

**Floating Slabtrack Systems in Tunnels**  
**A case study with different FST systems**  
**Metro Lisbon ó Red Line Extension**

Patrick Carels  
CDM S.A.

Reutenbeek 9-11, B-3090 Overijse, Belgium , Patrick.Carels@cdm.be

## **ABSTRACT:**

Floating Slabtrack systems (aka FST) are to date known as the ultimate ground borne noise & vibration mitigation technology. The concept is based upon the simple and practical transcription of the vibration isolation theory by imposing a low tuned resonant frequency of a single degree of freedom system through engineered selection of (1) inertial mass (2) with or without flexural stiffness (3) supported by a resilient system with tuned stiffness characteristics, all to reduce the vibrations generated by passing trains with minimal effect on track stability (low rail deformations).

This paper describes the FST designs and related works within the framework of the Red Line extension (2008-2010) for Metro Lisboa (ML) in Portugal. The Red Line Tunnel extension passes through a part of the City with low background N&V ( $v_{rms} < 10E-6$  m/s) and close to buildings with severe vibration criteria. Considering these parameters, ML requested an in-depth study to make sure that the new line met the stringent N&V criteria. The study defined different N&V isolated track solutions ranging from average 30 dBV to 35 dBV insertion loss in the 20-200 Hz. frequency range. The interesting part of this project is that in a same project 2 different FST designs are implemented ranging: mats with adaptable stiffness and discrete supported systems (pads and strips). An extensive vibration measurement campaign allowed confronting design and reality with interesting conclusions for future FST design and performance control methodology in operation.

**KEY WORDS:** Vibration isolation; floating slab track.

## **1 Introduction**

Floating Slabtrack Systems (aka FST) are to date known as the ultimate intervention technology to optimize mitigation of ground borne noise & vibration generated by rolling stock passage. The concept is based upon the simple and practical transcription of the vibration isolation theory by imposing a low tuned resonant frequency of a single degree of freedom system through engineered selection of (1) inertial mass (2) with or without flexural stiffness (3) supported by a resilient system with tuned stiffness characteristics, all to reduce the vibrations generated by passing trains with minimal effect on track stability (low rail deformations).

In the early days of noise & vibration control for public transport systems, there were essentially 2 track systems, one standard track (i.e. no vibration control measures) and one isolated track which was known at those days as the best solution, i.e. FST, which in many cases was an overkill. However as the technology advanced many vibration control systems came to the market. Nowadays there are many systems capable of meeting almost all vibration control

requirements ranging from a few dBV to almost 40 dBV of insertion loss. Also FST technology advanced with use of elastomer pads, helical springs, resilient mats, resilient strips and FST with discrete concrete inertial blocks (with and without shear connectors) and with continuous concrete slabs.

FST is still known to be the ultimate technology to reach optimal insertion loss, but strangely enough, we don't see important progress in the evolution of FST techniques. Lack of innovation in FST design, lack of system competition, and rigid material specifications, mostly guided towards unique resilient materials, are in many cases the herald of non-competitive costs.

When looking in details at papers describing FST presented throughout worldwide technical literature, one rarely finds demises or negative experiences with FST (like e.g. ref [1]) almost all are success stories. However, discussing in detail with permanent way owners (PWO) having experience with FST, one can indeed learn that apart from the success stories there are also failures, negative experiences with design concepts and resilient materials. The return on experience and the lesson drawn out of these failures has been rewarding for the profession and sure for the innovation to follow.

The FST systems described in this paper were based, unlike many tender specifications presently on the market, upon performance driven tender specifications allowing the bidding contractor to search for the best price/quality design to offer to the PWO, of course all within stringent RAMS specifications.

## 2 METRO LISBON RED LINE EXTENSION

This paper describes the FST designs and related works within the framework of the 2,21 km Red Line extension (construction period 2008-2010) for Metro Lisboa (ML) in Portugal. The Red Line Tunnel extension passes through a part of the city with low background N&V ( $v_{rms} < 10E-6$  m/s) and close to buildings with severe N&V criteria See Figure 1 for a map of the city with indication of the Red Line Extension and the location of the different types of mitigation solutions.

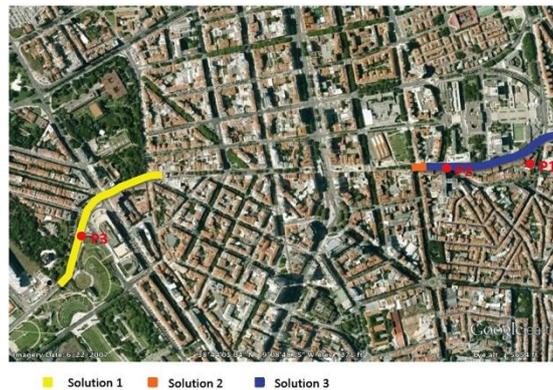


Figure 1. Location of different mitigation solutions applied on the Red Line Extension

Considering these parameters, ML requested in-depth study to make sure that the new line met the following N&V criteria

- For residential houses:  $v_{rms} < 30E-6$  m/s,
- For buildings within the Instituto Superior Técnico (IST) grounds, the equipment manufacturer recommended  $v_{peak-to-peak}$  limits ranging from 1 to  $5E-6$  m/sec (for highly sensitive equipment). IST finally imposed that  $v_{rms}$  levels due to train passage may not exceed the background vibration levels. The study defined different N&V isolated track solutions ranging from 30 dBV to 35 dBV average insertion loss in the 20-200 Hz. frequency range (see Table 1).

Solution Type	Average Insertion Loss
1	30 dBv

2 (transition zones)	30-35 dBv
3	35 dBv

*Table 1 Average insertion loss in the 20-200Hz frequency range for the different mitigation solutions*

The interesting part of this project is that in a same project various FST designs are implemented ranging from (1) resilient mats with adaptable stiffness to (2) discrete supported systems (pads and strips). An extensive vibration measurement campaign (see ref. [6]) allowed confronting design and reality with interesting conclusions for future FST design and a posterior control in operation.

Typical track cross sections of above FST designs are detailed in Figure 4 and Figure 6.

### 3 DEFINITION OF THE DIFFERENT FST SOLUTIONS

#### 3.1 The General Outline

It is now state-of-the-art to design track vibration mitigation systems by use of the insertion loss (IL) philosophy. The essence of this philosophy is to compute a resulting dynamic engineering parameter (such as point mobility, force, ...) as output of certain mathematical model (such as FEM, multi-DOF,...) under unit dynamic force excitation and compare the results of different model set-ups with defined vibration mitigation systems with a reference system without vibration mitigation. The technique has evolved in the recent years and is now widely accepted and referred to in recent norms and guidelines (see e.g. Ref. [2] and Ref.[5]).

#### 3.2 Specific Designs For ML

In order to come to solutions for the different ML FST solutions, the 4DOF model IL approach was used (see Ref.[2], Figure 2). The different solutions all consisted of a floating slab track (FST) supported by different support systems each characterised by the equivalent dynamic bedding module  $c_{\text{dyn-eq}}$  (unit [MN/m/m<sup>2</sup>]). The equivalent dynamic bedding module is obtained:

- For full surface mats:  $c_{\text{eq}}$  is the equivalent bedding module per trackslab surface unit ( $[c_{\text{eq}}] = \text{MN/m/m}^2$ ), which is the combination of all stiffness components acting in the vertical direction concentrated under the track slab surface ( $S_h$ ) being
  - Vertical stiffness of the mats on the horizontal surface per separate trackslab-length ( $S_h$ ):  $c_{v,S_h}$  measured via compression testing on a 300x300 mm<sup>2</sup> sample further to specs imposed by the PWO and depending on imposed load window (like eg. DIN-45673/7-2010)
  - Vertical stiffness of the lateral isolation mats on the vertical upstands per separate trackslab-length ( $S_v$ ):  $c_{v,S_v}$  mostly extrapolated from shear measurements on samples further to a predefined norm -  $c_{v,S_v} = [S_v * G]/t$  ( $G =$  shear modulus,  $t =$  thickness of the mat)
  - Total equivalent bedding module is then :
$$c_{\text{eq}} = [S_h * c_{v,S_h} + S_v * c_{v,S_v}] / S_h$$
- For discrete bearings: the equivalent bedding module per trackslab surface unit is the same combination of the stiffness components as defined for full surface mats, but the stiffness components are defined by discrete bearings with individual stiffness distributed over  $S_h$  and  $S_v$ .
  - Vertical stiffness of the discrete bearings ( $C_{v,S_h}$ ) distributed over the contact surface  $S_h$ , providing on the horizontal surface per separate trackslab-length ( $S_h$ ):
$$c_{v,S_h} = C_{v,S_h} * \text{NHB},$$
With NHB = # resilient bearings on contact surface  $S_h$  per surface unit
$$C_{v,S_h}$$
 is measured further to specs imposed by the PWO (like eg. DIN-45673/7-2010). Attention: load window on the resilient material is function of NHB and permanent and live load conditions, hence each new NHB demands new test program to define  $C_{v,S_h}$
  - Vertical stiffness of the lateral bearings ( $C_{v,S_v}$ ) distributed over the total lateral contact (if any !!) surface ( $S_v$ ) / vertical upstands per separate trackslab-length :
$$c_{v,S_v} = C_{v,S_v} * \text{NVB}$$

With  $NVB = \#$  resilient bearings on contact surface  $S_v$  per surface unit

- Total equivalent bedding module is then:

$$c_{eq} = [S_h * c_{v,Sh} + S_v * c_{v,Sv}] / S_h$$

- Recommended values for  $c_{v,Sv}$  :

For a safe and N&V optimised FST design, it is recommended to limit the stiffness component brought by the lateral support elements on upstands (lateral track stability!!) to  $< 10\%$  of the stiffness component brought by the resilient elements below the slab

$$c_{v,Sv} < 0.10 * S_h / S_v * c_{v,Sh}$$

### 3.3 Typical Track Design And Model Parameters

- Rail 50E1 (U50)
- Booted twin block ties :  $C_{stat,rail\ pad} = 80 \text{ MN/m}$  (dyn.180 MN/m) -  $C_{stat,sleeper\ pad} = 10 \text{ MN/m}$  (dyn.27 MN/m)
- Distance between ties = 750 mm
- Axle load 100.8 kN (non-supported mass 15% of axle load)
- Axle/Axle distance: 2100 mm
- Smallest Bo/Bo distance : 11100 mm
- Typical 500 mm. Thick Reinforced Concrete (RC) slab with a width of 3750mm for solution 1 and 2750 mm for FST on discrete bearings (solutions 2 & 3)
- Resilient support systems for the slab each characterized by their specific equivalent bedding module (static and dynamic) see Table 2 for maximum equivalent dynamic bedding moduli
- Stiff tunnel invert
- Design speed 60 kph
- Maximum elevation 150.mm
- Minimum radius 100 m.

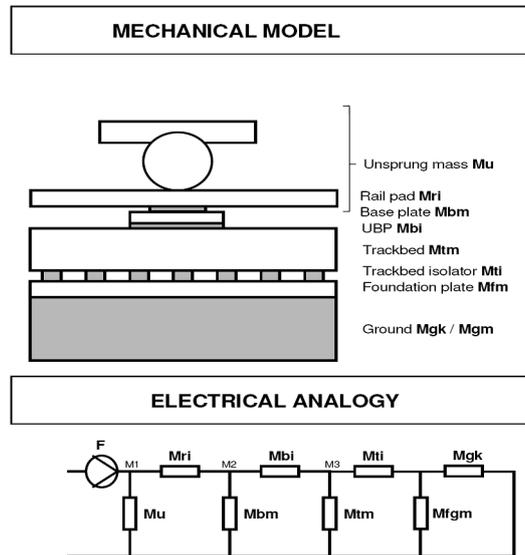


Figure 2 : 4DOF mechanical model / electrical analogy

As a result of the calculations using the 4DOF model (see Figure 2), the maximum equivalent dynamic bedding modules were defined to meet the minimum IL requirements. Table 2 gives an overview of the maximum equivalent dynamic bedding modules to be introduced to meet IL requirements

Solu tion	$c_{eq,dyn}$ (MN/m/)	Typical Resilient Support System
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	m <sup>2</sup> )	
1	< 17	CDM-TOMAS-M8/RR
2	< 18	CDM-FSP-M10/RR
3	< 7	CDM-FSP-M9/RR

Table 2. Maximum equivalent dynamic bedding modulus for the different mitigation solutions

## 4 RESILIENT SUPPORT MATERIALS DESCRIPTION

### 4.1 Resilient Material Choice

Based upon the last decades evolution in resilient material technology to be applied in difficult and harsh conditions in tunnels as to temperature, humidity and chemical environment, it was decided to use microcellular resilient materials from the CDM-RR-range (high quality resin bonded rubber granules), known for their better resistance to most common destructive agents found in tunnels (immersion, pH, temperature, etc.) with proven track record since late 1990s (see eg. Ref. [1], Ref. [3], Ref.[4], Ref.[7]). In this particular project, there are essentially 2 technologies of FST resilient support systems used.

### 4.2 Solution 1 ó CDM-TOMAS Technology: Resilient Mats With Adaptable Stiffness

This technology is typically a hybrid solution between proper resilient surface mats (CDM-FSM) and discrete bearings techniques (see solution 2 & 3). It combines ease of installation as a surface mat (with integrated formwork) with the possibility to adapt and optimize the stiffness. From the range of CDM-TOMAS solutions was chosen CDM-TOMAS-M8, with  $c_{eq,dyn} = 17\text{MN/m/m}^2$  (including influence of vertical upstands)

Figure 3 shows the different steps of the production process.

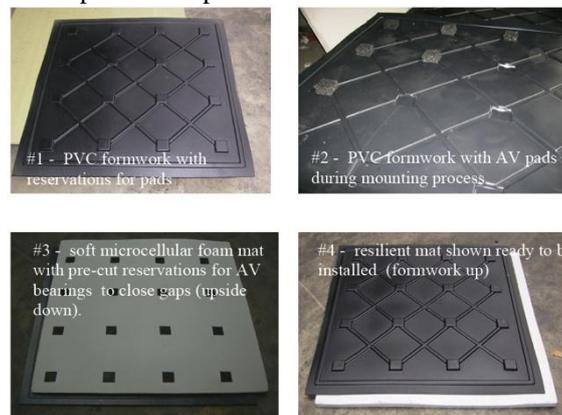


Figure 3 : Details of solution 3: CDM-TOMAS technology

A typical cross section of solution 3 is depicted in Figure 4:

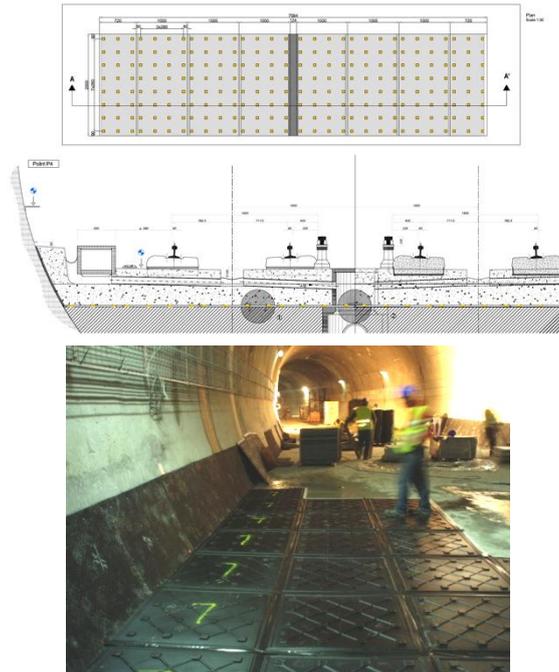


Figure 4 : Typical FST cross section and layout with CDM-TOMAS

### 4.3 Solution 2&3 ó CDM-FSP Technology: Discrete Resilient Bearings (Natural Rubber, Springs, Cork & Rubber, PUR Foam Pads, Resin Bonded Rubber).

#### 4.3.1 General description

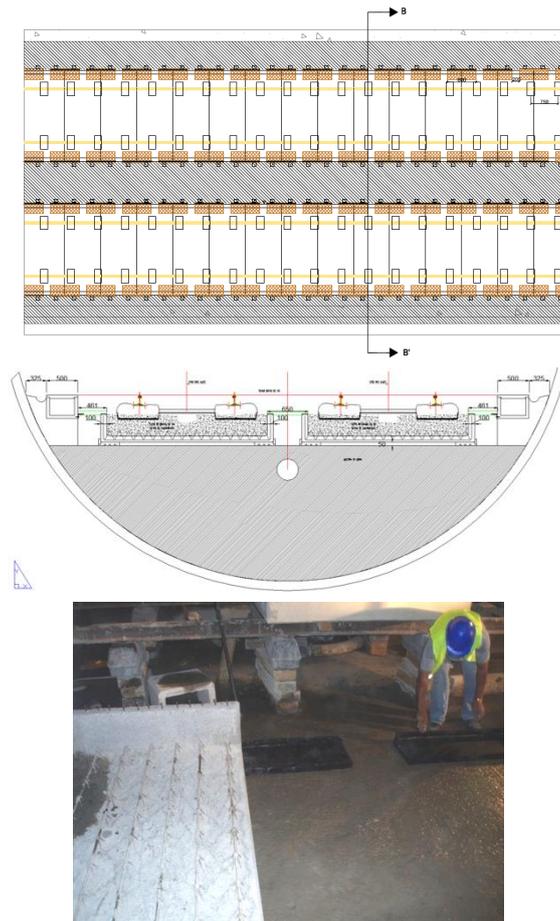
This technology is probably the oldest known track vibration mitigation technology, because it is the technology allowing to reach the lowest possible equivalent bedding modules with adaptable stiffness (eg in curves with cant, transition zones, ...). The main disadvantage of this technology is the more complex installation process, the need for reinforcement of the concrete to span the distance between the different bearings and less lateral stability (need for lateral restraint bearings depending on type of resilient material and lateral loads at stake). For the ML-project, CDM-FSP/RR bearing pads were used

Figure 5 shows the some details of the CDM-FSP bearings. The bearings (300x1250x50 mm) were designed with water evacuation grooves at the bottom of the bearings and with an L-shaped upstand to lock them in place, left and right of the track slab. (Technology developed in the re-engineering process of Linha 3 ó MSP see also ref. [1]).



Figure 5 : Details of FST with discrete AV bearings

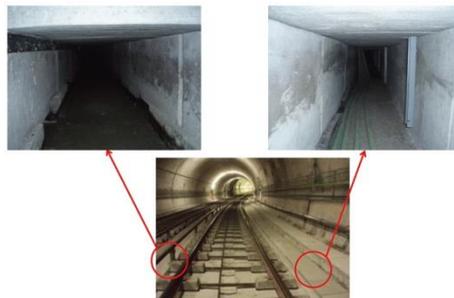
A typical cross section of solution 2 and 3 is depicted in Figure 6.



*Figure 6 : Typical FST cross section and layout with CDM-FSP discrete bearings*

For the ML-project, prefabricated elements were used (see Figure 6) to ease the installation of the track. The AV bearings were distributed evenly (every 1.8m, 2 bearings) on the tunnel invert. The prefabricated concrete U-troughs (Length of 1.8m, with reinforcement bars sticking out on the inside of concrete troughs) were laid down on top of the AV bearings. The classic ML bi-block track system was installed, the rails aligned, and the concrete poured inside the troughs to fix the bi-block system and to create one long continuous slab.

Access to the bearings has been foreseen, to allow inspection and eventual replacement of the bearings if necessary (see Figure 7)



*Figure 7 : Details of access to the elastomer bearings*

#### **4.3.2 Solution 3A: FST on straight line**

This FST is supported by

- CDM-FSP-M9/RR system, made from CDM-RR family (resin-bonded rubber), Distribution NHB = 0.4/m<sup>2</sup> (2 strips per 1.8 m and 2.75 m. width).
- Bedding module CDM-DFSA-M9 = 25 MN/m<sup>3</sup> +/- 20%.
- For a length of 1.8 m, the equivalent stiffness = 2 strips x (25 MN/m<sup>3</sup> x (1.25 x 0.30)) = 18.75 MN/m.

- This *support stiffness* of 18.75 MN/m gives an *equivalent static bedding module* (18.75 MN/m) / (2.75 x 1.8) = 3.78 MN/m<sup>3</sup> (3.5 MN/m<sup>3</sup> ± 20 %).
- So  $c_{eq,stat} > 3.5 \text{ MN/m/m}^2$  and  $c_{eq,dyn} < 7.0 \text{ MN/m/m}^2$
- In longitudinal direction, there is a space of approximately 550 mm between the strips to allow air circulation and allow installation of lifting equipment to replace the strips, if necessary.

### 4.3.3 Solution 3B: FST slab in curve

For FST in curve, the length of the prefab formwork troughs was reduced from 1.8 m. to 0.9 m in order to limit the gap between to prefab elements when installed in curve. This floating slab is supported by resilient L-shaped strips 300x625x50mm (#2/0.9lmst), type CDM-DFSA-M9/RR. These strips are made of CDM-RR (resin-bonded rubber) material and have an equivalent static stiffness of about 3.5 MN/m<sup>3</sup> (for a slab width of 2,75 m). In longitudinal direction, there is a space of approximately 275 mm between the strips to allow air circulation and allow installation of lifting equipment to replace the strips.

### 4.3.4 Solution 2: Transition zone

Since the track resilience ratio between the FST zones and the typical standard ML track system is more than 2, there is need for a transition zone. The minimum length of the transition zone is further to UIC formula ( $L=0.5 \text{ sec} * \text{design speed} = 8.5 \text{ m.}$ ). In the project the transition zone length was fixed to be 10 m. It was materialized at both limits of solution 3 zone, by elastomer bearing strips with same dimensions of 300x1250x50 mm with an adjustable stiffness. All these transition zones are in straight line. This floating slab is supported by resilient L-shaped strips 300x1250x50mm (#2/1.8lmst), type CDM-FSP-M10/RR. These strips are made of CDM-RR (resin-bonded rubber) material and have an equivalent static stiffness of about 9 MN/m<sup>3</sup> (against 3.5 MN/m<sup>3</sup> for the connecting 3A zone). In longitudinal direction, there is a space of approximately 550 mm between the strips to allow air circulation and allow installation of lifting equipment to replace the strips.

### 4.3.5 Lateral stability calculations for solution 2&3

#### Inertia mass of floating slab

Considering a reinforced concrete with mass density 2.5 t/m<sup>3</sup>, the inertia mass of the different FSP solutions:

- Solution 3A: 3.09 t/m → Gravity force per linear meter:  $F_g^{slab} = 30.9 \text{ kN/m}$
- Solution 3B: 3.609 t/m →  $F_g^{slab} = 36.09 \text{ kN/m}$
- 

This results in a difference of inertia mass of +16 %.

#### Centrifugal force per linear meter of track

The centrifugal force may be calculated as follows

$$F_c = \frac{m \times v^2}{R} = \frac{2457 \text{ kg} \times 20^2}{100} = 9.8 \text{ kN/m}$$

with

- Mass of rolling stock (max. 40.32T/car ó length 16.41 m. ) per linear meter : 2457 kg/m →  $F_{RS} = 24.57 \text{ kN/m}$
- Maximum speed in elevation  $v = 60 \text{ kph} + 20\% \text{ safety} \rightarrow v = 72 \text{ km/h} = 20 \text{ m/s}$
- Minimum radius:  $R = 100 \text{ m}$

#### Force distribution in the curve (see Figure 8)

The resulting horizontal and vertical forces per linear meter of single track, on the level of the AV bearings, are:

$$\begin{cases} F_H = F_c \times \cos(6^\circ) = 9.74 \text{ kN/m} \\ F_V = F_g^{slab} + F_{RS} - F_c \times \sin(6^\circ) = 59.63 \text{ kN/m} \end{cases}$$

(The gravity force on the rolling stock and on the slab is considered to be in the same axis to simplify the calculation)

The center of gravity is given by:

$$x_c = \left( \frac{x_1 A_1 + x_2 A_2}{A} \right) = 1.492 \text{ m}$$

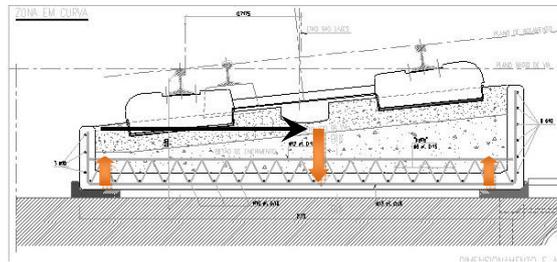


Figure 8 : Typical FST Cross Section on Bearings in Curve

Due to the asymmetric location of the centre of gravity, the vertical force  $F_v$  is unequally distributed over the 2 supports. The reaction force of the left support (inner side of the curve) and the reaction force of the right support (outer side of the curve) are:

$$\begin{cases} F_v = F_L + F_R = 59.63 \text{ kN/m} \\ M_L = 0 \Rightarrow F_R \times x_R - F_v \times x_c = 0 \end{cases}$$

$$\Leftrightarrow \begin{cases} F_R = 32.35 \text{ kN/m} \\ F_L = 27.28 \text{ kN/m} \end{cases}$$

Thus, the force on the right support is 18 % higher.

This load difference results in a different vertical deflection on the left and right side of the track. In order to estimate the deflection on the strips, we consider the forces on 0.9 m, and not on 1 m.

$$\begin{cases} \delta_R = \frac{F_R}{K_v} = 3.10 \text{ mm} \\ \delta_L = \frac{F_L}{K_v} = 2.61 \text{ mm} \end{cases}$$

The difference between  $\delta_R$  and  $\delta_L$  is 0.49 mm and may be considered small enough not to justify any alternate strip design for the load bearing supports on the high end of the curve.

## Horizontal displacement in longitudinal track direction

Considering the emergency break of a full train ( $a=2.2 \text{ m/s}^2$ ) and taking into account a track section of 120 m (single pouring of the concrete in one time) , a total train length 49.23 m and total max. train mass  $m_{RS} = 112.24$  tons

$$F_H = m_{RS} \times a = 247 \text{ kN}$$

The relevant lateral stiffness resisting the forces

$$\begin{aligned} K_H &= \frac{G \times S}{H} \\ &= \frac{0.65 \times 10^6 \times (1.25 \times 0.3) \times 2 \times \frac{1}{1.8} \times 120 \text{ (m)}}{0.05} \\ &= 650.10^6 \text{ N/m} \end{aligned}$$

(  $G = 0.65 \text{ MN/m}^2$ )

This results in a horizontal deflection:

$$\delta_H = \frac{F_H}{K_H} = \frac{247 \text{ kN}}{650000 \text{ kN/m}} = 0.38 \text{ mm}$$

## Horizontal displacement perpendicular to track direction

To calculate the lateral displacement due to the force in curve, use is made of the *Prudhomme criterion* (see ref. [8] 6 pag.406-407)) which takes into account the total lateral force as a worst-case scenario.

Lateral resistance

$$H \geq \frac{P}{3} + 10 \text{ for each axle}$$

For a length of 16.41 m (succession of 2 bogies) we have, with an axle load of 100.8 kN/axle

$$F_H = \left( \frac{100.8}{3} + 10 \right) \times 4 \text{ axles} = 174.4 \text{ kN}$$

This force is applied on 16.41 m, meaning that all the strips in the curve will have to be considered for a length of 16.41 m.

$$\begin{aligned} K_H &= \frac{G \times S}{H} \\ &= \frac{0.65 \times 10^6 \times (0.625 \times 0.3) \times 2 \times \frac{1}{0.9} \times 16.41 \text{ (m)}}{0.05} \\ &= 88,88 \times 10^6 \text{ N/m} \end{aligned}$$

(G = 0.65 MN/m<sup>2</sup>)

Resulting in a horizontal (lateral) displacement of

$$\delta_H = \frac{F_H}{K_H} = \frac{174.4 \text{ kN}}{88.88 \times 10^3 \text{ kN/m}} = 1.962 \text{ mm}$$

Which is OK when compared to the max allowable lateral displacement for a 50 mm high elastomer bearing (lateral stability criterion)

$$\delta_H = 1.96 < \frac{H}{3} = 16.66$$

The elastomer bearing is therefore considered to be sufficiently stable against lateral sway and no lateral buffer is required.

## 5 NOISE & VIBRATION MEASUREMENT CAMPAIGN AND results

In order to evaluate the performance of the different solutions, a measurement campaign was done early 2011 (3 months after start of the operations ó ref. [6]).

### 5.1 Vertical Vibration On Trackbed And Invert (Transmission Loss):

2 different techniques were used to measure simultaneously the vertical vibration on the trackbed and invert:

- Measurements under normal circulation of trains (average of 5 to 10 metro train passages).  
Attention:
  - Additional measurement points were taken in the Blue Line (see Table 3) in zones with classic ML track infrastructure (non-isolated track) so as to have a reference track condition to compare the vrms on the invert for the different mitigation interventions.
  - Rail Roughness: further to Metro Lisbon, the track was recently ground, so that it may be considered that rail roughness was for all cases reasonably similar.
  - Rolling Stock speed (see Table 3): was for all cases between 45 and 60 kph. In the analysis we have not taken into account possible differences in vibrations due to speed, who may add up to approx. 1 to 2.
  - The highest injection of vibration energy by the rolling stock was found around 63Hz
- Measurements under mechanical impulses on the rails using a falling mass of 6 kg

### 5.2 Vertical Vibrations In The Buildings Nearly Vertical Above And Closest To The Tunnel

Vertical vibrations were measured in the building near to the tunnel at several locations. Figure 9 shows the 3 measurement points (P1, P2, P3) along the Red Line. In the Blue Line (connection with Red Line in S. Sebastião

Station), additional measurements were done to allow comparison with the reference track. Table 3 shows an overview of all the measurement points and special conditions linked to each of them.



Figure 9 : Location of the measurement points along the Red Line

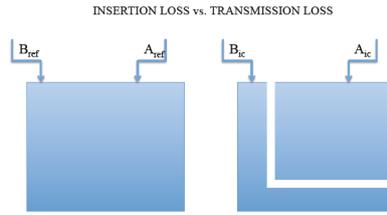
	Point	Local Conditions	N&V Solution	Train speed
Alameda ó S. Sebastião (Red Line)	P1	Near old tunnel entrance	3	60 kph
	P2	Near transition	3	60 kph
	P3	Reduced speed ó switch	1	45 kph
Sta. Apolónia - S. Sebastião (Blue Line)	P4	Reinforced tunnel ó curve	1	45 kph
	EXTRA	Near transition	ML Reference Track	45 kph

Table 3. Measurements overview and associated special conditions

### 5.3 Measurement Results

#### 5.3.1 Considerations regarding ãInsertion Loss/Insertion Gainã (IL/IG) vs ãTransmission Lossã (TL)

Figure 10 shows a typical set-up of a reference and isolated situation.



**Figure 10. Typical set-up of isolated and non-isolated track**

Insertion Loss (IL) (some authors use the term Insertion Gain in order to make a ñegative lossö have a õpositiveö connotation) is defined as

$$IL_{ic} = 20 \cdot \log (B_{ic} / B_{ref}) \text{ (if } B_{ic} < B_{ref} \text{ i.e. isolation } \Rightarrow IL_{ic} < 0 \text{ so negative value!)}$$

Whereas Transmission Loss (TL) is defined as (for reference or for isolated case)

$$TL = 20 \cdot \log (A / B)$$

It is less time-consuming and complex to measure TL than IL. Measuring IL requires, to be 100% correct, that: (1) the reference case is measured on the exact location where the isolated case will be built (in order to have the exact same boundary conditions) (2) the isolated case is built on that location (3) the isolated case is measured on the same location. In practice this is hardly feasible and IL is therefore measured mostly by comparing 2 similar locations (assuming same boundary conditions), of which one is the reference and the other the isolated case. TL, on the other hand, is easier to evaluate and to measure.

The difference between both IL and TL can be appreciated as follows

$$TL_{ic} = 20 \cdot \log (A_{ic} / B_{ic})$$

$$TL_{ref} = 20 \cdot \log (A_{ref} / B_{ref})$$

$$\begin{aligned} \hat{e} TL &= (TL_{ic} - TL_{ref}) \\ &= 20 \log (A_{ic} / B_{ic}) - 20 \log (A_{ref} / B_{ref}) \\ &= 20 \log (A_{ic} / A_{ref}) - IL_{ic} \end{aligned}$$

As a result

$$IL_{ic} = 20 \log (A_{ic} / A_{ref}) - \hat{e} TL$$

If distance between A and B locations is not important, it may be considered  $A_{ref} \approx B_{ref}$ , so  $\hat{e} TL \approx TL_{ic}$ . Considering that the introduced energy levels  $E_{ic}$  et  $E_{ref}$  may be kept reasonably identical, it may be assumed that  $A_{ref} / A_{ic}$  is proportional to  $(f_{ic} / f_{ref})^2$  at higher frequencies ( $f > 50-63$  Hz.),  $f_{ref}$  being the base resonance frequency of the reference case and  $f_{ic}$  the base resonance frequency of the isolated case.

$$\text{So, } IL_{ic} \approx 40 \log (f_{ref} / f_{ic}) - TL_{ic}$$

In FST cases compared to non FST cases (with  $f_{ref} > f_{ic}$ ), the  $f_{ref} / f_{ic}$  ratio can vary considerably up to a factor approx. 5. Considering therefore a correction factor  $40 \log (f_{ref} / f_{ic}) < 30$  dBV, it may be stated that  $TL_{ic}$  measurements gives at higher frequencies ( $f > 50-63$  Hz.) a good indication of FST mitigation performance.

### 5.3.2 Considerations regarding base resonance frequencies

The most recent DIN-45673 norm (ref.[5]) , defines ways to evaluate the base resonance frequency of track infrastructure systems essentially modeled as a single degree of freedom system. Application of this approach to the different cases in this project is summarized in Table 4.

Parameter	Unit	ML ref.	Sol 1	Sol 3
$C_{dyn,eq} \text{ (max)}^{(1)}$	MN/m	27.0	17.0	18.8

Total Mass <sup>(2)</sup>	kg	450	1400	3372
$f_{res}$ <sup>(3)</sup>	Hz	39.0	17.5	11.9
$I_L$ @ 63Hz <sup>(4)</sup>	dBV	-8.3	-22.3	-29.0
Calculated correction factor <sup>(5)</sup>	dBV	-	13.9	20.6
Estimated $T_L$ <sup>(6)</sup>	dBV	-	36.2	49.6
Measured $T_L$ <sup>(7)</sup>	dBV	-	32.0	45.0
Variation Estimated vs Measured $T_L$	%	-	12.0	9.0

(1) per booted twin-block system, CDM-FSP bearing or CDM-TOMAS panel

(2) Inertia + non-suspended mass

(3) As calculated by DIN-45673 norm (ref.[5])

(4)  $I_L = 40 \log(f_{res}/63)$

(5) Correction factor =  $40 \log(f_{res\_ref}/f_{res\_sol})$

(6)  $T_L = 40 \log(f_{res\_ref}/f_{res\_sol}) - I_L$

(7) See figure 12

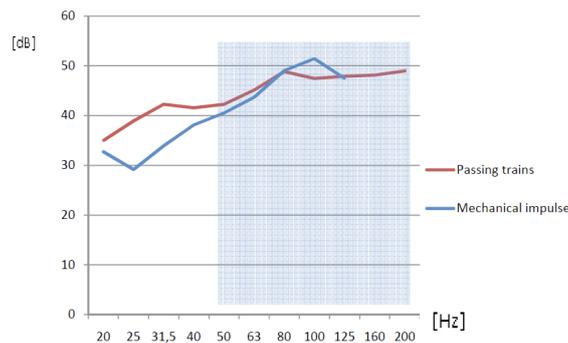
**Table 4.  $I_L$  vs  $T_L$  relationship**

It can be appreciated from Table 4, that the calculated transmission loss gives a reasonable good correlation with the measured transmission loss (difference < 15%), which supports the statement that for higher frequencies  $T_L$  measurements give a good indication of FST mitigation performance, considering a correction factor of  $40 \log(f_{ref}/f_{ic})$ .

### 5.3.3 Transmission losses ( $TL_{ic}$ )

As an example, the transmission loss measurements (comparison between the simultaneous vibration signals on trackbed ( $A_{ic}$ ) and invert ( $B_{ic}$ ) for solution 3 are shown in Figure 11.

It is noted that both excitation techniques (passing trains and impact hammer) to measure  $TL$  give reasonably good coherence starting from higher frequencies ( $f > 50-63$  Hz.)



**Figure 11 : Average transmission loss  $\delta$  Point 1 - comparison between passing train and mechanical impulse values**

Figure 12 shows the average transmission loss under passing train for the different solutions.

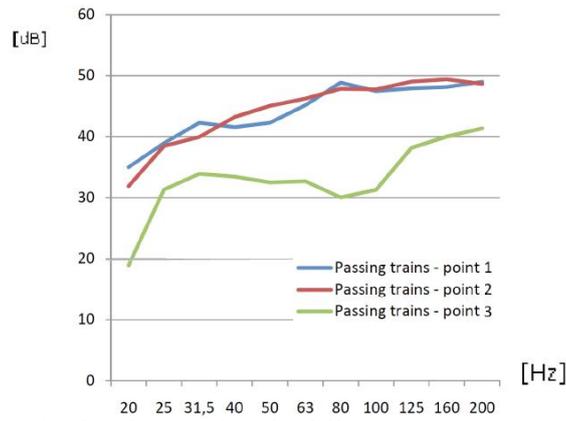


Figure 12 : Average transmission loss  $\delta$  comparison for different measurement points under passing trains.

### 5.3.4 Insertion loss

Figure 13 shows an estimate measured IL values for all introduced FST mitigation systems. They are measured by comparing the vibration levels on the tunnel invert ( $B_{ic}$ ) for the different cases in comparison to vibration level on the tunnel invert for the reference track ( $B_{ref}$ ), without taking into consideration any correction for difference in speed (45 kph in some cases and 60 kph in other cases - see Table 3). As was previously indicated in this paper, the IL curves shown in Figure 13 are only an approximation of the real insertion loss, as they were obtained comparing vibration levels at 2 different locations (assuming the same boundary conditions).

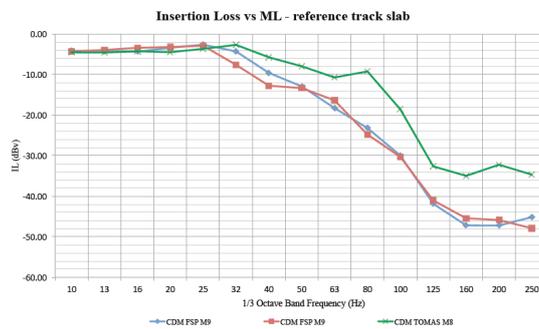


Figure 13. Insertion loss of the different mitigation systems compared to the ML reference track slab

### 5.3.5 Exterior Vibrations

Table 5 represents the global results of the various measurements made outside the tunnel, reflecting the absolute vibration levels for the surrounding buildings. More detailed information and graphs are available upon demand.

	<b>Residual vibration</b>	<b>Vibration during train passages</b>	<b>Vibration Exceedence vs. Residual</b>
	<b>v<sub>rms</sub></b>	<b>v<sub>rms</sub></b>	<b>dBv</b>
	<b>(m/sec)</b>	<b>(m/sec)</b>	<b>(ref 1E- 9m/sec)</b>
P1	2.1 E-6	2.1 E-6	0.0
P2	2.1 E-6	2.2 E-6	+0.4
P3	1.9 E-6	2.7 E-6	+3.0
P4	2.6 E-6	2.8 E-6	+0.6

*Table 5 Absolute vibrations levels measured in the surrounding buildings*

The exterior vibration measurements results are in accordance to the ML recommended limit of 30E-6 m/s and have confirmed the reaction of neighbors, in the sense that the metro trains were not noticeable.

## 6 CONCLUSIONS

In this paper a comprehensive overview is presented of the introduction of different FST systems in the recent extension of the Red Line of the Metro Lisbon.

The different FST systems were described in terms of their respective dynamic performance characteristics and engineering detailing for their implementation.

The executed vibration measurements campaign, which is part of the quality insurance program imposed by Metro of Lisbon, has allowed drawing the following conclusions

- The dynamic characterization of resilient materials in terms of dynamic stiffness is the basis to predict the vibration isolation performance of track systems integrating said resilient materials.
- TL measurements with impact hammer on FST show quite good correlation with transmission loss measurements under passing trains for frequencies > 50-63 Hz.
- TL measurements are easier and less complex to proceed with than IL measurements. For higher frequencies (> 50-63Hz), it is shown that by applying a correction factor based upon the ratio of the base resonance frequencies  $f_{ref}$  and  $f_{ic}$ , calculated by use of the SDOF model suggested by the most recent version of DIN-45673, it is possible to have a reasonable approximation of the IL performance of an installed FST system, creating as such an easy and more cost efficient procedure for FST performance check as part of a quality insurance program.
- The installed FST vibration mitigation systems, ranging from resilient surface mats to discrete resilient supports with varying dynamic stiffness performance characteristics show good correlation with predicted performance, the most performing vibration mitigation system remaining the FST on discrete resilient supports.
- The installed FST vibration mitigation systems have proven to be effective in mitigating the vibrations in the surrounding buildings during train passage

The design of the FST on discrete bearings (CDM-FSP) gives Metro of Lisbon the possibility to inspect the resilient bearings and if needed to replace them. The elastomer bearings in this system were designed as such to be sufficiently stable against lateral sway so that no lateral buffers are required, consequently reducing the overall installation costs.

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