In Situ Test and Analysis on Ground Vibration and Noise Induced by Tram Passing Small-Radius Curve Track

Deyun Ding and Haiyuan Fang

Abstract In order to explore the characteristics of ground vibration and noise due to tram operation, a small-radius curve section of a trial operation tram line in a city is selected as the test object, as well as a straight-line section. During the in situ test, the same tram is used to run repeatedly at different speeds, and the measured data of ground vibration and noises inside and outside the tram are obtained. The test results show that: (1) The ground vibration acceleration in the small-radius curve section is mainly concentrated between 80 and 400 Hz, and the noise is mainly between 1000 and 8000 Hz, which are both greater than those in the straight-line section. The noise inside the tram is slightly greater than that outside in the frequency band below 630 Hz in the small-radius curve section; but they exchange when it above 630 Hz. In the straight section, the noises inside and outside the tram are basically same. (2) With the increase of the train speed, there is no significant difference in ground vibration below 100 Hz, but above 100 Hz, the maximum vibration difference is between 5 and 8 dB. The maximum increase of noises inside and outside the tram is, respectively, about 6 and 2 dB(A). (3) The ground vibration acceleration level outside the curve is larger than that inside, and the maximum difference is about 15 dB, meanwhile, the noise inside the small-radius curve is greater than that outside, and the maximum difference is about 6 dB(A).

Keywords Tram · Vibration and noise · Small-radius curve track · In situ test

1 Introduction

With the speedy development of urban rail transit in China, tramway as a medium and low volume rail transit has entered a large-scale, high speed and supernormal development period [1, 2]. By the end of December 2017, 20 tramway lines in 14

D. Ding (✉) · H. Fang
Beijing Jiuzhouyigui Shock and Vibration Isolation Technology Co., Ltd., Beijing 100070, China
e-mail: dyding2301@163.com

E. Tutumluer et al. (eds.), *Advances in Environmental Vibration and Transportation Geodynamics*, Lecture Notes in Civil Engineering 66,
https://doi.org/10.1007/978-981-15-2349-6_1

cities or regions have been operated, and the operation mileage is up to 236.14 km. Moreover, more than 39 tramway lines with a total mileage of 620.55 km have been under construction in 22 cities or regions. In addition, according to incomplete statistics, there are more than 565 planning tramway lines in over 100 cities or regions, with a total mileage of 10,378 km.

With the improvement of people's requirement for environmental quality, the vibration and noise induced by tramway operation have attracted increasing attention in recent years [3, 4]. The tramways are built on the arterial roads in cities, which influences on the residents life in the adjacent buildings. So that influence of tramway operation cannot be ignored, especially in the small-radius curve section.

In China, the characteristics of ground vibration and noise caused by tramway passing through small radius section are poorly studied [5, 6]. Based on the in situ test, the characteristics of ground vibration and noise induced by tram operation are revealed in this paper.

2 Project Outline

A selected tram line has a length of 19.592 km and includes a total of 25 stations, and its engineering investment has reached up to 3.11 billion RMB.

The small radius of the main line is equal to 50 m. The type of the track is monolithic bed with no-sleepers, and the thickness of the track bed is 290 mm. The type of rail is 60R2 groove rail, and the elastic material packages are installed at both sides of the rail Web. The CM-A ordinary fasteners are used in the track.

The tram as shown in Fig. 1 is a kind of 100% low floor vehicle, including five modules with three bogies. The full length of the tram is 34.8 m long, and has an

Fig. 1 Trial operation of a selected tram line

axle weight of 11 tons. During the trial operation, strong vibration and noise radiation have appeared in the small-radius curve section.

3 In Situ Tests

3.1 Trial Sections

Based on the condition of the trial tram line, a typical small radius section (R = 50 m) and a typical straight-line section are adopted, as shown in Fig. 2, to test the ground vibration and the background noise and noises outside and inside the tram. Test range is within 10 m from the rail of the track.

In order to ensure the accuracy of the test data, the same tram is used to run repeatedly on the same test track. At different speeds of 8 and 13 km/h, the tram has been carried out five reciprocating tests on above-mentioned sections.

3.2 Experimental Setup

On small radius section, the accelerometers as shown in Fig. 3a were mounted in the middle of the small-radius curve, and four measurement points were numbered by VCI-1, VCI-2, VCO-1 and VCO-2, which were, respectively, placed at the distances of 1.3, 8, 1.3 and 6 m from the left and right rails, as shown in Fig. 2. On straight-line section, four measurement points were assigned by VLI-1, VLI-2, VLO-1 and VLO-2, and they were also placed at the distances of 1.3, 8, 1.3 and 6 m from the left and right rails, as shown in Fig. 2.

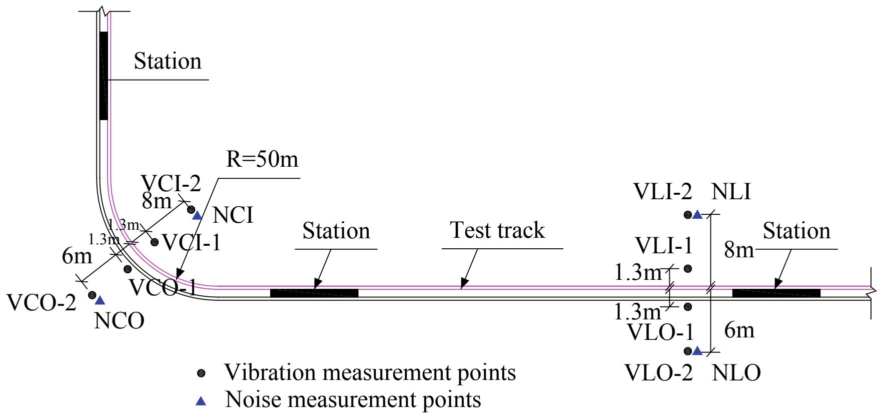

Fig. 2 Trial sections and measurement points

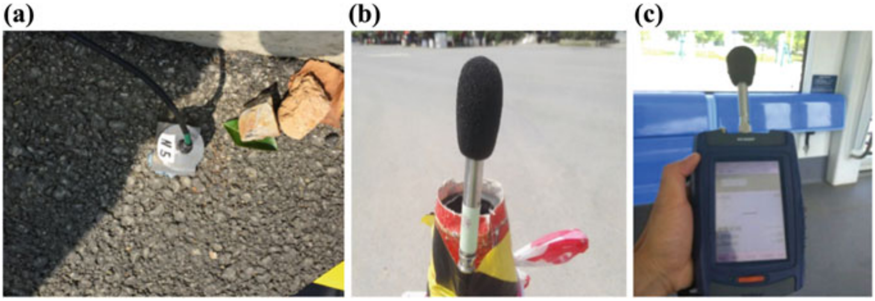

Fig. 3 Experimental set up: accelerometer (**a**), sound pressure sensor (**b**) and hand-held noise collector (**c**)

On small radius section, the sound pressure sensors were arranged in the middle of the small-radius curve, and two measurement points were numbered by NCI and NCO, which were, respectively, placed at the distances of 8 and 6 m from the left and right rails, as shown in Fig. 2. On straight-line section, two measurement points were assigned by NLI and NLO, and they were also placed at the distances of 8 and 6 m from the left and right rails, as shown in Fig. 2. The height of all sound pressure sensors as shown in Fig. 3b was 0.8 m from the ground.

A hand-held noise collector as shown in Fig. 3c was used to test the noises inside the tram. It was located in the middle of the tram, and with a height of 1.2 m from the tram ground.

3.3 Test Equipment

The ground vibration signals and noise signals outside the tram were recorded using Dynamic Data Acquisition and Analysis System made by China Orient Institute of Noise & Vibration. A high-performance hand-held noise collector was used to record the noise signals inside the tram. Some main test equipments are listed in Table 1.

4 Analysis of Test Data

4.1 Vibration Acceleration Level

The vibration acceleration level (VAL, dB) is expressed by:

Table 1 Test equipment

Name	Model type	Manufacturer
Dynamic data acquisition and analysis system	INV3020C	China Orient Institute of Noise & Vibration
Accelerometer	9828	China Orient Institute of Noise & Vibration
Accelerometer	LC0130	QUATRONIX Electronics Co., Ltd.
A high-performance hand-held noise collector	INV3080P	China Orient Institute of Noise & Vibration
Sound pressure sensor	INV9206	China Orient Institute of Noise & Vibration
Sound pressure sensor	46AE	G.R.A.S
Sound calibrator	46AB	G.R.A.S

$$\mathrm{VAL} = 20\lg\left(\frac{a}{a_0}\right) \tag{1}$$

where a is the root mean square (RMS) of vibration acceleration, and $a_0 = 10^{-6}$ m/s^2 is the reference vibration acceleration.

Figures 4 and 5 show the relationship between ground vibration acceleration level and one-third octave center frequency in the small radius section and in the straight-line section. It can be obvious that the ground vibration acceleration in the small-radius curve section is mainly concentrated between 80 and 400 Hz. With the increase of the train speed, there is no significant difference in ground vibration below 100 Hz, but above 100 Hz, the maximum vibration difference is between 5 and 8 dB. The ground vibration acceleration level outside the curve is larger than that inside, and the maximum difference is about 15 dB.

4.2 A Sound Pressure Level

Figure 6 illustrates the one-third octave band spectrum of noises in the small radius section, considering the *A* weight calculation. It can be seen that main energy of the noise is mainly concentrated between 1000 and 8000 Hz. The noise inside the tram is slightly greater than that outside in the frequency band below 630 Hz, but they exchange when it above 630 Hz.

There are two peak points in the 1000 and 4000 Hz, respectively, and the peak value at the 4000 Hz is more prominent, which has the obvious characteristic of roaring noise. The main reason is that when the tram passes through the small-radius curve section, the frictions between the inner and outer wheels of the bogie and rails are completely inconsistent.

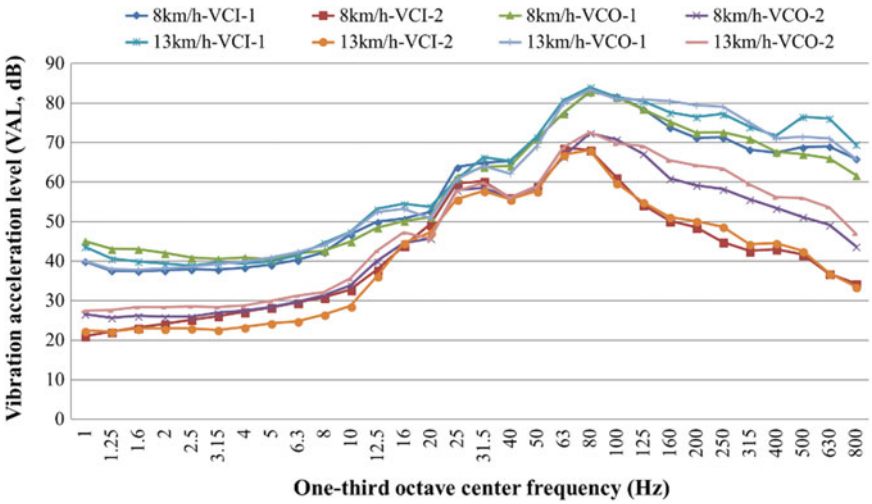

Fig. 4 Ground vibration acceleration level versus one-third octave center frequency in the small radius section

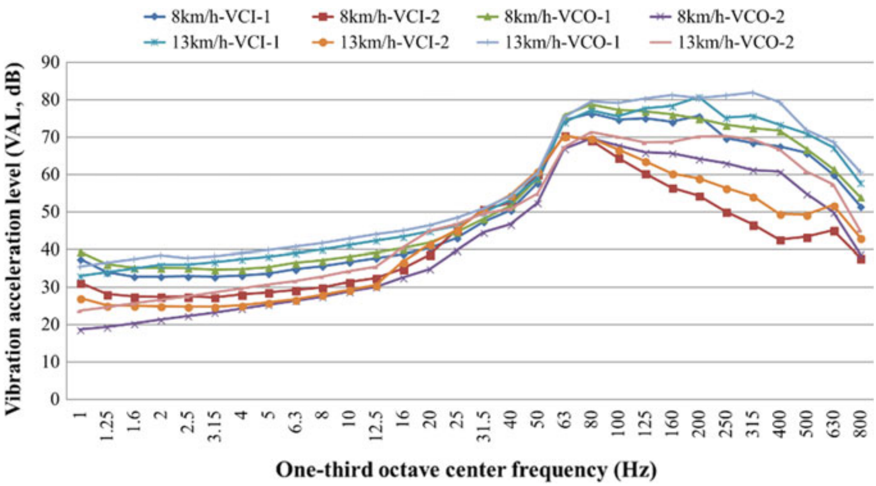

Fig. 5 Ground vibration acceleration level versus one-third octave center frequency in the straight-line section

Figure 7 shows the one-third octave band spectrum of noises in the straight-line section, considering the *A* weight calculation. In the straight-line section, the noises inside and outside the tram are basically same. Main energy of the noise is mainly concentrated between 160 and 2000 Hz.

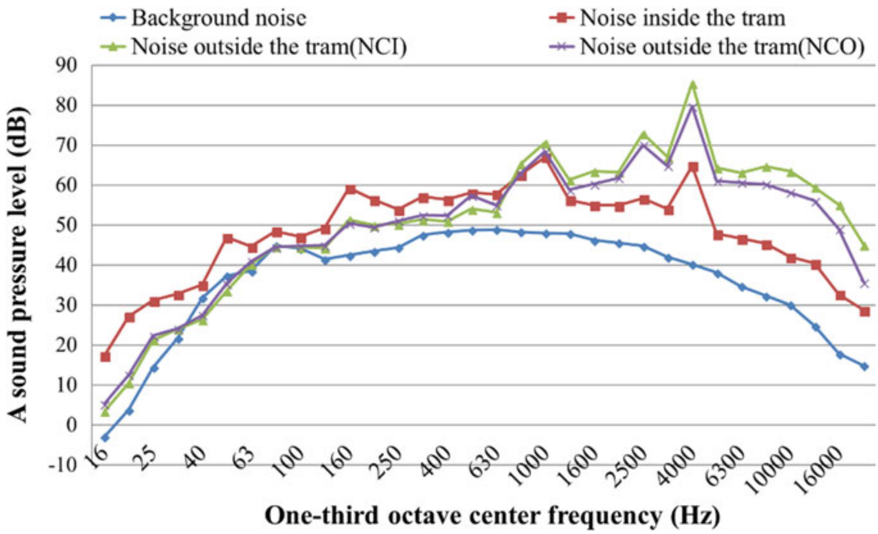

Fig. 6 One-third octave band spectrum of noises in the small radius section, considering the *A* weight calculation

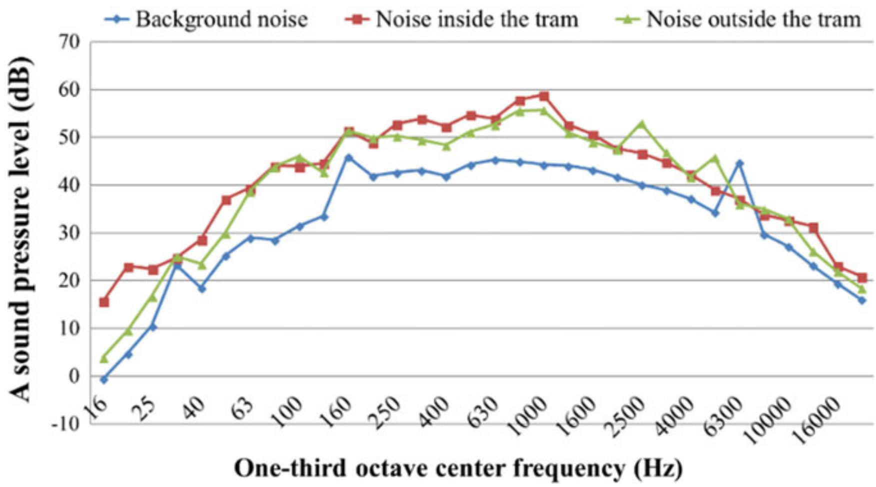

Fig. 7 One-third octave band spectrum of noises in the straight-line section, considering the *A* weight calculation

4.3 *Equivalent Sound Pressure Level*

Equivalent sound pressure level is defined by average energy of *A* sound pressure level at a specified time, and it is represented by $L_{A\mathrm{eq}}$ and can be obtained by:

$$L_{Aeq} = 10\lg\left(\frac{1}{T}\int_{0}^{T} 10^{0.1L_A}\,\mathrm{d}t\right) \tag{2}$$

where L_A is instantaneous sound pressure level at t time, and T is the prescribed measurement time.

Table 2 summarizes the L_{Aeq} inside and outside the tram and L_{Aeq} of background noise. In general, the noise in small radius section is greater than that in the straight-line section. With the increase of the tram speed, the maximum increase of noises inside and outside the tram is, respectively, about 6 and 2 dB(A). The noise inside the small-radius curve is greater than that outside, and the maximum difference is about 6 dB(A).

4.4 Beyond Limit Analysis

Table 3 listed the measured value and limit value of noise at a speed of 13 km/h. It can be seen that with reference to GB 14892-2006, the limit value of noise inside the tram is 75 dB(A) [7], and there is no exceeding standard in the small radius curve section. Meanwhile, referring to the standard VDV154-2011, the maximum of noise exceeding standard inside the tram is 4.35 dB [8]. With reference to GB/T 7928-2003, the limit value of noise outside the tram is 80 dB [9], and the maximum of noise exceeding standard outside the tram is 9 dB in the small-radius curve section. Meanwhile, referring to the standard VDV154-2011, the maximum of noise exceeding standard outside the tram is 14 dB. In the straight-line section, measured values of noise are less than the limit values, in other words, they satisfy noise control requirement.

Table 2 L_{Aeq} statistics

Type	Tram speed (km/h)	NCI [dB(A)]	NCO [dB(A)]	NLI [dB(A)]	NLO [dB(A)]
Noise outside the tram	8	83.16	78.70	62.54	64.65
	13	89.00	83.84	65.68	66.65
Noise inside the tram	8	70.35		63.40	
	13	72.35		64.50	
Background noise	–	56.35		57.04	

Table 3 Comparison of measured and limit values of noise at a speed of 13 km/h

Type	Description	Noise in curve section [dB(A)]	Noise in line section [dB(A)]
Noise inside the tram	Measured value	72.35	64.65
	Limit value 75 dB(A) (GB 14892-2006)	√	√
	Limit value 68 dB(A) (VDV 154-2011)	× (4.35)	√
Noise outside the tram	Measured value	89.00	66.65
	Limit value 80 dB(A) (GB/T 7928-2003)	× (9)	√
	Limit value 75 dB(A) (VDV 154-2011)	× (14)	√

5 Conclusions

This paper summarizes important observations of ground vibration and noise measurements performed in a trial tram line with the small radius section. The following conclusions can be drawn from the present analysis.

(1) The ground vibration acceleration in the small-radius curve section is mainly concentrated between 80 and 400 Hz, and the noise is mainly between 1000 and 8000 Hz, which are both greater than those in the straight-line section. The noise inside the tram is slightly greater than that outside in the frequency band below 630 Hz in the small-radius curve section, but they exchange when it above 630 Hz. In the straight section, the noises inside and outside the tram are basically same.
(2) With the increase of the train speed, there is no significant difference in ground vibration below 100 Hz, but above 100 Hz, the maximum vibration difference is between 5 and 8 dB. The maximum increase of noises inside and outside the tram are, respectively, about 6 and 2 dB(A).
(3) The ground vibration acceleration level outside the curve is larger than that inside, and the maximum difference is about 15 dB, meanwhile, the noise inside the small-radius curve is greater than that outside, and the maximum difference is about 6 dB(A).
(4) With reference to GB 14892-2006, the limit value of noise inside the tram is 75 dB(A), and there is no exceeding standard in the small-radius curve section. Meanwhile, referring to the standard VDV154-2011, the maximum of noise exceeding standard inside the tram is 4.35 dB(A).
(5) With reference to GB/T 7928-2003, the limit value of noise outside the tram is 80 dB(A), and the maximum of noise exceeding standard outside the tram is 9 dB(A) in the small-radius curve section. Meanwhile, referring to the standard VDV154-2011, the maximum of noise exceeding standard outside the tram is 14 dB(A).

The experimental results could be regarded as a reference for developing methods to control ground vibration and noise and for adopting countermeasures.

Acknowledgements This work was supported by the Beijing Nova Program (Grant No. Z161100004916054).

References

1. China Association of Metros (2018) 2017 annual statistics and analysis report of urban rail transit in China. China Association of Metros News, 17
2. Modern Tram Branch of China Association of Metros (2017) Blue book of China tram
3. Esveld C (2001) Modern railway track, 2nd edn. MRT-Productions, the Netherlands
4. Ding D-Y, Liu W-N, Li K-F, Sun X-J, Liu W-F (2011) Low frequency vibration tests on a floating slab track in an underground laboratory. J Zhejiang Univ Sci A (Appl Phys Eng) 12 (5):345–359
5. Ding D, Gupta S, Liu W, Lombaert G, Degrande G (2010) Prediction of vibrations induced by trains on line 8 of Beijing metro. J Zhejiang Univ Sci A (Appl Phys Eng) 11(4):280–293
6. Jiang X (2017) Characteristics and optimization of the vibration and noise reduction of an embedded track structure for tram. Southwest Jiaotong University
7. GB 14892-2006 (2006) Noise limit and measurement for train of urban rail transit
8. VDV 154-2011 (2011) Noise from mass transit rail vehicles acc. to BOStrab
9. GB/T 7928-2003 (2003) General technical specification for metro vehicles