A field investigation on the vibroacoustic impact of an underground metro line

Original
A field investigation on the vibroacoustic impact of an underground metro line / Masoero, Marco Carlo; Bronuzzi, Fabrizio; Bertetti, Carlo Alessandro; Falossi, Marco. - In: PROCEEDINGS OF MEETINGS ON ACOUSTICS. - ISSN 1939-800X. - ELETTRONICO. - 28:(2016). [10.1121/2.0000443]

Publisher:
Acoustical Society of America

Published
DOI:10.1121/2.0000443

Proceedings of Meetings on Acoustics

A field investigation on the vibroacoustic impact of an underground metro line

--Manuscript Draft--

Manuscript Number:	
Full Title:	A field investigation on the vibroacoustic impact of an underground metro line
Article Type:	2016 ICA Paper
Corresponding Author:	Marco Carlo Masoero Politecnico di Torino Torino, TO ITALY
Order of Authors:	Marco Carlo Masoero
	Fabrizio Bronuzzi
	Carlo Alessandro Bertetti
	Marco Falossi
Abstract:	The paper presents the approach used in a field investigation on the vibration impact of a new underground metro line, focusing on population annoyance. The metro consists of a double barrel tunnel equipped with a slab track system: rails are fastened to elastically supported sleeper blocks embedded in a floating concrete slab, cast on a resilient mat. Vibrations were measured over four weeks inside the metro tunnel (on the rail, floating slab and tunnel ring wall) and inside a selected sample of buildings. Transits were monitored with video recordings. Approximately 30000 vibration recordings were collected. A systematic approach was applied to identify the cases in which the vibrations detected inside the buildings could be attributed to metro transits with a high degree of confidence. This task is critical due to the highly variable soil properties and building structures, and to the presence of diverse vibration sources such as surface transportation and building technical systems. The dispersion of the results due to the different characteristics of the rolling stock was also investigated. The results of the study provided a basis for implementing mitigation measures at the sites in which the vibration levels exceeded the limits prescribed by applicable standards.
Section/Category:	Structural Acoustics and Vibration

Proceedings of Meetings on Acoustics

Volume 28 http://acousticalsociety.org/

22nd International Congress on Acoustics
Acoustics for the 21st Century

Buenos Aires, Argentina
05-09 September 2016

ICA 2016 BUENOS AIRES

FIA FEDERACIÓN IBEROAMERICANA DE ACÚSTICA

ASOCIACIÓN de ACÚSTICOS ARGENTINOS

Structural Acoustics and Vibration: Paper ICA 2016 - 116

A field investigation on the vibroacoustic impact of an underground metro line

Marco C. Masoero and Fabrizio Bronuzzi
Department of Energy, Politecnico di Torino, Torino, Italy; marco.masoero@polito.it, fabrizio.bronuzzi@polito.it

Carlo A. Bertetti and Marco Falossi
Studio Progetto Ambiente Srl, Torino, Italy; ac.bertetti@progambiente.it, m.falossi@progambiente.it

The paper presents the approach used in a field investigation on the vibration impact of a new underground metro line, focusing on population annoyance. The metro consists of a double barrel tunnel equipped with a slab track system: rails are fastened to elastically supported sleeper blocks embedded in a floating concrete slab, cast on a resilient mat. Vibrations were measured over four weeks inside the metro tunnel (on the rail, floating slab and tunnel ring wall) and inside a selected sample of buildings. Transits were monitored with video recordings. Approximately 30000 vibration recordings were collected. A systematic approach was applied to identify the cases in which the vibrations detected inside the buildings could be attributed to metro transits with a high degree of confidence. This task is critical due to the highly variable soil properties and building structures, and to the presence of diverse vibration sources such as surface transportation and building technical systems. The dispersion of the results due to the different characteristics of the rolling stock was also investigated. The results of the study provided a basis for implementing mitigation measures at the sites in which the vibration levels exceeded the limits prescribed by applicable standards.

Published by the Acoustical Society of America

1. INTRODUCTION

This paper discusses the methodology and results used in an extensive vibration measurement campaign aimed at verifying the compliance with specified vibration limits in a set of buildings located in the proximity of a new underground metro line. The metro consists of a double barrel tunnel excavated using a Tunnel Boring Machine at a depth of 13-25 m. The metro infrastructure adopts a slab-track system, in which the rails are fastened to elastically supported sleeper blocks, which are embedded in a floating concrete slab, cast on a resilient mat[1].

A preliminary measurement campaign, completed shortly after the line went into operation, showed that in the entire set of 73 investigated buildings the requirements for the preservation of structural integrity[2] were satisfied, while in a subset of 19 buildings vibration levels exceeded the specified limits for human exposure[3]. However, the preliminary campaign did not investigate the origin of the measured vibration, which could be caused also by sources different from the metro line, such as surface road and rail transport, building services, and occupants' behavior.

A four-week additional measurement campaign was therefore carried out in order to identify the origin of the problems reported in the 19 buildings, and to obtain information useful to define the vibration mitigation actions. Simultaneous vibration measurements inside the metro tunnels and in the buildings were performed; approximately 30000 recordings were collected in the campaign. A survey of the concurrent surface activities was also developed. The synchronization of building and underground measurements has proven to be very useful in order to identify the actual vibration transmitted from the tunnels to the buildings, as discussed in sections 2 and 3 of the paper.

This working methodology allowed us to verify that only one fourth of the critical buildings where actually exceeding the reference values because of the metro passages, the remaining part being due to concurrent sources or local events occurring inside the building.

Measurement results also showed that problems are mostly due to the lack of performance of the floating track slab, which is not dissipating energy in the expected frequency range. Reasons for this situation can be numerous, but there is evidence that local connections between the floating slab and the tunnel rings may be the likely cause of the problem. Interventions on the track have then been designed to recover the full functionality, but success of this action is not sure because the existence of additional problems in the slab execution cannot be a priori excluded. After the application of the interventions, instrumental testing will show if the goal is completely achieved, and if the vibration values in the buildings comply with the reference values. In case of enduring lack of conformance, an intervention on the rail fastening system is required, to be designed and executed taking in due consideration the need of preserving the operation of the metro line.

2. TUNNEL MEASUREMENTS

Recording of vibrations in the tunnel provides a time history with a clear identification of train passages on the two tunnel barrels, which can be reliably synchronized with measurements in the buildings. A sure reference for the temporal localization of each passage is in fact indispensable for an objective evaluation of the metro transit effects, in presence of concurrent sources of vibration acting on the building. Furthermore, these measurements give the opportunity to evaluate the dispersion of metro train emission values, due to differences in train characteristics, equipment wear, maintenance, etc.

A. Technical approach

Measurements in the metro tunnels were performed using continuously operating instruments. For each of the 19 investigated buildings, a reference tunnel measurement section was defined. In each reference section, measurements were taken on both tunnels, installing accelerometers on the tunnel rings, on the track slab, and on the rail. A camera was also positioned to record the metro passages and to compute the pass-by train speed. Every night, during the suspension of the metro rides, the instrumentation was repositioned to a different measurement section in order to get a complete coverage of the line, whose total length equals approximately 6 km. The reference tunnel measurement sections were defined using the following criteria:

1. the section must be possibly placed under the building;
2. the section can be used as a reference for more than one building, provided the buildings are sufficiently close to each other (maximum distance of about 50 m);
3. the section cannot be used for two buildings if different types of resilient mats have been installed under the track slab for vibration damping.

A tentative location of the 14 reference sections was initially identified on the as-built plans. The final position was specified in the operative phase by taking into account the actual possibility to install the instruments (available fastening facilities, cabling, safety, etc.).

Vibration measurements in the tunnels were taken using two four-channel digital acquisition units, composed by a digital acquisition board connected to a laptop PC equipped with a signal processing SW[4]. The characteristics of the data acquisition systems are reported in the following:

- 2 mA IEPE signal conditioning for microphones and accelerometers
- 50 kS/s per-channel maximum sampling rate
- AC-coupled (0.5 Hz)
- 24-bit resolution
- 102 dB dynamic range
- antialiasing filters
- 4 simultaneously sampled analogue inputs
- ±5 V input range
- smart TEDS sensor compatibility

Four accelerometers were used per each tunnel with the following characteristics:

- sensitivity: 500 mV/g
- range: ±10 g
- frequency range: 1-10.000 Hz
- resonant frequency: > 35 kHz
- transverse sensitivity: 5% max
- supply current: 2-20 mA

Accelerometers were positioned on the tunnel rings 1.2 m above the railhead by means of a steel plate fixed to the wall by anchors and bolts. The plate fastening system may be adjusted to compensate the tunnel ring curvature, allowing the application of the accelerometers in the vertical and transversal directions. Sensors are then covered with a plastic box to avoid disturbances due to the strong wind generated by piston effect in the tunnel. For the slab sensor, a simple steel plate was cemented to the concrete, which allows screwing the accelerometer in the vertical direction. A plastic box was used for cable ducting and protection against wind. The sensor is generally placed in the space between two consecutive rail-fastening blocks. The rail sensor was installed with a magnetic mounting on the back of the rail's base flange.

Data acquisition is made as a continuous recording, from start to end of the measurement interval, on the laptop PC connected to the acquisition board. The alias-free sampling is made at 2000 samplings/second, synchronous on the four channels. Video recordings were taken using a digital camera fixed with a clamp to the cabling channels or pipes and connected to a digital recorder with continuous operation.

B. Results

Results from the measurements taken in the tunnels have two main purposes:

1. Supporting the identification of metro passages in the evaluation of the events occurring during the buildings measurements;
2. Evaluating the vibration emission levels from the tunnels and identifying possible uneven performance of the mitigation measures.

For the first aspect, the time history and the spectral content of the events provide a reference for the evaluation of the building measurements. For the second one, synthetic indicators are required to assess the results.

All trains passing in the time window defined for the measurements inside the buildings were evaluated in their time and frequency evolution. Figure 1 represents an example of the measurement reports produced for the tunnel measurements.

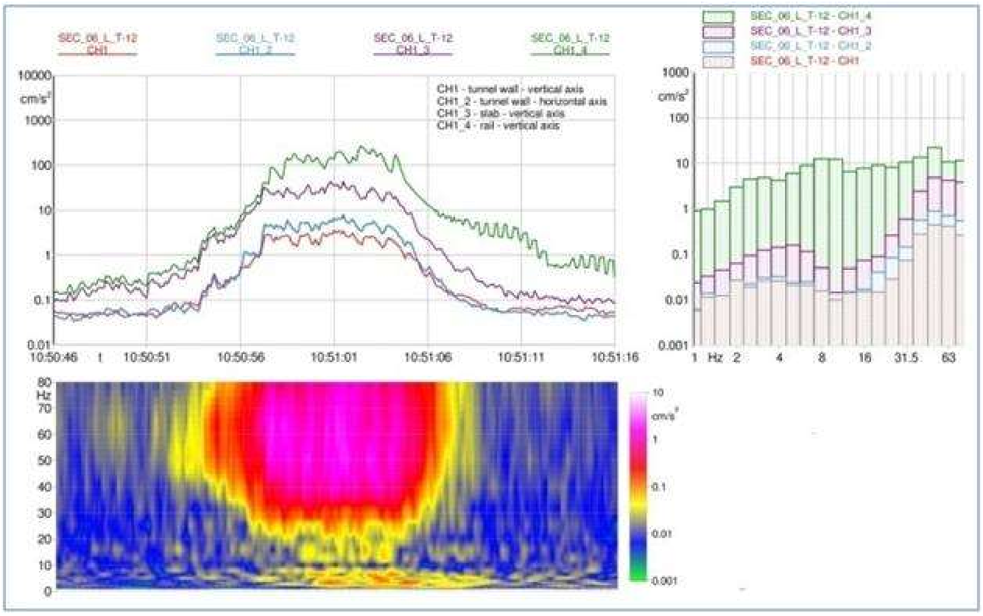


Figure 1. Example of the report about the tunnel measurements.

The upper left part of the figure shows the time history of the overall values (in the 1-80 Hz frequency range) for the four measurement channels. The upper right part contains the 1/3rd octave band spectra of the four tracks reported in the previous plot. The lower left part of the figure provides a spectrogram plot for the wall vertical vibration, showing the time evolution of each frequency component in the same time window of the time history. The color scale shown on the right-end side of the plot represents the acceleration amplitude. This reporting format gives a strong visual support in understanding the phenomenology of the train passages and is useful for the extraction of the events recorded inside the buildings.

Synthetic values are required to compare the results from different train passages. Two kinds of indicators were chosen, the maximum overall value of acceleration (A_{max}) and the Single Event Level (SEL_v). The former indicator is the maximum value in the time history reported in the upper left plot of Figure 1. The latter indicator is normally used for sound exposure evaluation[5], but can also be applied to the evaluation of vibration effects. This parameter represents the effect of the train passage normalized to a one-second period. It is normally expressed in decibels, but in our case, the result is converted to an acceleration for homogeneity with the other data. The mathematical definition in decibels is the following:

$$SEL_v = 10log_{10} \int \left(\frac{a(t)}{a_0} \right)^2 dt \qquad (1)$$

where $a(t)$ is the measured acceleration and a_0 is the acceleration reference value equal to 10^{-6} m/s^2. The SEL_v is useful when comparing events with different duration. Such duration is here conventionally defined - as customary in railway noise and vibration analyses - as a window cut at -20 dB below the maximum value on the time history. The same indicator is used for the evaluation of the spectral characteristics of the phenomena.

C. Statistical evaluation of the train vibration emission

Tunnel measurements have been evaluated in the time interval corresponding with the building measurements. The number of evaluated train passages is therefore a subset of the entire observation period.

The charts in Figure 2 show the resulting synthetic indices A_{max} and SEL_v for the metro passages measured on the tunnel rings in the horizontal and vertical directions. These values represent the effective emission of the metro line, as long as the structure of the tunnels is well connected with the soil propagating the vibrations to the buildings foundations. The charts show the scatter plot of the results against the train speed and the regression curve. A first evidence is that the measured train speeds range between 32.0 km/h and 62.7 km/h in the investigated sections. A dependence with the speed is visible, revealing an increasing trend of the vibration values with train speed, as expected. It is at the same time evident that the values are quite dispersed, with small values of the coefficient of determination R^2. Considering the effect of the logarithmic scale, it can be observed that the intensity indices of some passages are more than double in size than the mean value.

Reasons for this significant dispersion can be numerous, but at least two of them are worth mentioning:

- Maintenance of trains and rails cannot be uniform among the fleet units and along the tracks. This condition determines plenty of possible combinations of train/track couplings that have been acquired during the monitoring campaign;
- Train composition is fixed for all the train runs, but the payload varies as a function of the number of people using the metro line at different times of the day. This is another uncontrolled variable in the monitoring campaign which can lead to an increased dispersion of the results, considering that the weight of the train at full load is nearly double than in empty condition.

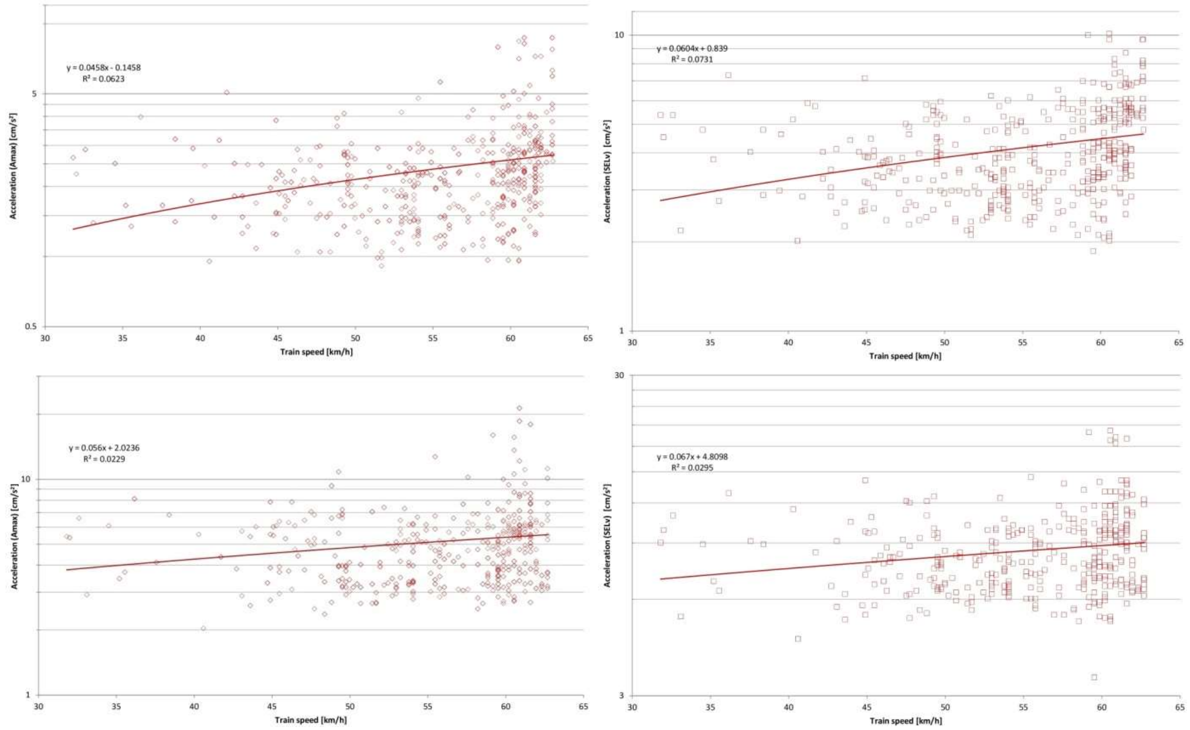


Figure 2. Scatter plots and regression curves of A_{max} (left) and SEL_v (right) vs. train speed for the wall vertical component (top) and wall horizontal component (bottom).

Further evaluations can be made on the spectral composition of the events and on the transfer functions between the different measurement points. The chart on the left of Figure 3 reports the mean spectra of the wall horizontal component, computed as the mean value of each 1/3rd octave frequency band of the train transits. Maximum and minimum band values are also reported to outline the variability of the measured values. A dominant frequency component at 50 Hz can be observed, with a second maximum at 4 Hz, but with a difference in amplitude of more than one order of magnitude. The chart on the right of Figure 3 reports, for each 1/3rd octave frequency band, the ratios of the acceleration values measured at the different measurement points: Rail/Slab, Slab/Wall (Horizontal), and Slab/Wall (Vertical). It can be seen that a strong attenuation is introduced at 10 Hz in the transmission from rail to slab, while the transfer function from the slab to the wall (vertical component) is most effective at 80 Hz with an amplitude attenuation of more than 20 times.

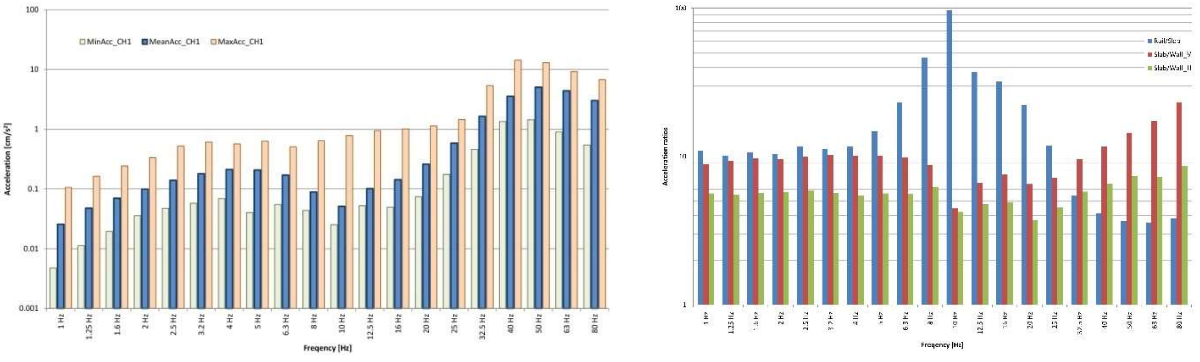


Figure 3. Frequency analysis of the acceleration SEL_v for the wall horizontal component (left) and ratios of acceleration values from the four measurement channels (right).

3. BUILDINGS MONITORING

Buildings were monitored in the same measurement points used in the preliminary campaign for human perception evaluation. An additional measurement point was placed, when possible close to the foundations, in a position not influenced by local events caused by the people living in the investigated rooms.

A. Technical approach

Measurements were performed as a continuous acquisition, and train passages were extracted in the post-processing phase. Sensors were installed, where possible, in the same position of the previous campaign. For each measurement point, at least 40 train passages were generally captured. The operator's presence permitted to evaluate and take note of the anomalous effects due to extraneous factors. A particular attention was paid to the concurrent vibration sources.

For every measurement point, three accelerometers were positioned. Each sensor was installed along the three axes: one vertical and two horizontal. The orientation of the sensors are consistent with the previous campaign. Accelerometers were mounted on a massive metallic plate and screwed or fixed with a magnet. The set of three accelerometers was connected to an acquisition system having technical specifications similar to the ones used in the tunnels.

B. Results

In order to evaluate human exposure to metro train vibration, measurements have been analyzed extracting 25 train passages for each measurement point. For each building, the measurement report, composed by four sections, provides the following data:

- General overview of the building and measurement points (geographic location, description of concurrent vibration sources, plans and pictures specifying the sensors position, etc.);
- Comparison plot of the vibration measured at the tunnel wall (red curve), building basement (green curve), and building room (black curve), see Figure 4;
- Summary of numerical results for each metro passage, see Table 1;
- Graphical representation and analysis of the measurement results, see Figure 5.

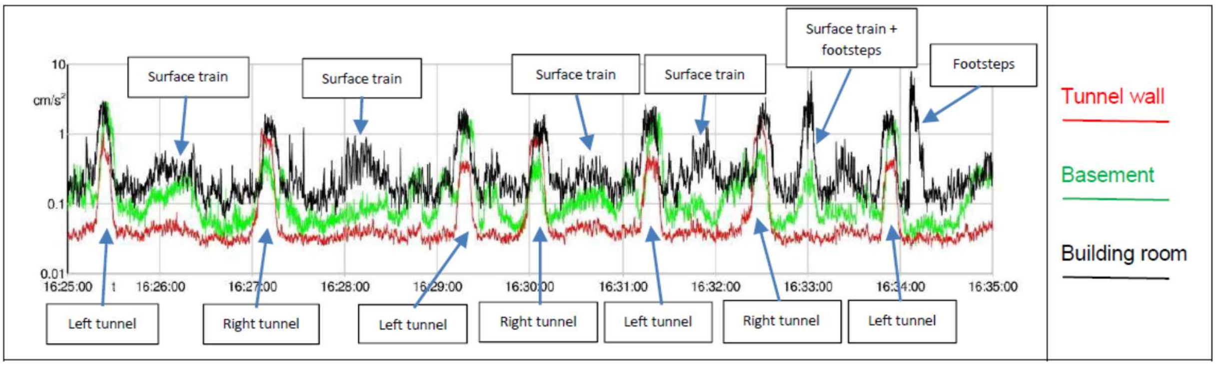


Figure 4. Superposition of the measurement records in the tunnel and building.

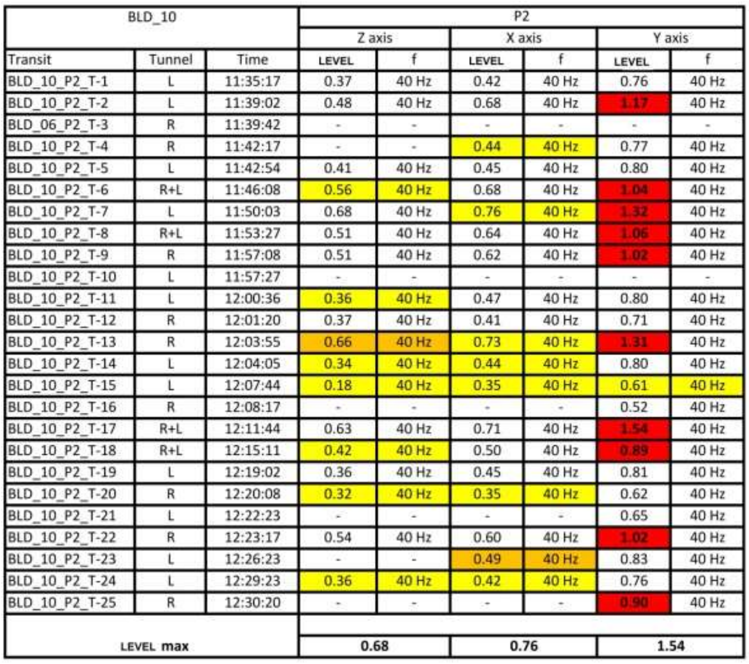
As a first step, building measurements and tunnel pass-by time histories were analyzed in order to identify the right and left metro transits. Where possible, these data were also compared with the building basement measurements. These plots are useful in order to identify the origin of the vibration events detected inside the building by comparing the time histories in the different measurement points (an example is shown in Figure 4).

The time interval from which the 25 metro transits were extracted has been defined as to include the most intensive passages in the observation period, in conjunction with the lowest effects of concurrent sources possibly acting on the building. Every metro passage was then extracted and every channel was evaluated.

Table 1 provides the summary of the results for a sample building. The first three columns contain general information about each single metro transit: the identification name, the tunnel in which the passage occurred, and the passage time. The following six columns give the acceleration levels for each measurement axis and the corresponding frequency. The bottom line shows the maximum value measured for each axis. The analysis of the acquired data has identified specific events, which are marked in the table with different cell color-coding:

- White cells: compliance with limits (acceleration level < 0.85) and no anomalies;
- Red cells: exceedance of the limits (acceleration level > 0.85);
- Yellow cells: the event is affected by vibration sources different from metro transits and the maximum acceleration level occurs at a frequency which is not ascribable to a train passage. In this case, these extraneous frequency values have been removed from the final evaluation; the acceleration level values are lower than the limit before frequency masking;
- Orange cells: the event is affected by vibration sources different from a metro transit and the maximum acceleration level occurs at a frequency which is not ascribable to train passages. In this case, these extraneous frequency values have been removed from the final evaluation; the acceleration level values are higher than the limit before frequency masking;
- White cells with dash: the metro transit has been invalidated, either because of concurring sources dominating the vibration phenomena, or because it cannot be in any way detected, since it does not generate any vibration effect on the measurement point.

Table 1 – Results summary table for the 25 train passages



BLD_10			P2					
			Z axis		X axis		Y axis	
Transit	Tunnel	Time	LEVEL	f	LEVEL	f	LEVEL	f
BLD_10_P2_T-1	L	11:35:17	0.37	40 Hz	0.42	40 Hz	0.76	40 Hz
BLD_10_P2_T-2	L	11:39:02	0.48	40 Hz	0.68	40 Hz	1.17	40 Hz
BLD_06_P2_T-3	R	11:39:42	-	-	-	-	-	-
BLD_10_P2_T-4	R	11:42:17	-	-	0.44	40 Hz	0.77	40 Hz
BLD_10_P2_T-5	L	11:42:54	0.41	40 Hz	0.45	40 Hz	0.80	40 Hz
BLD_10_P2_T-6	R+L	11:46:08	0.56	40 Hz	0.68	40 Hz	1.04	40 Hz
BLD_10_P2_T-7	L	11:50:03	0.68	40 Hz	0.76	40 Hz	1.32	40 Hz
BLD_10_P2_T-8	R+L	11:53:27	0.51	40 Hz	0.64	40 Hz	1.06	40 Hz
BLD_10_P2_T-9	R	11:57:08	0.51	40 Hz	0.62	40 Hz	1.02	40 Hz
BLD_10_P2_T-10	L	11:57:27	-	-	-	-	-	-
BLD_10_P2_T-11	L	12:00:36	0.36	40 Hz	0.47	40 Hz	0.80	40 Hz
BLD_10_P2_T-12	R	12:01:20	0.37	40 Hz	0.41	40 Hz	0.71	40 Hz
BLD_10_P2_T-13	R	12:03:55	0.66	40 Hz	0.73	40 Hz	1.31	40 Hz
BLD_10_P2_T-14	L	12:04:05	0.34	40 Hz	0.44	40 Hz	0.80	40 Hz
BLD_10_P2_T-15	L	12:07:44	0.18	40 Hz	0.35	40 Hz	0.61	40 Hz
BLD_10_P2_T-16	R	12:08:17	-	-	-	-	0.52	40 Hz
BLD_10_P2_T-17	R+L	12:11:44	0.63	40 Hz	0.71	40 Hz	1.54	40 Hz
BLD_10_P2_T-18	R+L	12:15:11	0.42	40 Hz	0.50	40 Hz	0.89	40 Hz
BLD_10_P2_T-19	L	12:19:02	0.36	40 Hz	0.45	40 Hz	0.81	40 Hz
BLD_10_P2_T-20	R	12:20:08	0.32	40 Hz	0.35	40 Hz	0.62	40 Hz
BLD_10_P2_T-21	L	12:22:23	-	-	-	-	0.65	40 Hz
BLD_10_P2_T-22	R	12:23:17	0.54	40 Hz	0.60	40 Hz	1.02	40 Hz
BLD_10_P2_T-23	L	12:26:23	-	-	0.49	40 Hz	0.83	40 Hz
BLD_10_P2_T-24	L	12:29:23	0.36	40 Hz	0.42	40 Hz	0.76	40 Hz
BLD_10_P2_T-25	R	12:30:20	-	-	-	-	0.90	40 Hz
LEVEL max			0.68		0.76		1.54	

Finally, detailed data sheets for each measurement point were composed. Figure 5 reports an example of the metro transit analysis for one of the measurement channels.

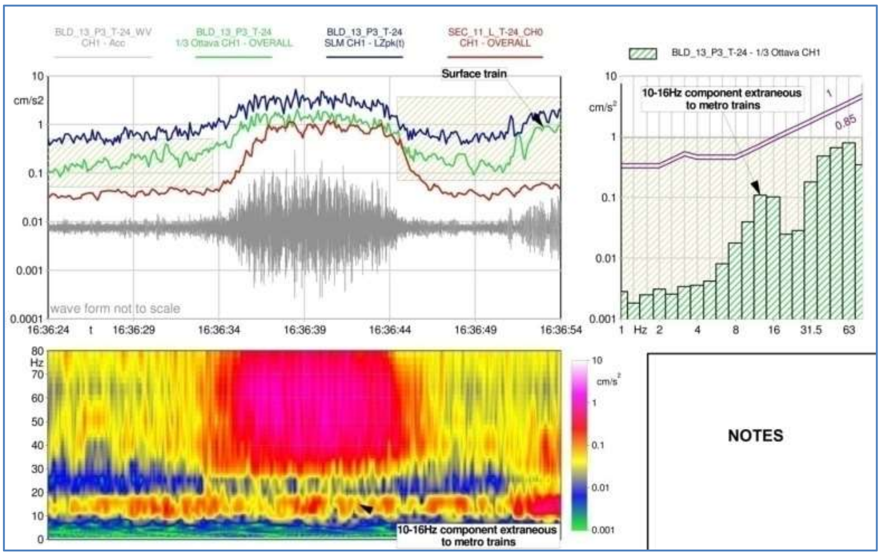


Figure 5. Building vibration analysis report.

The upper left graph of Figure 5 compares the time histories of the metro transit peak vibration (blue line), RMS vibration (green line), building room vertical component (red line) and waveform (grey line, not to scale with the other traces and the plot reference). The RMS time history was masked in order to identify and extract the metro events. This masking operation permits to investigate the metro transit data only, whereas the remaining (masked) part of the record was excluded from further analyses. Specifically, only the part of the time history for which the RMS acceleration value exceeds 20% of the maximum peak acceleration is attributed to the metro transit. Wherever this criterion was not applicable because of the presence of exceedingly high background vibration values, the transit was masked using the timeline provided by the tunnel measurement data. Specifically, if a good temporal correspondence between the tunnel and the building measurements was identified, the transit event masking could be based on this correlation. Otherwise, it was possible to estimate the transit contribution by combining the information provided by the sonogram and by the time history of the tunnel measurement: in fact, the temporal alignment between the two plots permits to extract the event, masking the remaining values. In some cases, where metro transit had no effect on the measurement point, no masking was performed, but the vibration values were reported as a large over-estimate of the actual metro effects. Meaningful annotations are also indicated on the plots in case of unexpected events occurring inside or outside of the measurement position.

The histogram at the right-hand side of Figure 5 represents the 1/3rd octave band spectrum of the RMS channel (green line of the time history on the left-hand side). Superimposed to the spectral values, the limit curves are shown representing the vibration limits not to be exceeded. Such limit curves represent the envelopes of the horizontal and vertical limit values, as specified by the ISO standards on human exposure to vibration in the 1 Hz – 80 Hz frequency range. Values here reported are already purged of masked data.

The lower left-hand side of Figure 5 shows a spectrogram plot of the RMS values for the current channel component, showing the time evolution in the same time window of the time history. These two graphic representations permit to identify and evaluate the frequency components extraneous to metro transits. The presence of extraneous vibratory frequencies can be identified by examining the temporal behavior of the phenomena. In the example of Figure 5, it is clearly possible to observe that the intense events falling in the 10-16 Hz frequency range have a temporal duration that does not follow the metro transit evolution and are therefore definitely caused by other sources. Finally, comments may be annotated on the lower right part of the report.

This kind of evaluation was carried out for all the three measurement channels of each of the 25 selected metro transits. In some cases, the event was overlapped by other vibration sources, or the metro transit levels were so much lower than background vibration levels that it was not possible to evaluate its effects. In these cases, the event was eliminated and not taken into account. In other cases, when some vibratory effects can be seen from the plots, but it is not possible to recognize a clear distinction between the transit effects and background values, the vibration record was not masked and the resulting values were reported as an over-estimate of the actual effects of the metro transit.

C. Summary of the results in buildings

Compliance with human exposure limits has been verified in all the measurement points previously investigated in the 19 buildings. The results of the in-depth studies highlight a full compliance in 14 buildings (74% of the samples). These results have been classified with a color-coding having the following meaning:

- “Green buildings” (n. 14 buildings): compliance with limits for human disturbance in all measurement points in the building;
- “Red buildings” (n. 2 buildings): claims from inhabitants, noncompliance with limits in all the measurements points;
- “Orange buildings” (n. 2 buildings): no claims, no complaints from inhabitants, noncompliance with limits limited to one measurement point, noncompliance with limits due to train emission greatly above the average, or with metro trains overlapped with intensive road traffic (in this case metro levels are strongly affected by road components);
- “Red flats” (n. 1 building): claims and complaints from a single inhabitant, compliance with limits in one of the two measurement point in the flat, noncompliance with limits in the other measurement point of the same flat.

4. RECOMMENDED MITIGATION MEASURES

Mitigation measures have been recommended only for the most critical situations, namely for the “Red buildings” as previously defined, where noncompliance with limits for human perception vibrations is extended to more than one measurement point and claims or complaints from inhabitants are reported.

This situation suggests the adoption of two possible kinds of intervention:

- improvement of slab flotation;
- improvement of rail-slab connection.

Rails are in fact fastened to a massive slab that is unconnected from the tunnel rings by mean of a vibration-insulating mat (**Errore. L'origine riferimento non è stata trovata.**), whose performance has been defined in the design stage with thickness values ranging from 12 to 25 mm. This kind of vibration mitigation intervention is quite effective, but the performance of the system is guaranteed only in case of perfect decoupling of the floating mass from the tunnel rings. Local inspections of the tunnel revealed some problems in the A and B points, as outlined in **Errore. L'origine riferimento non è stata trovata.**. In fact, in some points along the metro line, adherences have been found between the slab and the ring, which are probably due to some concrete overflow during the casting process.

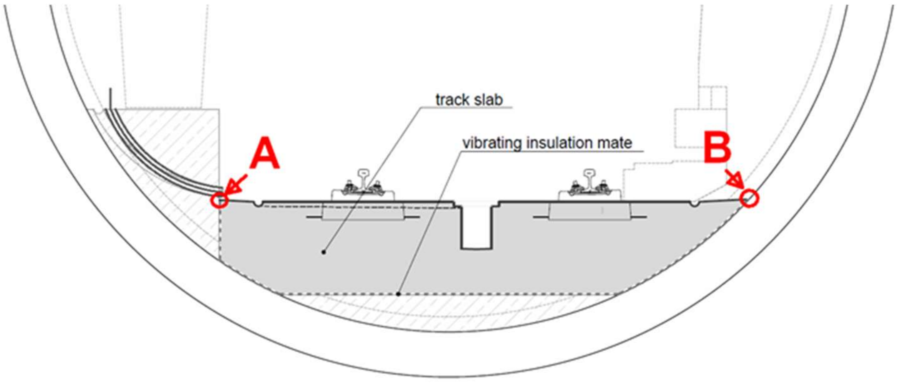


Figure 6. Typical tunnel section and location of the rigid connection points.

The aim of the first kind of intervention is to eliminate the adherences or localized connections possibly existing between the floating slab and the wall at the walkway side (A), and/or the tunnel rings (B) that in some points may have been inadvertently realized during the casting of the concrete slab. This can be achieved by cutting a wedge of the slab on both sides by means of a circular saw with diamond blades. The angle and position of the cutting should be defined after deeper inspections, in order to be certain to bring to the light the mat, make an accurate removal of any concrete part, and finally renovate the surface continuity for water collection with a resilient material.

If no other construction problem is present, the intervention should be adequate to recover the design performance of the vibration mitigation system, but this can only be verified after the execution of *post-operam* dynamic response tests on the slab and vibration measurements in the interested buildings. In case of poor results, the next option consists of replacing the rail fastening system with a new one having lower stiffness, down to 10 kN/mm of static performance and with dynamic stiffening factors lower than 1.4, able to provide for the lack of performance of the floating slab. This option is quite intrusive, keeping in mind that the line operation should be maintained as much as possible.

Application of the first kind of interventions is presently ongoing, and one further monitoring campaign will be developed after the completion of the works to understand if the expected results have been obtained. Results will be the object of further publications.

5. CONCLUSIONS

A detailed vibration measurement campaign has been conducted during the operation of a new metro line in order to assess the potential disturbance induced on the nearby buildings. The working methodology described in this paper allowed verifying that only one fourth of the buildings initially identified as critical where actually exceeding the reference vibration values because of the metro transits (5 of the 19 buildings investigated), while for the remaining part concurrent sources or local events occurring inside the building had determined the exceedance of the limit values.

Measurement results also showed that problems are mostly due to poor performance of the floating track slab, which is not dissipating energy in the expected frequency range. Reasons for this anomaly can be numerous, but often the problem is caused by the presence of rigid connections or contact points between the floating slab and the tunnel rings. Such anomalies are often produced during the concrete casting process and are localized at the outer edge of the floating slab. Works for cutting and cleaning the slab edges, which should likely solve the problem, are presently ongoing.

REFERENCES

[1] Thompson, D.; Jones, C.; Gautier, P. "Railway Noise and Vibration: Mechanisms, Modelling and Means of Control", Elsevier Science Ltd, Amsterdam, 2008.

[2] ISO Standard 4866: 2010. "Mechanical vibration and shock – Vibration of fixed structures – Guidelines for the measurement of vibrations and evaluation of their effects on structures", Geneva, 2010.

[3] ISO Standard 2631-2: 2003. "Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 2: Vibration in Buildings (1 Hz to 80 Hz) ", Geneva, 2003.

[4] Noise & Vibration Works version 2.8.0. http://www.nwwin.it/index.html

[5] ISO Standard 3095: 2013. "Acoustics – Railway applications – Measurement of noise emitted by railbound vehicles", Geneva, 2013.