GROUNDBORNE VIBRATIONS FROM UNDERGROUND METROS: THE EXPERIENCE IN METRONAPOLI

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ABSTRACT

The metro line in Naples, opened in sections starting from 1992, is characterized by four different infrastructure types: ballasted track on viaducts, double tracked tunnel (cut and cover) with indirect rail fastening to the concrete slab, single tracked deep tunnel with indirect rail fastening to the concrete slab and single tracked deep tunnel with floating slab (mass-spring system).

Some complaints, relative to vibrations annoyance, were presented from the inhabitants of the buildings over the line, especially in the portion were the cut and cover tunnel is present.
In a test campaign in collaboration with the University of Florence, the vibration levels in various sites along the line were monitored on the infrastructure (track and tunnel). The difference in vibration levels between the three tunnel infrastructures was investigated along with the influence of the rail corrugation.

The influence of track formation and maintenance practices are discussed, together with some proposal for vibration annoyance control.

INTRODUCTION

The metro line object of this paper, "Linea 1" exploited by Metronapoli and owned by the municipality of Naples, is one of the many railway lines that serve the city of Naples. Of all the lines in the urban area, it is the only one that has all the distinctive features of a classical metro line (e.g. type of infrastructure, type of rolling stock, signalling system, ecc…).

The line is 14 km long, with a maximum gradient of 55 mm/m and a minimum curvature radius of 204 m. The line has 14 stations, is electrified at 1500 V DC with overhead wire, the signalling system includes an ATP system and it is designed for a minimum interval between trains of 90 seconds. The maximum train speed is 70 km/h.
Trains are made of homogeneous rolling stock. Each train consists of four or six cars; each pair of vehicles is semi permanently coupled and forms the base unit called UdT (traction unit, in Italian *Unità di Trazione*). Each UdT has four full traction bogies with an AC three phase motor per axle actuated by a GTO inverter. The maximum axleload is 12 tons.
In a typical day of service (6:00 o clock to 23:00 o clock) 232 train are exploited with a minimum interval between trains of 6 minutes.

The line was built and opened to public service at different times, and the infrastructure is not uniform depending on the period of construction and/or the depth under the surface of the line itself. Four types of track are currently in service as follows (refer to Figure 1 and Figure 2):

A) double-track cut and cover tunnel, in the section between Vanvitelli and Medaglie d'Oro (opened in 1992), slightly extending towards Montedonzelli (Fossa Muzii area). Indirect fastening with the so-called "attacco tipo Milano", with two stages of suspension (baseplate pad and railpad) and Vossloh clips (referred in the following as "cut&cover");
B) single track deep bored tunnel, with indirect fastening "attacco tipo Milano" on the tunnel invert, from Fossa Muzii to Colli Aminei, opened in 1995 (referred in the following as "slab track");

C) single track deep bored tunnel, with Nabla indirect fastening on booted sleepers in a floating slab, from Vanvitelli to Dante, opened in 2000/3 (referred in the following as “floating slab track”);
D) ballasted track in open sections (not considered in this paper) from Colli Aminei to Piscinola.

Figure 1. Map of Metronapoli Linea 1. Locations where pass by vibration measurements were performed are shown in red.

Figure 2. “Attacco tipo Milano” fastening system on “slab track” (left) and Nabla fastening system on booted sleepers on “floating slab track”.

Switches and crossings are located in the areas of Vanvitelli and Medaglie d’Oro (more specifically in an area called “fossa Muzii”) that served as the terminus and maintenance depot during 1992-1995. In these areas some complaints were recorded especially in the early years of service.
Other switches and crossings are located in Dante (South terminus), Colli Aminei and Piscinola (North terminus and link to the depot), but these S&C did not give rise to any complaint for the local conditions (no buildings / on viaduct / on floating slab).

GROUNDBORNE VIBRATIONS ANNOYANCE

During the years of service, complaints regarding vibrations perceived in the houses along the line during trains pass by were presented from citizens.

Table 1 summarizes the complaints officially addressed to Metronapoli.

Location	**Date**	**Line section**
Via Bernini 104	1998-2002	Vanvitelli - Medaglie d'Oro
Via Bernini 70	1999-2005	Vanvitelli - Medaglie d'Oro
Cinema Plaza (Via Bernini)	2001	Vanvitelli - Medaglie d'Oro
Via S. Gennaro al Vomero	02/2001	Vanvitelli - Medaglie d'Oro
Via M. Fiore 5	02/2001	Vanvitelli - Medaglie d'Oro
Via Stasi (angolo via Nutta)	03/2001	M. d'Oro-Muzii
Piazzetta Aniello Falcone	03/2001-11/2005	Cilea-Vanvitelli
Via Fontana 19	2001-04/2006	Muzii-Montedonzelli

Table 1: List of official complaints presented to Metronapoli

Looking at Table 1 some observations can be made:

- the greatest part of complaints come from the “cut&cover” line stretch between Vanvitelli and Medaglie d’Oro stations, although, with just one exception in via Bernini 70, official complaints were not presented after 2002;
- one complaint comes from the “slab track” between Medaglie d’Oro and Montedonzelli. This situation is considered “still active” because the last communication to Metronapoli is quite recent;
- one complaint, also quite recent, comes from a deep tunnel with the “floating slab track” formation. This situation is really uncommon considering the characteristics of the line and the outcomes from the measurements described in the following.

In order to get an insight in the groundborne vibrations disturbance phenomenon, Metronapoli started in 2005 a collaboration with the university of Florence aimed both at the measurement of the levels of vibration on the infrastructure and at the identification of the most influencing parameters.

The activities carried out by Metronapoli and University of Florence can be summarized as follow:

- analysis of any documentation regarding groundborne vibrations previously measurements on the line by government offices (Health Offices);
- vibration measurements on the road surface above “cut&cover” tunnel during trains pass by;
- vibrations measurements on the line during trains pass by *on all the track formations* where complaints were presented;
- vibration measurements during trains pass by with different levels of rail corrugation, before and after grinding;
- characterization measurements (with impact hammer) on tunnels with “slab track” and with “floating slab track”.

The aim of all these activities was to find out the current level of vibration that can be measured *at the tunnel wall*, considering this element as the input of vibrations into the soil and therefore in the urban environment in all the different underground infrastructures. The performance of each infrastructure in terms of reduction of rail vibrations of the rail to the tunnel wall was also estimated.

All of the types of track formation are heavily affected by low rail corrugation and almost negligible transverse wear profile. As already mentioned, the line has very steep gradients and combined with very tight curves, and it is worth to mention that the gauge in the curves is the same as in tangent track

(1435 mm). These factors, joined with full traction of UdTs, are probably at the origin of very high levels of rails corrugation that reappear extremely fast after grinding and that are responsible of several important consequences:

- high running noise and low comfort for passengers and drivers;
- high dynamic loads on track and rolling stock components;
- a greater input into the tunnel/soil system.

At this stage no measurements have been performed inside buildings.

ACCELERATION MEASUREMENTS

Measurements of vibrations were performed in three different ways:

- acceleration measurements on the infrastructure during trains pass by during normal revenue service;
- acceleration measurements on the surface during normal revenue service;
- acceleration measurements using impact excitation for Frequency Transfer Function estimation between rail and slab and tunnel wall.

Piezoelectric ICP® accelerometers, were mounted on the tunnel following the scheme shown in Figure 3, trying to "follow" the vibrations path from their origin on the wheel/rail interface to their exit on the tunnel wall to the environment. All accelerometers were screwed to a metallic base glued on the wall or on the slab or on the rail. A treadle has been used for pass by measurement in order to find axle positions in the acceleration signals and to calculate train speed. All data acquisitions have been performed with a sampling frequency of 1000 Hz using anti aliasing filters.

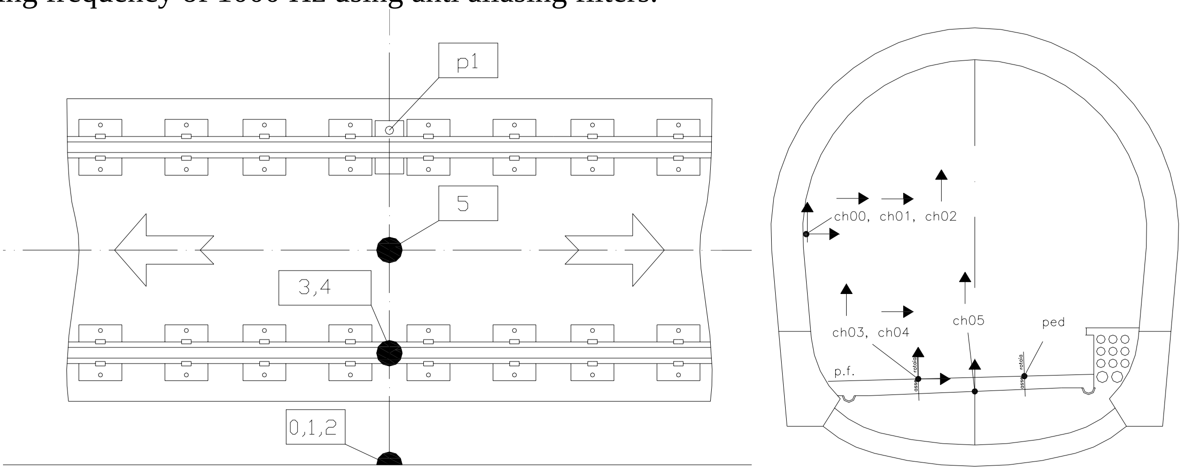

Figure 3 Location of accelerometers on track and tunnel (left: top view, right: cross section)

The same accelerometer configuration was used to estimate the rail/tunnel the transfer function with impact excitation by using an instrumented hammer. During measurements on the road surface a monoaxial high sensitivity accelerometer fixed on a metallic base glued to the pavement on was used.

The traffic is absolutely homogeneous, the whole fleet being composed of only one type of vehicles. As passing speed is quite constant (Table 2), it can be considered of negligible influence on the results shown in the next paragraph.

Location	V Max [km/h]	V Min [km/h]	V Mean [km/h]
Medaglie d'Oro - Montedonzelli	60	34	51.5±9.0
Vanvitelli – Medaglie d'Oro	61	40	53.5±6.5
Museo – Materdei	62	47	56.5±5.2

Table 2: Pass-by speeds recorded during test campaigns

DATA PROCESSING

Typical signal time histories recorded during trains pass by are shown in Figure 4. Data were processed in order to extract the content in frequency range 0.8-80 Hz that is considered the most significant for grundborne vibration annoyance, but also the content in the 20-250 Hz was extracted for investigation in a wider frequency range.
From time histories filtered in the proper frequency range, the root-mean-square RMS value was calculated for each pass by and for each channel. Levels of vibration were calculated from RMS accelerations in the corresponding section by using a reference level of 10^{-6} m/s^2 as follows:

$$Level = 20\log_{10}\left(\frac{RMS}{10^{-6}}\right)$$

Results are summarized in Table 3 for the 0.8÷80 Hz frequency range and in Table 4 for the 20÷250 Hz frequency range. A calculation of the attenuation between several pairs of instrumented points of the infrastructure is also reported; although this calculation is simply based on levels ratios, and should therefore not be considered as the real transfer function, it provides useful indications about the ability of the different track forms to filter rail vibrations.

The following conclusions can be drafted:

- in both frequency intervals the attenuation performance of “floating slab track” is very high. As expected the attenuation is mostly located between the floating slab and tunnel wall;
- the worst situation is located in the single track tunnel curve between Medaglie d’Oro e Montedonzelli (“slab track”). Levels are highly affected by rail corrugation.
- in the “cut&cover” area levels are not extremely high, existing a non negligible attenuation between the tunnel invert and the tunnel wall.

The results on the “cut&cover” infrastructure are completed with results from surface measurements that can be summarized in a mean level of 75.5 dB for Southbound trains and 81.4 dB for Northbound trains.

The great number of complaints coming from the Vanvitelli - Medaglie d’Oro area until 2002 were probably due to the use of the Vanvitelli station as a terminal with consequent very frequent use and wear on switches. Nowadays trains run straight on switches at moderate speed and therefore vibrational annoyance is much lower.

Measurements on the “slab track” in the curve in the Medaglie d’Oro - Montedonzelli section show that the performance of the infrastructure in reducing vibrations is not as good as for the “floating slab track” and the presence of the rail corrugation led to relatively high levels of vibration on the tunnel wall. For the reasons mentioned above, probably at the moment this is the portion of the line where groundborne vibrations have to be controlled with more attention.

The difference in attenuation performance between “slab track” and “floating slab track” were investigated more deeply by estimating FRFs using impact excitation given with an instrumented hammer of appropriate mass. These measurements confirmed with a more rigorous method the performances of the two types of track formation in terms of vibration attenuations. Figure 5 shows an example FRF.

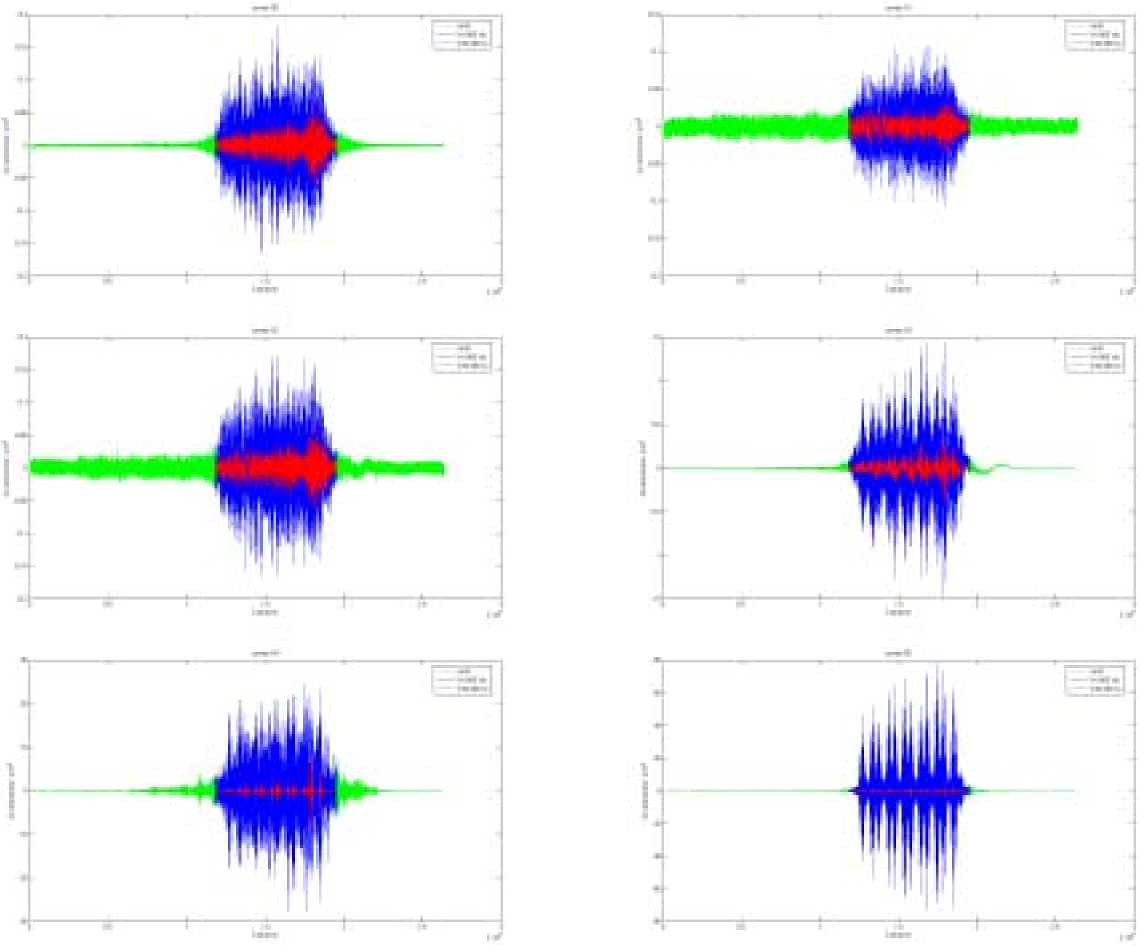

Figure 4. Time histories of acceleration on the instrumented points (slab track): wall horizontal (top left), wall vertical (top right), wall horizontal (backup sensor, mid left), slab vertical (mid right), rail horizontal (bottom left), rail vertical (bottom right). Green plot is all the signal in all the frequency range, blue plot is the portion of the signal used to calculate RMS, red is the same portion in the 0.8÷80 Hz frequency range.

Line section	Track formation	Average speed [km/h]	Wall level [dB]	Rail level [dB]	Slab level [dB]	Slab/rail [dB]	Wall/slab [dB]	Wall/rail [dB]
Medaglie d'Oro - Montedonzelli before grinding	Slab track	55.8±2.9	94.1±2.5	113.6±3.0	103.0±2.5	-10.6	-9.0	-19.5
Medaglie d'Oro - Montedonzelli after grinding	Slab track	51.5±9.0	85.4±2.9	109.7±3.0	95.5±2.5	-14.2	-10.1	-24.3
Vanvitelli – Medaglie d'Oro	Cut&cover	53.5±6.5	84.7±4.2	110±5.1	98.0±4.5	-11.9	-13.3	-25.2
Museo – Materdei	Floating slab track	56.5±5.2	70.0±2.0	114.3±3.4	108.5±2.1	-5.8	-38.5	-44.3

Table 3: Acceleration levels in the 0.8÷80 Hz frequency range

Line section	Track formation	Average speed [km/h]	Wall level [dB]	Rail level [dB]	Slab level [dB]	Slab/rail [dB]	Wall/slab [dB]	Wall/rail [dB]
Medaglie d'Oro - Montedonzelli before grinding	Slab track	55.8±2.9	123.2±0.8	145.2±0.2	123.7±0.5	-21.5	-0.3	-21.8
Medaglie d'Oro - Montedonzelli after grinding	Slab track	51.5±9.0	106.7±2.5	129.8±6.2	110.7±1.8	-19.1	-4.0	-23.1
Vanvitelli – Medaglie d'Oro	Cut&cover	53.5±6.5	93.6±2.1	137.1±2.0	123.5±2.6	-13.6	-29.9	-43.5
Museo – Materdei	Floating slab track	56.5±5.2	74.5±0.9	142.6±1.8	135.6±0.9	-7.0	-61.1	-68.1

Table 4: Acceleration levels in the 20÷250 Hz frequency range

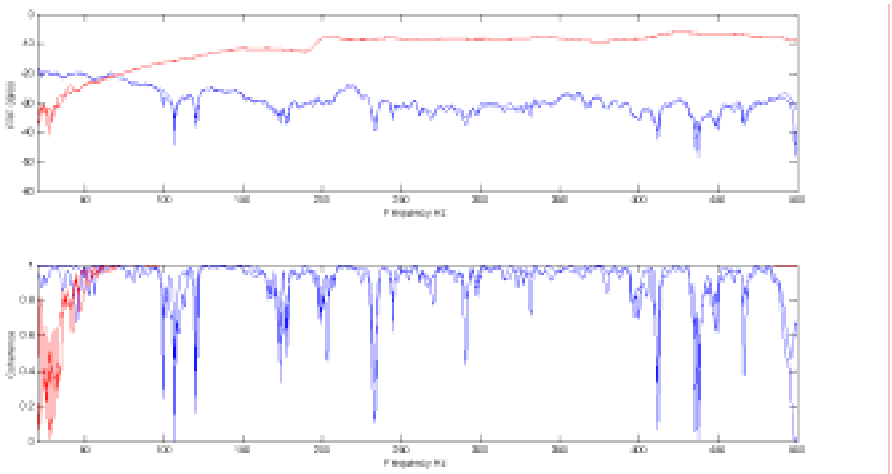

Figure 5. FRF and relative coherence function estimated with impact excitation on the rail and response recorded on the tunnel wall, for "slab track" (red) and "floating slab track" (blue).

INFLUENCE OF RAIL CORRUGATION

On the Medaglie d'Oro - Montedonzelli section of the line, where rail grinding was planned, the measurements were made just before and just after the removal of the rail corrugation, making possible the evaluation of the influence of this parameter. It is known in fact that rail corrugation influences the amount of dynamic load that is generated at the wheel/rail interface that represents the excitation for the track/tunnel system.

The rail corrugation in the two situations (pre and post grinding) was measured with a CAT (Corrugation Analysis Trolley). Displacements and wavelength spectra are shown in Figure 6.

Results of the measurements in both the rail conditions were already shown in Table 3 and Table 4, where the influence of the corrugation can be evaluated in both frequency ranges. In the 0.8÷80 Hz frequency range the influence is around 9 dB at tunnel wall, in the 20÷250 Hz frequency range the influence is around 17 dB.

From these results the influence of corrugation appears as non negligible, and the presence of this type of rail wear can influence the level and thus the perception of the vibration inside the buildings along the line. The influence of corrugation becomes very important as the source of vibration towards the environment mainly where the attenuation performances of the infrastructure are not particularly high. Corrugation makes the difference between a quiet and a very noisy vibration residential environment.

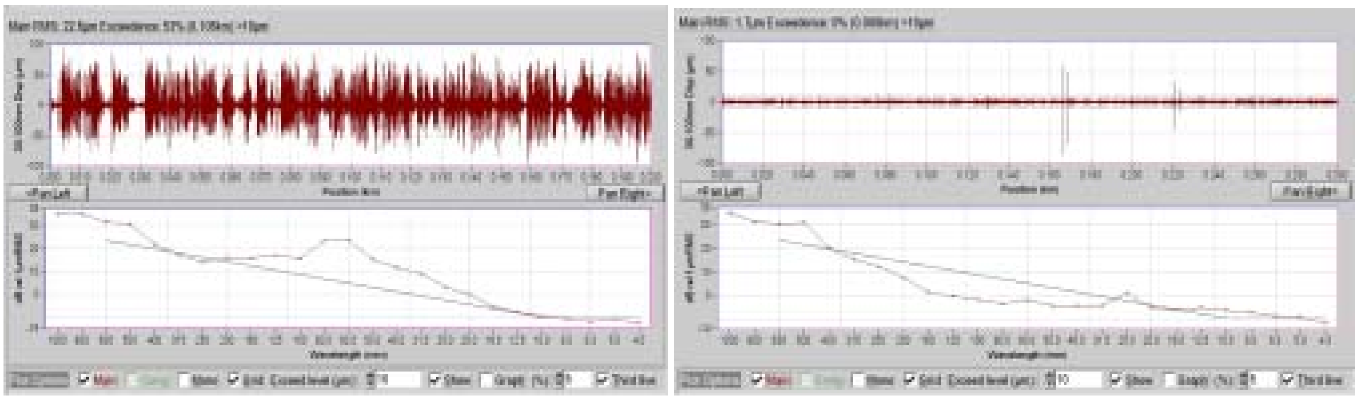

Figure 6 Corrugation displacement (top) and wavelength spectra (down) before (left) and after grinding (right). Different wavelengths and amplitudes of heavily corrugated and just ground rails are clearly visible.

CONCLUSIONS AND DEVELOPMENTS

The high effectiveness of the "floating slab track" in reducing groundborne vibrations was confirmed, while for the other two types of track formation an important parameter influencing the vibrations was found to be the amplitude of the rail corrugation. With low levels of rail corrugation, vibrations remain acceptable also for "cut&cover" tunnels; with high levels of corrugation, vibrations increase and also on "slab track" one complaint was presented.

At the moment the only countermeasure adopted systematically is rail grinding. A series of actions, including semi-automatic monitoring of vibrations levels, measurement of rail corrugation (with a corrugation measuring trolley and via axlebox accelerometers), attenuation of corrugation growth with the use friction modifiers were already implemented. At the moment also the installation of a very low stiffness rail fastening system is forecast in the portion of the line were complaints are more frequent.

Results that come from the activities described above, most off witch are measurements and testing activities, gave Metronapoli a better understanding of the situation of groundborne vibration on the "Linea 1" metro line. Performance of all track formation present on underground portion of the line were investigated in terms of vibration injected into the environment and in terms of vibration attenuation between the rail and the tunnel wall.

The influence of rail corrugation on groundborne vibration was assessed. In order to mitigate the negative effects of corrugation where infrastructure properties are poor in terms of attenuation a series of countermeasures were partly adopted including:

- constant monitoring of rail corrugation with CAT;
- development of a "fast" corrugation measuring system based on axlebox accelerations;
- installation of friction modifiers dispensers to reduce corrugation growth;
- preventive and frequent rail grinding.

Moreover, a semi automatic vibration measuring station was installed in the Medaglie d'Oro - Montedonzelli section of the line in order to observe the evolution of vibrations levels in time and to try highlight any possible influence of different trains in terms of wheelflats or, more generally, of any out-of-roundness that generate high levels of tunnel wall vibrations.

Where the combination of high and rapidly growing corrugation and poor infrastructure is present, i.e. the "Milano" fastening on "slab track", the installation of a fastening system much softer then the current fastenings is planned. The use of a soft fastening system should introduce a sufficient attenuation to reduce vibration levels also in presence of moderate rail corrugation. At the moment this is considered the only technically feasible option to retrofit the “slab track”, as the installation trackworks could be done on the existing infrastructure relatively easily without the need to close the line during normal service hours.

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