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The development of the vibration control objectives at Metro de Santiago

Edgardo González

Universidad de Chile

Abstract

This paper describes how the Santiago Metro has been addressing vibration control objectives on its last three lines, two of which, Line 6 and Line 3, are currently in operation, while the third, Line 7, which has just started construction (2022), will start operating in 2027. The Line 6 and Line 3 projects established ground-borne vibration control only, while the Line 7 project has established ground-borne vibration control and ground-borne noise control. To establish of the maximum levels in each case, different regulations were considered. This paper is based on the information that Santiago Metro has provided through the Environmental Impact Assessment System of Chile (SEIA) for the three lines, whose environmental processes are public.

Keywords: subway vibrations, ground-borne vibration, ground-borne noise, vibration control.

1 Introduction

The current network of the Santiago Metro is 140 km, distributed in 6 lines and 136 stations, 34 of which conform 17 transfer stations. The railway track support is concrete slab in all network [1, 2, 3]. In structural terms, the network has been built approximately like 15 % open trench, 15 % closed trench (underground), 15 % elevated viaduct and 55 % underground tunnel [4]. Table 1 shows more information.

A new line, Line 7, which has just started construction (2022), will start operating in 2027 [5]. Figure 1 shows Santiago Metro network towards 2027 [6].

Line	Start of operating	Length	Stations number	Type of roll
1	1975	20.4 km	27	Rubber tires
2	1978	20.7 km	22	
5	1997	30.0 km	30	
4	2005	24.7 km	23	Steel wheels
4A	2006	7.7 km	6	
6	2017	15.3 km	10	
3	2019	21.2 km	18	

Table 1: Santiago Metro current network.

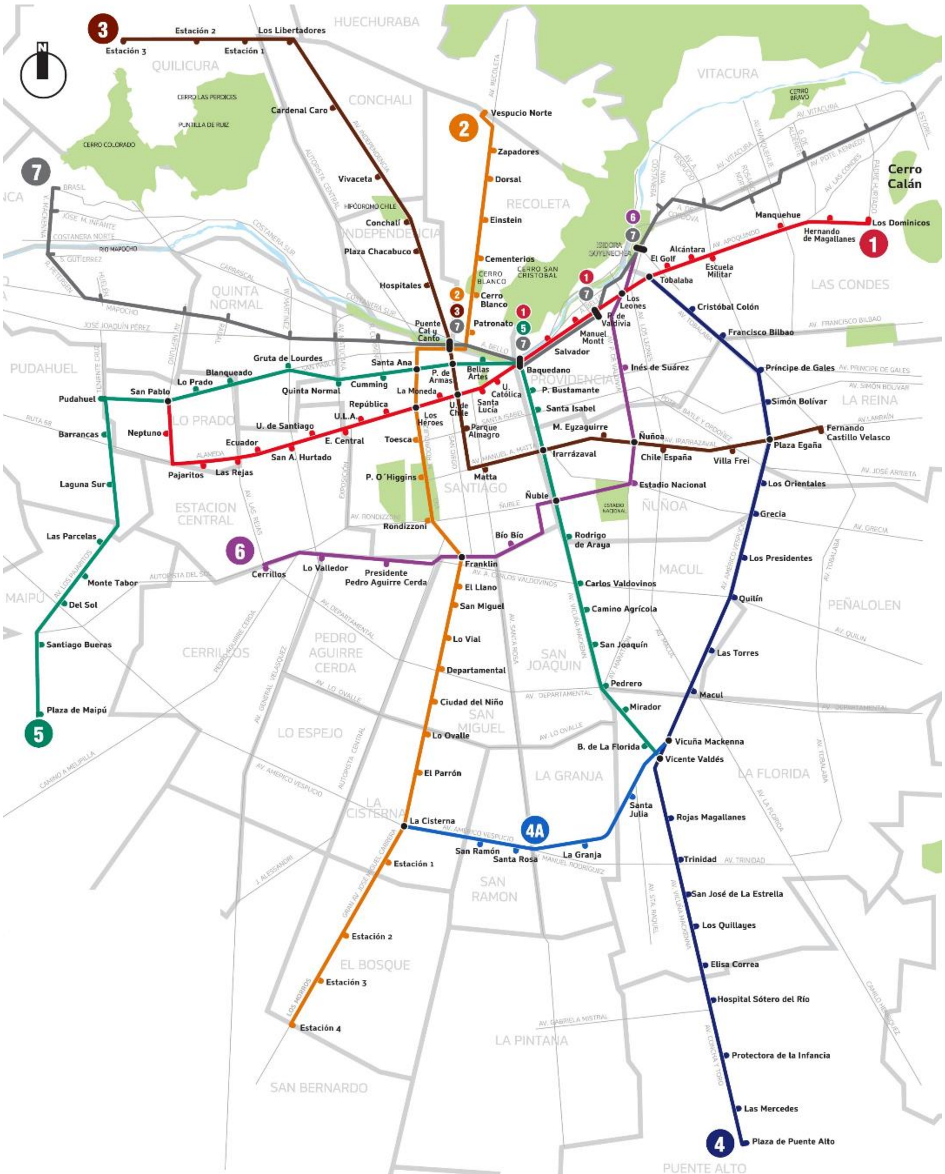

Figure 1: Santiago Metro network towards 2027.

Line 7, which has been designed with railway tracks supported on concrete slabs and trains with steel wheels, will add 25.9 km of underground tunnel and 19 stations to the network, forming two new transfer stations and the first two triple transfer stations. Line 7 project includes the Line 6 Extension to the East project, which will add 1.0 km and one station to the network.

Figure 1 includes Line 2 Extension and Line 3 Extension projects, both under current construction [7,8]. Both extensions will add 8.6 km of underground tunnel and seven stations to the network, which will start operating in 2023. Figure 1 doesn´t included the Line 6 Extension to West, recent project which will add 2.8 km and one station to the network [9]. This project will start operating in 2026.

Line 6 and Line 3 projects considered the projection of ground-borne vibration (GBV) levels during operation and established a regulation for the control of the maximum levels [2,3]. Line 7 project has considerate the projection of GBV levels and ground-borne noise (GBN) levels during operation and has established regulations for the control of both maximum levels [5]. Following sections show the vibration guidelines used by the three lines.

2 Methods

Given that Chile doesn´t have specifics regulations on subway vibrations, the owner of each project must propose the use of foreign guidelines to the Environmental Authority. Table 2 shows the guidelines adopted by Santiago Metro for the projection of GBV and GBN levels, for the limits of those levels and for the vibration control objectives [10,11,12].

	Line 6	Line 3	Line 7
GBV	ISO 2631-2:1989 Evaluation of human exposure to whole-body vibration - Part 2: Continuous and shock-induced vibrations in buildings (1 to 80 Hz)		FTA Report No.0123 Transit Noise and Vibration Impact Assessment Manual (USA, 2018)
GBN	Was not considered		EPA Guidelines for the assessment of noise from rail infrastructure (Australia, 2013)

Table 2: Vibration guidelines adopted by Santiago Metro for Lines 6, 3 and 7.

In Line 7 case, for the projection of GBV and GBN levels, Santiago Metro complements FTA with ISO 14837-1:2005 Mechanical vibration - Ground-borne noise and vibration arising from rail systems - Part 1: General guidance [12]. For the GBN limit, Santiago Metro indicates that EPA and FTA establish a limit of 35 dBA for the nocturnal residential condition, but that EPA also provides comments about “how the criteria or limits guidelines must be executed” [12].

Santiago Metro considers a safety factor for the projection of GBV and GBN levels, which applies by adding 8 VdB and 8 dBA to the calculated levels, respectively. Santiago Metro indicates that the safety factor is associated with the uncertainty of the GBV and GBN projection model based on the FTA [12]. To feed this model, Santiago Metro carried out numerous field measurements. These measurements began with the determination of the influence area of the Line 7, where around 4,000 receivers were identified. On these receivers the base line of vibrations and noise was measured, prior clustering and election of the most representative receivers of each cluster. This work also allowed estimating the magnitude of the building vibration response factors (BVR) [12].

Parallel, the execution of the transfer mobility tests was made. The test positions were determined by combining 3 criteria: depth projected of the railway tracks, characteristics of the stratigraphic profile and structural characteristics of the receptors located in the influence area. Using clustering procedures, 20 points were determined for the execution of tests. The estimate of the force density level was based in measurements on the railway tracks and the train circulations of Lines 3 and 6 [12].

3 Results

Tables 3, 4 y 5 show, respectively, the minimum vibration control objectives calculated in Lines 6, 3 and 7 to satisfy the regulatory limits [10,11,12]. Figure 2 [12] complements Table 5. Also, the tables indicated show the vibration control objectives committed by Santiago Metro to the Environmental Authority [2,3,12].

The committed objectives are obviously more demanding than the minimum objectives. The committed objectives are those that Santiago Metro incorporates in its tenders for the design and construction of railway tracks. For this reason, the committed objectives aim to simplify the implementation of vibration control solutions. Figures 3 and 4 [12] allow to understand the difference between both vibration control objectives.

<table>
<tr><th>Minimum vibration control objectives</th><th>Distribution</th><th>Committed vibration control objectives</th></tr>
<tr><td>---</td><td>12,500 m (81.7 %)</td><td>10 VdB</td></tr>
<tr><td>10 VdB (25 Hz - 50 Hz)</td><td>1,800 m (11.8 %)</td><td rowspan="3">20 VdB</td></tr>
<tr><td>10 VdB (25 Hz - 63 Hz)</td><td>550 m (3.6 %)</td></tr>
<tr><td>15 VdB (25 Hz - 63 Hz)</td><td>450 m (2.9 %)</td></tr>
</table>

Table 3: Vibration control objectives, minimum and committed, for Line 6.

<table>
<tr><th>Minimum vibration control objectives</th><th>Distribution</th><th>Committed vibration control objectives</th></tr>
<tr><td>---</td><td>19,050 m (89.8 %)</td><td rowspan="2">10 VdB</td></tr>
<tr><td>5 VdB (31.5 Hz - 50 Hz)</td><td>950 m (4.5 %)</td></tr>
<tr><td>10 VdB (25 Hz - 50 Hz)</td><td>1,100 m (5.2 %)</td><td rowspan="2">20 VdB</td></tr>
<tr><td>10 VdB (20 Hz - 63 Hz)</td><td>100 m (0.5 %)</td></tr>
</table>

Table 4: Vibration control objectives, minimum and committed, for Line 3.

Minimum vibration control objectives	Initial Distribution	Final Distribution	Committed vibration control objectives
$f_0 \leq 50$ Hz	12,830 m	14,280 m (55.0 %)	$f_0 \leq 38$ Hz
$f_0 \leq 38$ Hz	3,200 m		
$f_0 \leq 25$ Hz	1,300 m	3,050 m (11.8 %)	$f_0 \leq 20$ Hz
$f_0 \leq 20$ Hz	2,000 m		
$f_0 \leq 15.1$ Hz	3,350 m	5,300 m (20.5 %)	$f_0 \leq 15.1$ Hz
$f_0 \leq 12$ Hz	2,400 m	2,450 m (9.5 %)	$f_0 \leq 12$ Hz
$f_0 \leq 8$ Hz	820 m	820 m (3.2 %)	$f_0 \leq 8$ Hz

Table 5: Vibration control objectives, minimum and committed, for Line 7.

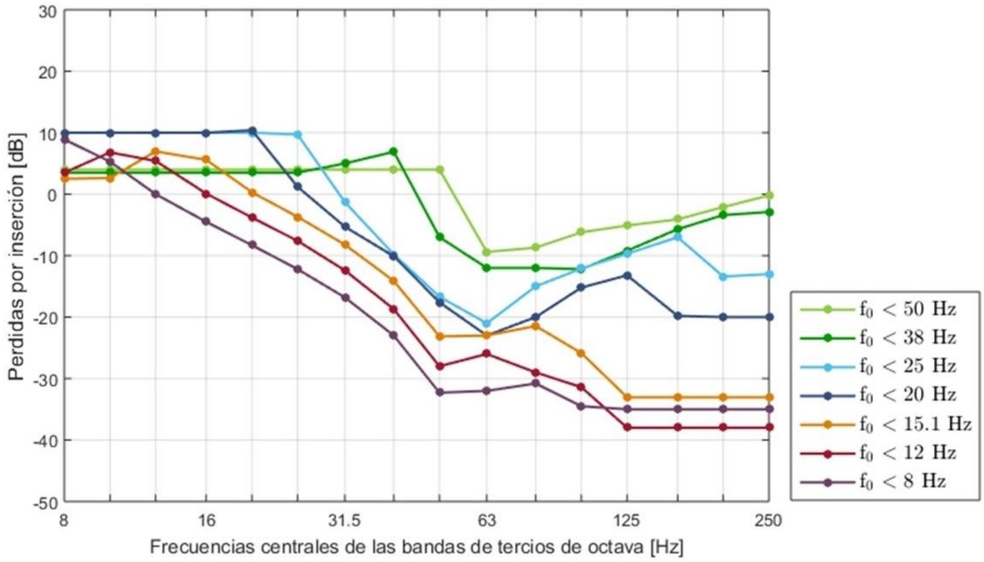

Figure 2: Required insertion loss according to Line 7 vibration control objectives.

Figure 3: Distribution of minimum vibration control objectives calculated on Line 7.

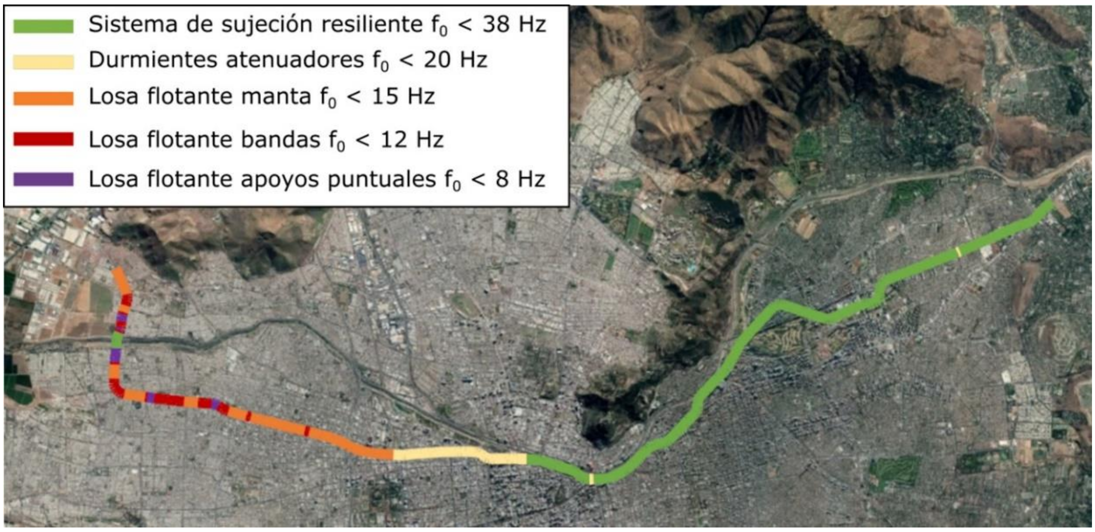

Figure 4: Distribution of committed vibration control objectives on Line 7.

Regarding the vibration control solutions shown in Figure 4, Metro de Santiago establishes that these solutions are only an alternative that satisfies the committed vibration control objectives [12]. The constructor can propose other solutions as long as it satisfies the committed vibration control objectives [12].

4 Conclusions and Contributions

This article highlights how the Santiago Metro has been developing its vibration control objectives. If it is assumed that the site conditions of Line 7 are similar to the site conditions of Lines 3 and 6, as well as the structural conditions of the receivers that are located on these three lines, it is possible to appreciate the influence that the consideration of GBN has on the vibration control objectives. While in Lines 3 and 6 the vibration control level reaches 20 VdB, in Line 7 this value must be exceeded.

Due to the above, Santiago Metro has a great challenge in the construction of vibration control solutions for Line 7. On Lines 3 and 6, Santiago Metro already has experience in the construction of concrete floating slabs on elastic full support. But now on Line 7, it will be necessary to build concrete floating slabs on elastic linear support and elastic point support, which requires more complex construction methods.

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