first peaks of the displacement time history provided by the laser system have been magnified in the upper graph of Figure 15. They reflect the passage of the first bogie of the train over the instrumented cross section. In the first, of the two lower graphs of that figure, the result of integrating, without phase correction, the signal provided for the first bogie of the train by the 2 Hz geophone is presented. When the integration was carried out after correction in the frequency domain, the time history shown in the lower graph of the figure was obtained. Comparing the two lower graphs of Figure 15 with the upper graph, it can be concluded that a good estimation of the rail deflections can be achieved by correcting only the phase distortion introduced in the captured signals by the 2 Hz geophone used to carry out this study.

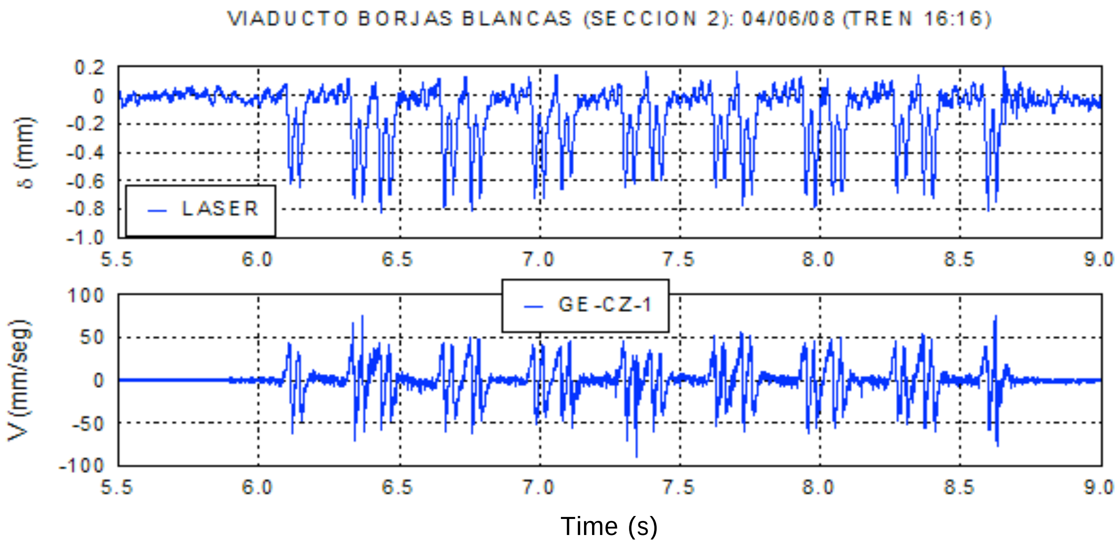


Figure 14. *Time histories induced by AVE S-103 train passing at 300 km/h*

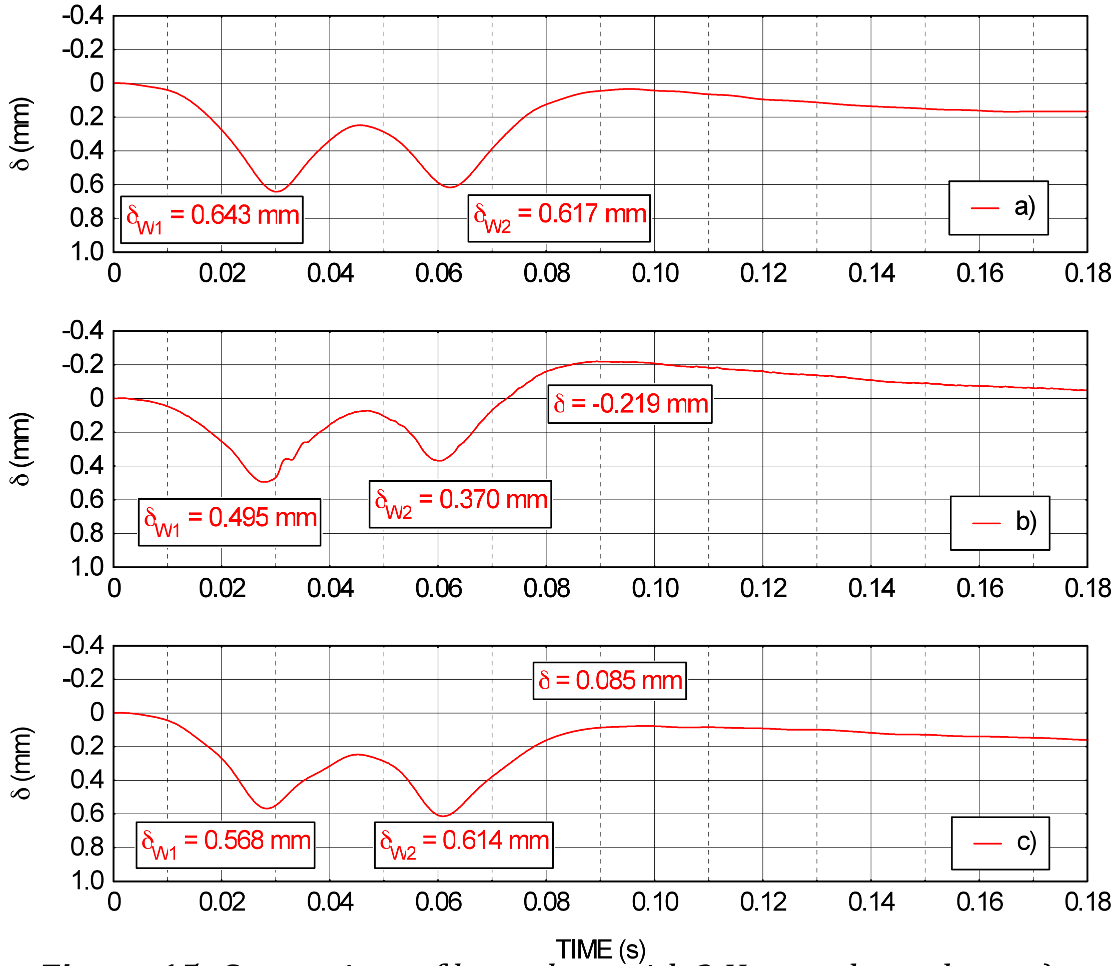


Figure 15: *Comparison of laser data with 2 Hz geophone data: a) Laser data; b) 2 Hz geophone with no phase correction; c) 2 Hz geophone with phase correction.*

Peak values of the same magnitude that those reported in Figure 15 where obtained by Bowness et al [21], when monitoring the passes of Series 373 TGV Eurostar trainset at Ashford, in a section of the channel tunnel rail link (CTRL), with 1 Hz geophones attached to the sleepers.

5. Local track stiffness within INNOTRACK: Panda

Penetration testing (static or dynamic) is widely used all over the world, it consist in driving a calibrated cone through the granular material and recording the driving resistance as a function of the depth. The penetrometer Panda has been used for several years for investigations on railway track: it is a quick set up which is very useful to obtain mechanical and geometrical information about the track structure.

5.1. Evaluation of track properties from measurements

The penetration test is a simple and useful test for characterizing soils and granular materials. Several studies have shown the link between cone penetration resistance and density for a given material at a defined water content. In other words, from material physical properties knowledge and from its cone resistance, it is possible to obtain the on-site material density if the relation connecting these two parameters has been established beforehand. A granular materials bank currently including more than 35 granular materials has been developed to this end. For each one of these materials, the relation between density and cone resistance has been established through experimental tests and with a light dynamic penetrometer with variable energy (Panda) (Fig. 15) developed at the Blaise Pascal University of Clermont-Ferrand .

This device uses 2 or 4 cm^2 cones which are fixed to the bottom of the penetrometer setup. The beating energy is manual and variable, using a hammer. It automatically supplies the energy required to penetrate the materials tested according to depth.

For each blow of the hammer, the depth of penetration and impact energy are recorded to calculate the dynamic cone resistance (q_d) with the corresponding depth [11 , 12] using the Dutch Formula [12].

$$q_d = \frac{1}{2} m V^2 \frac{1}{Ae} \frac{m}{m + m'} \qquad (10)$$

Where:

- V : velocity of the hammer at impact,
- A : section of the cone,
- e : depth of penetration,
- m : mass of the head of the PANDA,
- m' : mass of the tube + the cone.

Studies have proved the reliability of the results obtained by comparing with standard in situ tests. From Panda measurement the estimation of soil modulus is then possible using the Buisamn approximation where firstly the cone resistance is related to œdometric modulus (E_{oed}) then the œdometric modulus is linked to the elastic modulus (E) as follow :

$$E_{oed} = \alpha . q_d \quad , \quad E = E_{oed} \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \qquad (11)$$

Where α depends on the soil nature [10,12] and ν is the Poisson's ratio (taken to 0.3).

In order to use these correlations, it is necessary to have the soil characterization, which is obtained using the endoscope.

So, from the in situ measurements and the coupling with endoscopy, it is possible to evaluate the density of the soil which is governing the track bearing capacity

5.2. PANDA: Technical features

The device has been developed under the nickname PANDA which is a proprietary device that combines a cone penetrometer and an endoscope. In this section a short description is given.

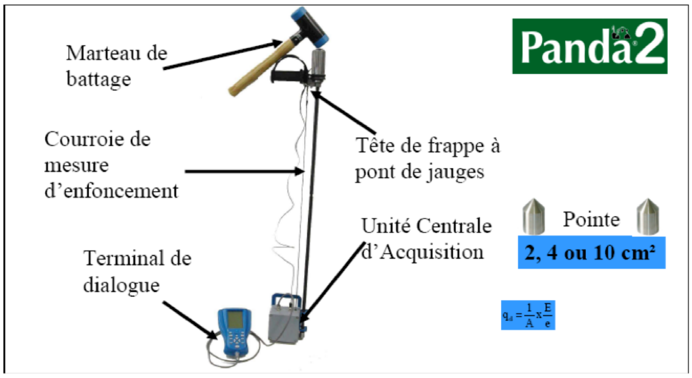


Figure 16: *Technical description of Panda penetrometer.*

The main advantage of this test consists in its quick set up and its local measure recording which allows to get precise information on the granular material resistance and to estimate the material behaviour variability. Provided that the material's physical properties are known, it is possible to find the in situ density of the granular material under study on the basis of the cone resistance. This technique has been applied for several years in order to provide control over the quality of road embankments (French Standart XP 94-105).

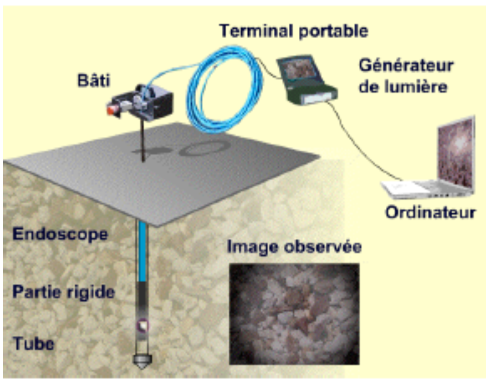


Figure 17: *Technical description of endoscopy.*

It should be toted that penetration testing is a "blind" test and a complete approach to granular material characterisation necessitates a material identification. Nowadays this identification is possible thanks to an endoscope introduced in the cavity created during the penetration test (Fig.17).

5.3. Application to railway track

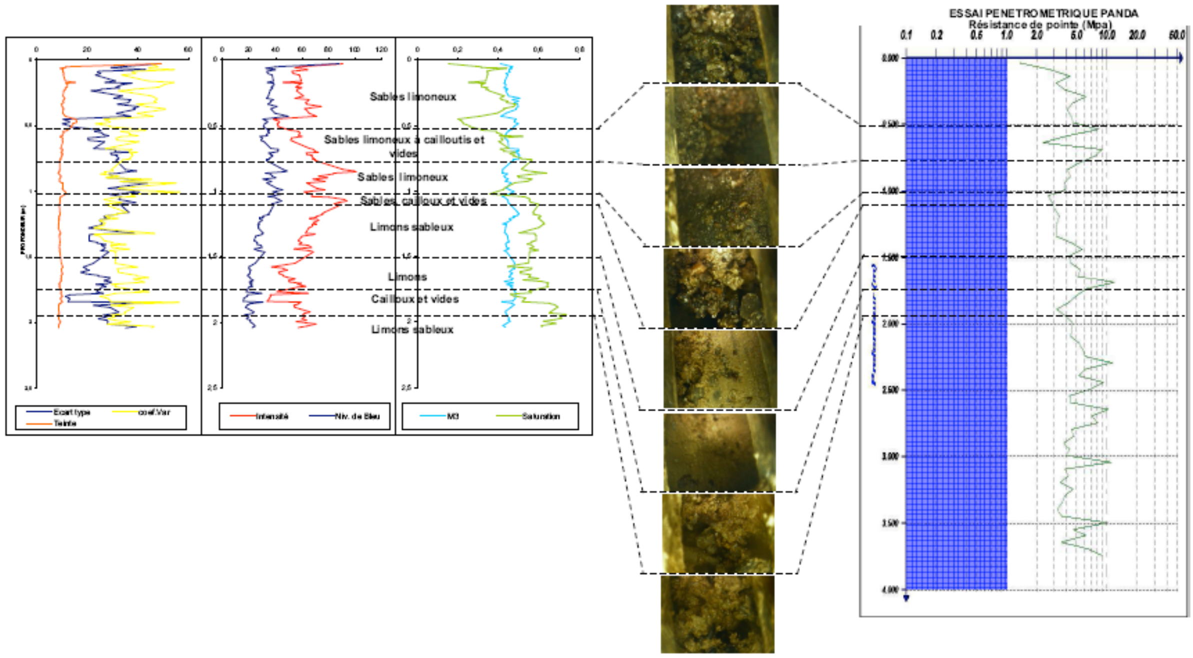


Figure 18: *Example of results obtain from the endoscopic and penetrometer analyse.*

Figure 18 shows the results of a whole investigation for one test. It is possible to identify the different layers of the track and their thickness and a cone resistance can be associated for each layer. From this analysis an evaluation of soil density can be proposed based on the bank of material which have been tested.

For the railway track it is important to underline the following points:

- the penetrometer Panda and the endoscopy are non destructive test, with a very light setup which is easy to use to investigate railway track,

- the information can be collected at every point of the track. It is clearly possible to do some test with 1 Hr of traffic stop and there is no restriction during the year to do this kind of tests,

- from the measurements it is possible to obtain local information about the properties of the track, in particular an evaluation of track stiffness, and by considering some statistical concept it will be possible to have a continuous description of the track properties from a whole series of tests.

6. State of the art: Other existing methods for rolling stiffness measurements

If standstill measurements have been used mainly for research purposes, rolling measurements have the potential to be used on a more regular basis for maintenance purposes. Whilst there are several different systems for measuring the vertical track stiffness along the track, most measure the displacement under one or two axles caused by the weight of the axles and the track flexibility. With knowledge of the static axle loads, the track stiffness can be calculated. In case of a two-axle system, the axle loads are different and the lightest loaded axle is used to remove the effect of track irregularities on the stiffness measurement. There are also devices based on dynamic measurements on a single axel. Two such devices (RSMV and Portancemetre) have been used in Innotrack and are described above.

The vertical track stiffness measured by each device is unlikely to be identical for a number of reasons as follows:

- **Static preload:** The static preloads applied are different and likely to cause different stiffness values being recorded for the same section of track.
- **Excitation frequency / speed:** Equipment using a static running wheelset to load the track will excite the track with some frequencies due to its speed. As the measuring speed increases, so will the frequency content. Since the dynamic track stiffness is frequency dependent, the stiffness determined is likely to differ.
- **Spatial resolution:** The different measurement techniques may have different spatial resolutions.
- **Model dependency:** The devices measure the deflection of the rail at different distances away from the wheelset. Where the deflection is not measured directly under the wheelset a model

for the rail bending has to be used in order to calculate the rail deflection under the wheelset. These models are approximations of reality and can introduce uncertainty and related errors.
- **Degree of influence from track irregularities:** Track geometry irregularities, especially those associated with the longitudinal level can influence the stiffness measurements since the displacement transducers used in the equipment in most cases measure a combination of deflection due to track flexibility and displacement due to track geometry irregularities. Wheel out-of-roundness and wheel flats introduce similar disturbances.

A number of organisations (besides the partners in Innotrack) have developed rolling devices to measure track stiffness. Some of these are summarised below:

FWD – Falling Weight Deflectometer

Although the FWD is a stand still device, measurements are fast enabling shorter distances to be covered. The FWD is most often used to measure the stiffness of the track structure excluding the rails. The standard FWD device consists of a mass that is dropped from a known height onto rubber buffers mounted on a footplate. The resulting impact is measured by a load cell on the centre of the plate and velocity transducers are used to determine surface velocity at various distances from the footplate. The velocities are integrated to give vertical displacements. The track stiffness is calculated from the load and deflections measured at some of the velocity transducers, depending on the application.

CARS, People's Republic of China

The China Academy of Railway Sciences (CARS) was one of the first organisations to develop a system for continuous track stiffness measurement [14]. Their system, which travels at speeds of up to 60 km/h, uses two track geometry chord measurement systems with different loading applied to each of the measurement axles (Figure 19). The chord lengths (x) are indicated in the figure. The light-weight car has a weight of 40 kN and is used to reduce the effect of track geometry irregularities on the stiffness measurement recorded by the heavy car. A weight of 40 kN was chosen as it was found to be sufficient to reduce the effects of voided sleepers. The axle load of the heavy car can be varied between 80 and 250 kN enabling the nonlinear characteristics of the same section of track to be investigated by repeating with different loads. The low load measured deflection/chord represents track irregularities, and by taking the difference between the high and low load measured deflections, only the flexibility of the track remains.

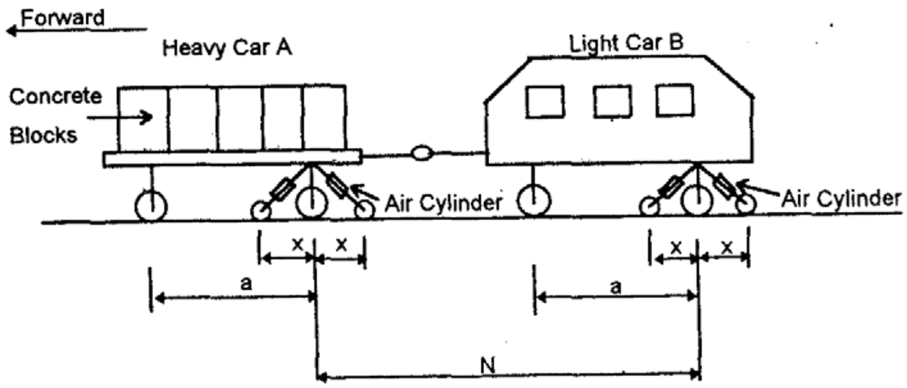


Figure 19: *Principle of Chinese track stiffness measurements [14].*

TTCI, USA

TTCI's track loading vehicle (TLV) has been developed to measure both lateral and vertical stiffness at standstill and when moving at speeds up to 16 km/h [15]. For rolling vertical stiffness measurements the TLV is coupled with an empty tank car where the reference measurements are done. Likewise the CARS-device, two chords with different axle loads is measured.

The TLV has a fifth wheelset (loaded bogie) mounted underneath the vehicle centre, that can be loaded hydraulically (both vertically and laterally) with vertical loads between 4 – 267 kN. A load of 178 kN is applied to the test axle of the static TLV. If two separate runs are used to differentiate the supports between the ballast and the subsoil, a light test axle load of 44 kN is used for the second run. The deflection is measured with the help of laser sensors, yielding a chord measurement of rail bending deflection.

Measurements are made under the empty car in case of only one passage test. This car is also equipped with a central loaded bogie with pneumatic actuators capable of applying a nominal load of 9 kN.

The low load measured deflection represents track irregularities, and by taking the difference between the high and low load measured deflections, only the flexibility of the track remains.

University of Nebraska, USA

The University of Nebraska at Lincoln (UNL) in the USA has developed a system to measure track stiffness [16]. The technique uses line-lasers to measure relative rail deflection between the bogie and the rail.

The measurement principle is shown in Figure 20 and Figure 21. The relative deflection is measured using two lasers and a camera that measures the distance, *d*, between the two lines and as the sensor moves with respect to the rail surface, the distance between the laser lines changes. The Winkler (elastic bed) model is used to relate the measured deflections to track modulus/stiffness.

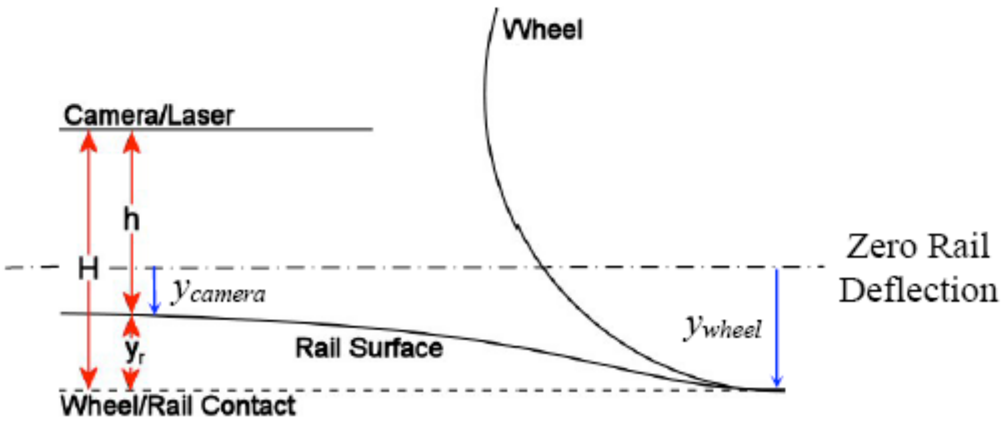


Figure 20: *Rail deflection / Sensor measurement of UNL-stiffness equipment [16]*

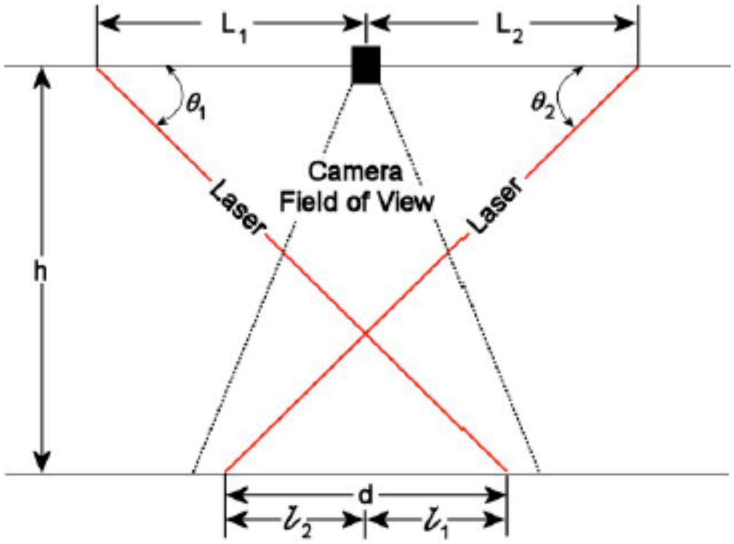


Figure 21: *Sensor geometry of UNL-stiffness equipment [16] .*

SBB Switzerland

Swiss Railways, Schweizerische Bundesbahnen (SBB), has developed a device (see Figure 22) which is similar to the Chinese and TTCI equipment and uses two geometry measurement systems [17].

Figure 22: *Swiss track stiffness measurement vehicle [17].*

FRA / Ensco / Volpe Center

Recently a test has been performed by Ensco and Volpe National Transportation System Center, sponsored by FRA [18]. The idea is to instrument two axles that have different static loads with accelerometers. After double-integrating the accelerations the result are two deflected track geometries (longitudinal level) stemming from different loads. From this result, the system is in principle similar to that of China, TTCI, and SBB. The measurement system is made rather uncomplicated and as sensor technology develops, accuracy may be sufficient.

Other published methods

A rebuilt tamper has been used in Czech Republic for track stiffness trials [19].

TU Delft had a promising project around year 2000, but didn't build a prototype for railway measurements [20], [1]. The High Speed Deflectograph (HSD) made use of laser doppler sensors attached to a moving railway vehicle, travelling at speeds of up to 130 km/h, to measure the rail bending velocity. The HSD has a number of advantages over other rolling devices including:

a) the effect of track geometry irregularities on the measurement of track stiffness is much less than when displacement transducers are used, although the effect of hanging sleepers still contributes to the rail bending velocity;

b) the rail bending velocity increases with train speed and as a result higher train speeds are likely to produce more accurate results.

7. User choices

Selecting the most appropriate method/device for stiffness measurements depends heavily on user requirements. Some examples of requirements may be:

- Stiffness of a specific site, shorter distance or larger part of network?
- How much traffic disruption is allowed?
- Is global or local stiffness of most interest?
- What kind of loading is needed; ordinary train traffic or specific loads and frequencies?

- What is the expected outcome from measurements?

Regarding specific site measurements, a stand-still TLV or track instrumentation measurements can be used. Depending on length of track to be measured, measurement speed is increasingly important in order to reduce traffic disruption and cover larger ranges of track. The RSMV is capable of measurement in 40-50 km/h. The Portancemetre prototype was tested in 15 km/h, however the design speed for future application is 30 km/h.

Instrumenting a track cross section for either direct (2 Hz geophone) and indirect measurement (laser position sensing device PSD) for rail deflections may take 20 -30 minutes including the deployment of the cables required to connect the sensors to the acquisition system. The attachment of extensometer shear band sets to the rail web for measuring wheel loads induced by passing trains must be done over night or at a longer stop of traffic (1-2 hours).

Measurement cars have negligible time of preparation.

Time needed for Panda measurements of local track stiffness greatly depends on the soil type and compaction density. However, it may be estimated about 15 minutes per meter of the depth for each test point.

Indicative prices for measurements valid 2009 are:

RSMV: 7000 Euro/day including basic evaluation. The price does not include transport to site and locomotive during measurement. The price is often negotiable for measurement campaigns longer than one week.

TLV: 4000 Euro/day plus transport. The price does not include data evaluation, transport to site and locomotive during measurement. The price is often negotiable for measurement campaigns longer than one week.

Portancemetre: 5000 Euro/day including basic evaluation. The price does not include transport to site and locomotive during measurement. The price is often negotiable for measurement campaigns longer than one week. The further and deeper analysis may be added by some complementary site exploration.

Track instrumentation: 6.000 Euro/day including data processing.

Panda: 50 Euro/meter/point including basic evaluation. The price does not include transport.

8. Conclusions

Techniques for track stiffness measurement are now available. The research in Innotrack has contributed to the development of measurement techniques and knowledge of track behavior.

Although track stiffness is considered an important parameter for train-track interaction and maintenance related questions, the use of track stiffness data is still not straight-forward. However stiffness measurement techniques are now mature and the report describes limitations and recommendations for the choice of method.

The next step may be to start a standardization group working on both measurements and advice on proper values.

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