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Research Article

A Case Study on Annoyance Noise Caused by Metro Railway at a TOD Developed Depot

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As an importance strategy to finance the transport infrastructure investment, transit-oriented development (TOD) for railway depot is rapidly growing in China. However, railway-induced noise emerged as the leading environmental nuisance triggering one of the most common public complaints. In order to discuss the influence of railway-induced noise on the neighbourhood residents in a TOD developed depot, a special case study is provided in this study. Measurement campaigns were conducted for responding to the complaints, and noise map was calculated for finding out a noise control solution. Based on the recommendation awakening threshold value of 42 dB (A) summarized from the Night Noise Guidelines for Europe (WHO, 2009), the measurement results confirmed that the neighbourhood residents were indeed suffering from the instantaneous railway noise, and the sleep disturbance correlated indicator L_{Amax} was more than 56 dB (A) at outside of buildings. Furthermore, calculation results indicated that the lower office buildings became mirrors which reflected the noise across over the cover structure to the higher stories of residents' buildings. At the ends, a kind of dissipative splitter muffler was proposed as a potential solution, and its performance was also simulated.

1. Introduction

A metro depot is a facility where trains are regularly parked for maintenance, testing, and storage. Traditional metro depots always require massive land; thus, they were commonly located far always from city center. But with the cities expanded rapidly in last decades in China, the areas of metro depots were developed as part of central urban [1–4]. The boundary of depot became barriers to isolate the land from not only the city but also the increasing value of housing. Transit-oriented development (TOD) is therefore recognized as a sustainable mode of development for depots which were located in highly dense megacities. Under the guiding principles of TOD, the basic ideas are to design an urban form in a relatively high density, compact, and mixed form and to provide high quality, efficient mass transportation services, together with a pedestrian friendly environment [5]. More important, the TOD mode improves the accessibility of housing to be developed and hence increases the land value, which helps finance the transport infrastructure investment [6–8].

However, the most serious impediment for TOD strategy conducted on metro depot is the environment issue. The main negative consequence of railway traffic is that the vibrations and noise induced by the train passage are easily transmitted to nearby buildings [9, 10], which results in disturbance of inhabitants, with consequences on living quality and health. Although such vibration usually do not imply damage on buildings, it manifests itself in two ways: low frequency vibration in the range 1–80 Hz is perceived by line side residents as whole-body feel able vibration, whereas higher frequency vibration in the range 16–250 Hz is radiated as sound inside buildings and is known as structure-borne noise [11–13]. Besides structure-borne noise, various sources contribute to the airborne noise, including rolling noise, engines and gear noise, and so on, which transmit directly through the air [14, 15]. In last decades, many solutions for railway noise have been suggested [16–19], partly based on common sense but sometimes also based on a deep understanding of the physical phenomena involved. By common consents, the railway noise reduction should be best started at the source or isolated by barriers installed at the propagation path or even relocated the residents to a greater distance from the railway lines. Traditionally, according to the Chinese environment law, the residential district must be keep at least 30 m off the railway line. To solve the conflicts between the noise problem and the TOD strategy, it requires considering control measures during all the steps of TOD development, including prediction, design, construction, and routine maintenance.

In this study, a special case study was provided to discuss the influence of railway-induced noise on the neighbourhood building in a TOD metro depot section. The research was carried out for responding to complaints from neighbourhood residents about railway noise; even the depot section almost totally covered under a hanging garden structure, which was considered as the barriers to isolate the direct propagation of noise. Measurement was therefore conducted for obtaining noise data at the positions of source, out-room, and in-room during the rush hours. After that, the software CadnaA was adopted to simulate the influence area of railway noise. Finally, the potential solution for noise reductions was suggested.

2. Project Background

The presented residential building is located in a TOD metro depot and close to the entrance/exist area. In this area, the train speed was limited under 25 km/h. However, in practice, the speed would be a little higher than 25 km/h when trains go out of the depot, while the speed would be lower than 25 km/h when trains go back. As in this area, there were quite a lot turnouts and rail joints which would result in high level of impact force related to low frequency vibration, and under ballast mat was therefore used to reduce the railway-induced vibration.

Furthermore, in this area, trains are always in the condition of speeding up or breaking down, causing higher annoy roll noise and breaking noise. As the result, although the railways are all ground lines, they were covered by a hanging garden structure for connecting the north and south land of the depot in one hand and reducing the noise impact for the other hand. The north side of cover structure was closed for noise isolation, while the south side was open for fire safety consideration.

The minimum distance between the foundation of building and the nearest track center is 31 m, while the distance between the building and the outward side of the cover structure is more than 60 m. Besides that, there are two office buildings located at the south side of the cover structure. The detailed location and real photos are shown in Figures 1 and 2.

However, although the result of the investigation indicated that it had already adopted many types of measures to attempt controlling the railway-induced vibration and noise, it seems to be failed because complaints come from neighbourhood residents once when the depot is under operation. In order to provide the solution, research studies were carried out as the responding to the complaints.

3. Measurement

3.1. Measurement Setup. Measurement campaign was conducted in the apartment of a cooperative complainant, which located on 15th floor. One sound meter was installed at the open balcony out of the bedroom (marked as MR1), while another was installed inside of the bedroom with windows totally closed (marked as MR2), as shown in Figure 3.

More than that, sound meters were located at outside of the depot cover structure to record the noise sourced from railway, as shown in Figures 4 and 5. It should be figured out that because the trains were not passing through the same track, it was not easy to collect the noise data according to ISO3095 [20], in which the noise source measurement points need to be installed at 7.5 m from track center. Thus, the edge of the cover structure was redefined as the noise source in this project.

The sound level measurement device adopted in this project was sound level meter B&K2270 (Brüel and Kjær, Denmark). The B&K2270 sound level meter is a flexible hand-held analyser with large frequency range, spanning from 20 Hz to 20 kHz. It is capable of measuring both the railway-induced airborne noise and structure-borne noise.

3.2. Noise Indicator Choose. To choose a reasonable noise indicator, need to consider both the equivalent sound pressure level and the number of sound events. Traditionally, many previous research studies indicated that the railway-induced noise was obviously characterized by high levels per event and low numbers. They even raised a conclusion that railway traffic noise causes less annoying other than road and air traffic noises due to the lower numbers because the A-weighted long-term average sound level was quite lower during a continuous period of time. But for the presented case in this study, the TOD development made residents suffering much high-frequency events during the rush hours in middle night and early in the morning. From a practical point of view, the sound level for each pass-by event is better useful to explain the instantaneous effects such as sleep disturbance to public, so that they can understand intuitively other than the yearly average of noise level.

According to the recommendation of the Night Noise Guidelines for Europe published by the WHO in 2009 [21], sleep disturbance correlates best with short-term effects that are mainly related to maximum levels per event $\mathrm{L}_{\mathrm{Amax,inside}}$. Table 1 provides the summary of effects and threshold levels for effects where sufficient evidence was available for the $\mathrm{L}_{\mathrm{Amax,inside}}$.

Therefore, considering the reality purpose of the case presented in this study is to provide responses to complaint from residents for waking up in the night and/or too early in the morning; the indicator $L_{\mathrm{Amax,inside}}$ was selected, and the value should be not limited at 42 dB (A). Moreover, considering the desire of a large part of the population to sleep with windows (slightly) open, in this study, the noise level

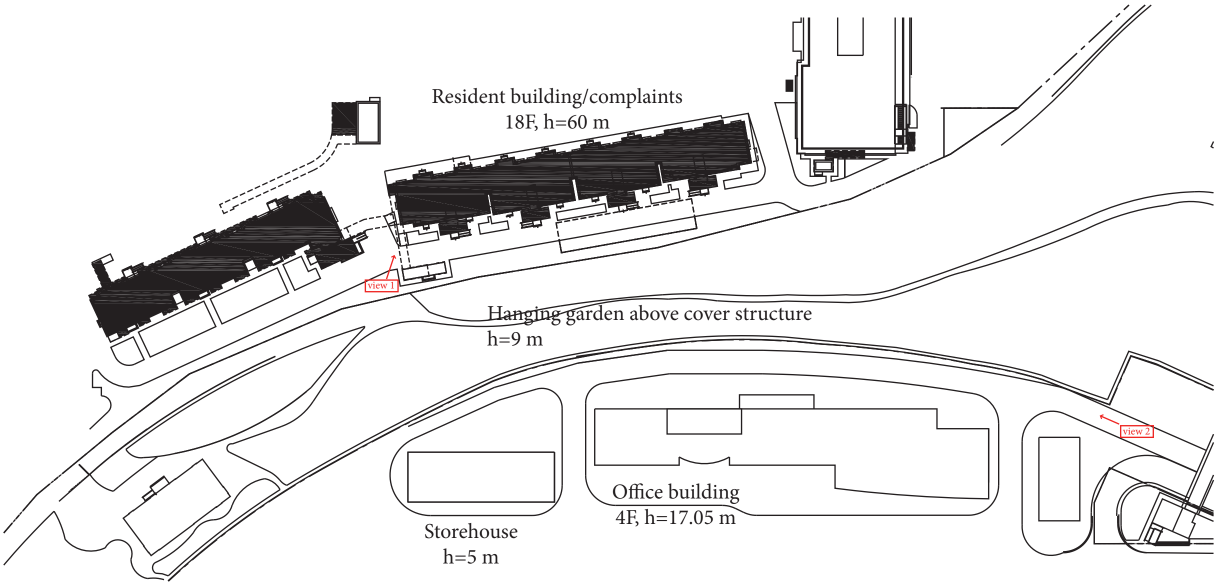


Figure 1: The plan view of presented TOD project.

(a)

(b)

Figure 2: The real photos for (a) view 1: looking down angle at 15th floor and (b) view 2: looking up angle at east side.

outside $L_{\mathrm{Amax,outside}}$ was adopted as the prediction indicator and the limited value should be less than 42 dB (A).

3.3. Measurement Results

3.3.1. Time History Record. Measurements were conducted during the rush hours. Especially, during 16 : 30 to 17 : 30, measurement was carried out for the noise that trains left out of the depot and passed though the measurement position in acceleration condition, while during 19 : 30 to 20 : 30, trains come back to the depot and passed through the measurement position in deceleration condition.

A-weighted sound pressure level (LA) during the measurement time history was recorded. An example of time history taken from the source measurement at position MS3 is shown in Figure 6. The reference time interval is 1 second.

3.3.2. Pass-By LA for Single Train. In order to identify the contribution of the train caused noise from other source, the detailed time history of pass-by LA for each single train was also selected, respectively. An example for trains left out of the depot is shown in Figure 7 and the condition when trains came back to depot is shown in Figure 8.

According to Table 2, the measurement data showed the excellent repeatability at all measurement positions for at least 16 pass-by trains selected simply according to the time order. It indicted that at bedroom when windows were fully closed, the short-term noise level per each pass-by event was less than 42 dB (A), but considering people have good reasons to sleep with their windows open, the outside noise level exceeded 12.6 dB (A) to 17.7 dB (A) than the sleep disturbance threshold value according to the recommendation of the Night Noise Guidelines for Europe published by the WHO in 2009.

3.3.3. 1/3 Octave Frequency Spectrum. In order to find out what was the typical spectrum than railway noise transit via such a long distance to the building, 1/3 octave frequency spectrum for all the measurement points was provided in this section and shown in Figures 9–13.

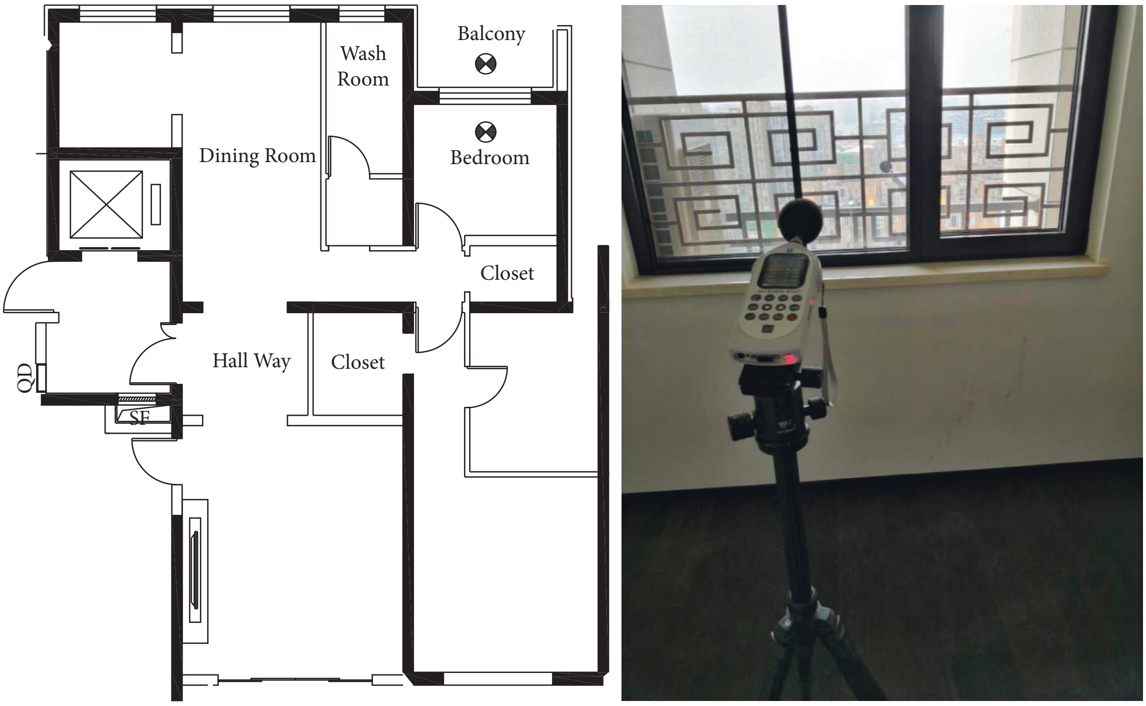


Figure 3: The location and view of measurement points for MR1 and MR2.

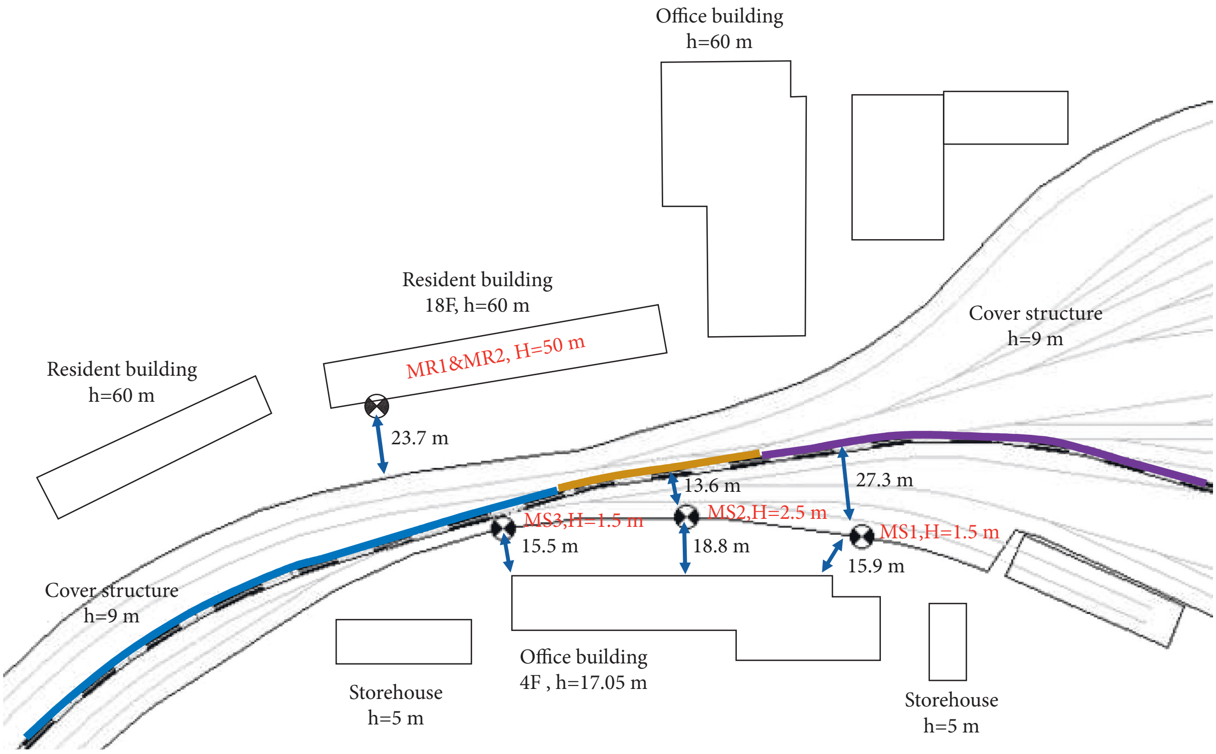


Figure 4: The detailed location of measurement points.

At the measurement point MS1, the sound meter was located at outside of the cover structure with the distance of 27.3 m from the track center of busy main line and 1.5 m in height. From Figure 9, it is clear that the sound pressure level remarkably raised from the background curve when metro trains passed by. Moreover, the typical frequency band occurred at the band of 40 Hz. It should notice that in this area, the trains were passing through turnout zone and the speed started increasing approximately from 5 km/h to 20 km/h when trains left out of depots.

(a)

(b)

(c)

Figure 5: The real photo of sound meters installation at the source. (a) MS1. (b) MS2. (c) MS3.

Table 1: The summary of effects and threshold levels on healthy for $L_{Amax,inside}$.

Effect	Detailed effects	Threshold, dB (A)
Biological effects	EEG awakening	35
	Motility, onset of motility	32
	Changes in duration of various stages of sleep, in sleep structure and fragmentation of sleep	35
Sleep quality	Waking up in the night and/or too early in the morning	42

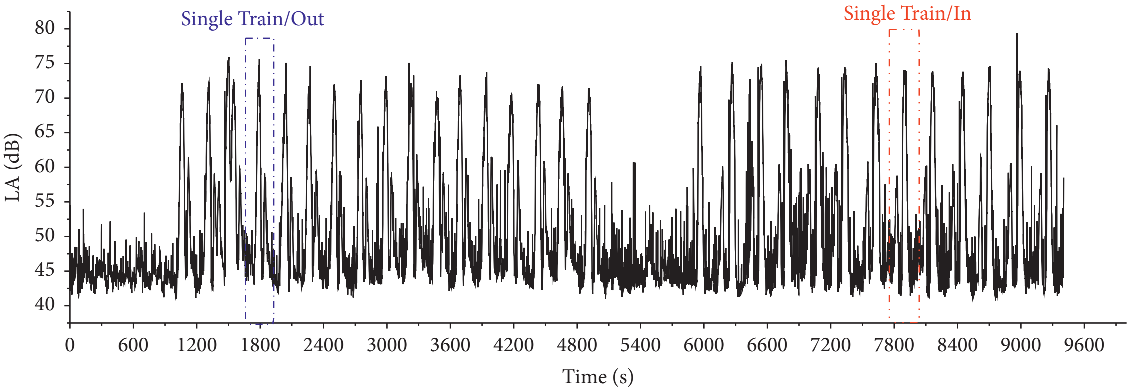


Figure 6: Example of time history for the whole measurement in rush hours (MS3).

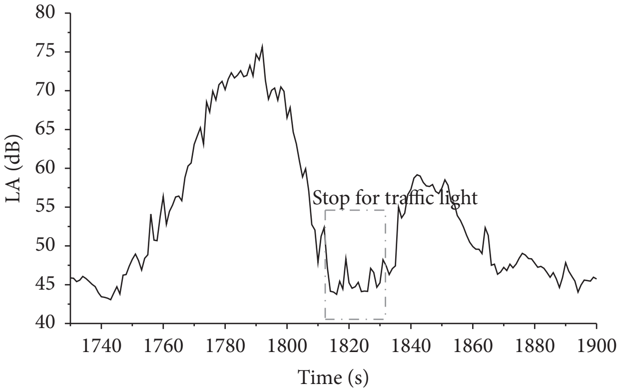


Figure 7: Example of selection of measuring time interval for a whole train passage (leaving out).

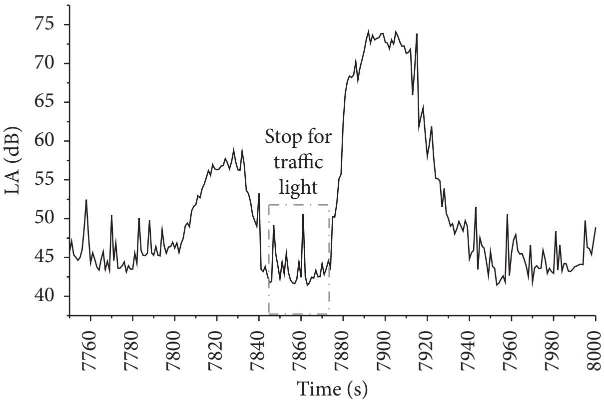


Figure 8: Example of selection of measuring time interval for a whole train passage (coming back).

Table 2: The maximum A-weighted sound pressure level per each pass-by.

No.	Time	Maximum A-weighted sound pressure level/dB (A)				
		MS1	MS2	MS3	MR1	MR2
1	Left out	72.7	81.2	74.5	56.6	33.1
2		71.5	84.5	73.3	58.3	32.7
3		77.0	84.1	74.6	59.7	33.9
4		71.6	78.9	76.8	56.1	32.4
5		71.8	77.5	73.7	57.3	32.1
6		76.0	80.4	74.0	57.3	33.1
7		77.9	85.0	73.5	56.9	33.2
8		77.5	85.2	73.7	56.7	32.7
1	Came back	75.2	86.9	76.5	57.4	34.2
2		77.1	87.1	76.1	57.1	33.8
3		68.2	80.8	78.7	55.9	32.9
4		76.5	78.5	75.7	56.1	33.1
5		69.0	79.8	76.1	58.8	32.6
6		74.7	80.8	77.5	55.6	32.4
7		66.4	78.9	76.0	56.0	33.1
8		67.6	79.6	76.7	56.1	33.2

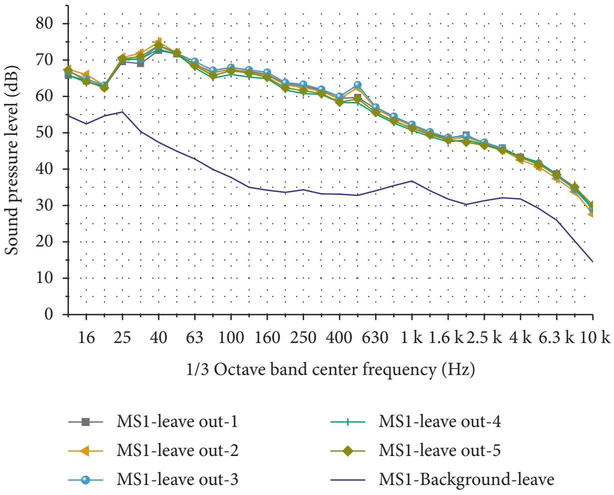


Figure 9: 1/3 octave frequency spectrum for measurement points MS1.

At the measurement point MS2, as the cover structure was half closed (Figure 5), the sound meter was located at outside of the cover structure with the distance of 13.6 m from the track center and 2.5 m in height. From Figure 10, it clear that the sound pressure level remarkably raised from the background curve when metro trains passed by. It may because that in this area, the trains were running at a higher speed than MS1 around 25 km/h, and the measurement position was in a shorter distance from the track center, the value of sound pressure level was larger than MS1, and the typical frequency band occurred at the band of 125 Hz.

At the measurement point MS3, the sound meter was located at outside of the cover structure and close to the track center of busy main line with 1.5 m in height. In this area, the trains decelerated from 25 km/h to 0 km/h for traffic light sign. From Figure 11, it clear that the sound pressure level remarkably raised when trains passed by. A remarkable peak appeared at 63 Hz, which was traditionally considered as one typical frequency of railway-induced rolling noise.

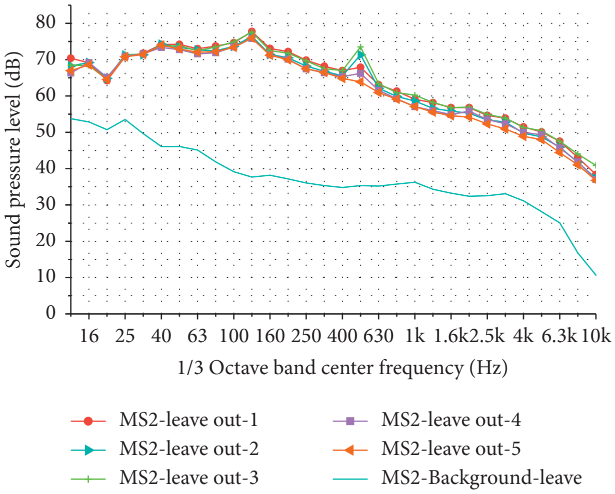


Figure 10: 1/3 octave frequency spectrum for measurement points MS2.

At the measurement point MR1, the sound meter was located at the outside balcony of 15th floor with about 50 m height from the ground. From Figure 12, it clear that the value slightly raised along all of the frequency bands, although the tendency of the pass-by curve remained almost the same with the background in the range of 20–100 Hz and 200–2000 Hz. It was able to identify the influence of railway at the bands of 40 Hz and 125 Hz, which, respectively, related to the typical frequency captured from MS1 and MS2.

Moreover, in the range of 2000 Hz–10 kHz, even though it not appeared as good reproducibility as in the range below 2000 Hz for all the pass-by train, the value dramatically increased against the background curve. It indicated that railway-induced noise provided significant contribution in the range of 2k–10 kHz at the position of MR1.

At the measurement position of MR2, the sound meter was installed in the bedroom with windows fully closed. From Figure 13, it clear that the pass-by sound pressure level curves tend to get close to the background curve. Especially, in the range of more than 800 Hz, there was no obvious difference between the background and pass-by curve. But in the range of 50–800 Hz, typical railway-related frequency bands were still able to be identified at 63 Hz and 125 Hz. Considering there were typical peaks on the background curve at 20 Hz, 31.5 Hz, 63 Hz, 125 Hz, and 200 Hz bands, which were normally related to the railway-induced vibration, it indicated a conclusion that the noise at 63 Hz and 125 Hz would be more likely as structure-borne noise other than airborne noise that came from outside via the direct path.

3.3.4. *Findings.*

Based on the measurement results, it was clear that the neighbourhood residents were indeed suffering from the railway-induced noise. Considering people have

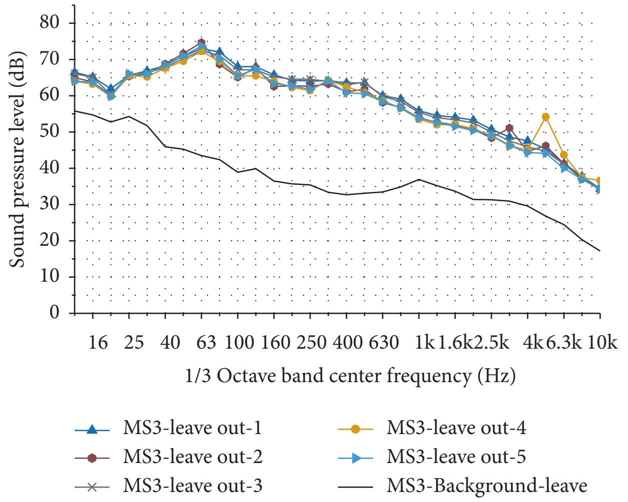


Figure 11: 1/3 octave frequency spectrum for measurement points MS3.

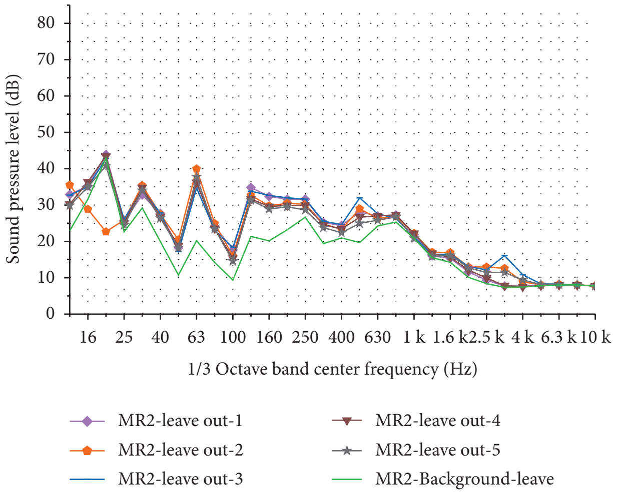


Figure 13: 1/3 octave frequency spectrum for measurement points MR2.

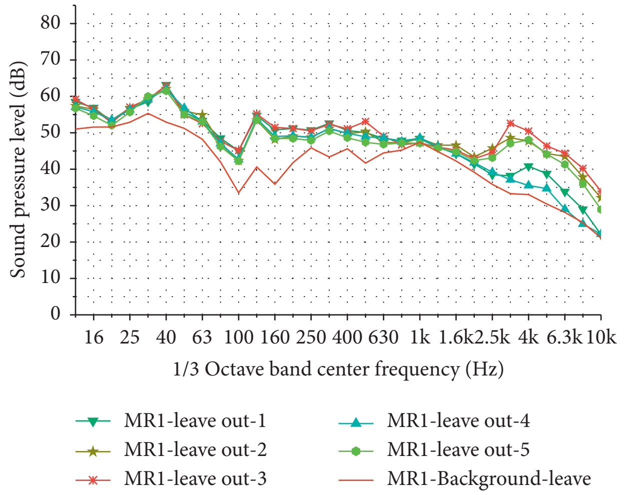


Figure 12: 1/3 octave frequency spectrum for measurement points MR1.

good reasons to sleep with their windows open, the outside noise level exceeded 12.6 dB (A) to 17.7 dB (A) than the sleep disturbance threshold value of 42 dB (A) according to the recommendation of the Night Noise Guidelines for Europe published by the WHO in 2009.

Although it was certain that the annoying noise was the consequence of railway system, the transit path for outside noise was still unclear. The noise in bedroom was more likely as structure-borne noise other than airborne noise that came from outside.

4. Noise Map Simulation

In order to find out the noise propagation path and make a noise control proposal, the noise map was simulated in this study. The software CadnaA was used to build the 3D model of the considered area with all structures and neighbourhood buildings in full scale, as shown in Figure 14. The default railroad module in software was used to simulate the noise generated by the metro trains.

In this simulation, the Schall03 (2014) prediction method was used, considering the order of reflection was 2 and the default ground absorption factor was 0.8.

Furthermore, selected one single train in random and reprocessed the source measurement data in the form of one octave frequency spectrum. The input data given in Table 3 were adapted as the railway noise emission for calculation.

The simulation model verification in the form of spectrum is shown in Figure 15. It is clearly indicated the simulation result agreed with the measurement data acquainted from the near field in MS1 ($L = 27.3$ m, $H = 1.5$ m). Even in the far field, the sound transits would be affected by some uncertain issues, such as temperature and winds speed. At the check point MR1 ($L > 50$ m, $H > 50$ m), the sound pressure spectrum remained in the highly accordant tendency.

Then, the simulation results were verified by the measurement data in the form of A-weighted sound pressure level, as given in Table 4. The maximal tolerances for calculation results were less than 0.5 dB (A), which indicated that the calculation was efficient for describing the noise influence scale. Therefore, the calculated noise map was provided as shown in Figure 15.

From Figure 16, the noise map indicated that the railway-induced noise resulted in obvious influence on the residents building at this TOD-developed depot. More than 90% area at the facade of neighbourhood residents' buildings that faced to the depot side were under the exposure of more than 45 dB (A) noise condition when metro trains passed by.

It was also clear that the partial closed side of cover structure became a new noise source. The shapes, locations, and adjacent relations of buildings played an important role on the acoustic field in this area. The comprehensive factors made the lower office buildings become mirrors which reflected the railway-induced noise across over the cover structure to the higher stories of residents building.

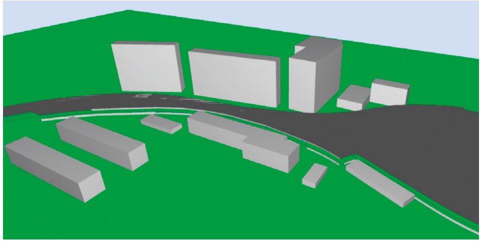


Figure 14: The 3D model of considered area established by CadnaA.

Table 3: The maximum A-weighted sound pressure level per each pass-by.

Frequency (Hz)	Value (dB)		
	MS1	MS2	MS3
63	93.7	94.9	87.6
125	91.1	94.6	80.1
250	87.0	88.4	79.3
500	83.8	88.9	76.2
1000	76.3	78.7	71.1
2000	72.5	75.4	67.3
4000	69.0	71.8	61.4
8000	64.4	66.8	55.0

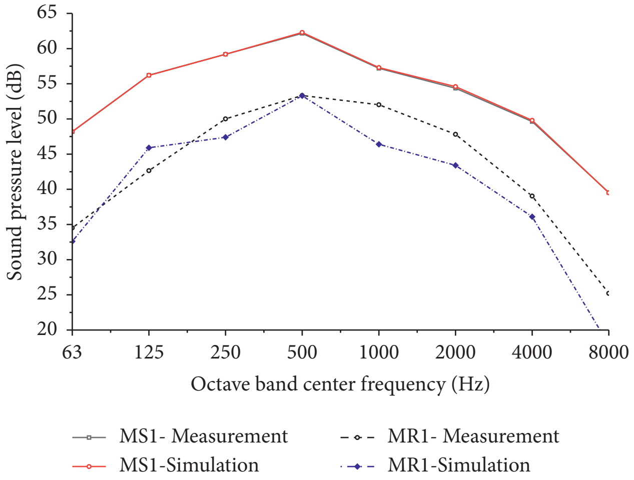


Figure 15: Simulation results verification.

Table 4: Simulation results verification.

	A-weighted sound pressure level/dB (A)			
	MS1	MS2	MS3	MR1
Measurement	72.7	81.2	74.5	56.6
Calculation	72.9	81.5	74.7	57.1
Tolerances	+0.2	+0.3	+0.2	+0.5

5. Proposal for Noise Control

For this existed project, it was too late to rearrange the locations of buildings or optimize the railway system; the noise control proposal would only be focused on setting

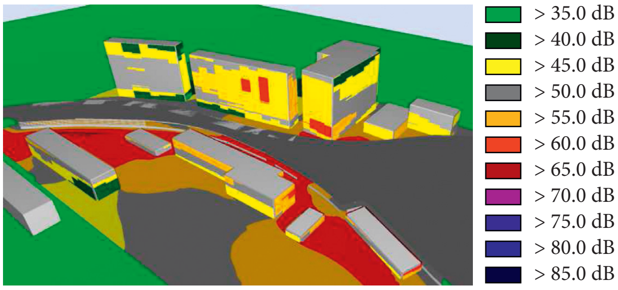
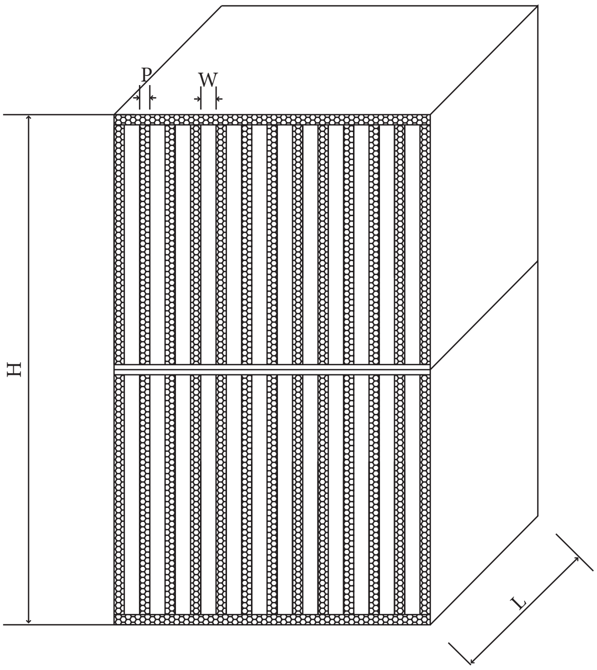


Figure 16: The map of calculated railway-induced noise.



- *The height H=5 m*
- *The thickness of each muffler sheet P=0.1 m*
- *The depth of each muffler sheet L=1.5 m*
- *The interval between two muffler sheet W=0.15 m*
- *The ventilation Rate ref. without mufflers*: 60%
- *Filling material : Sound absorbing glass wool*

Figure 17: Detailed parameter for splitter mufflers.

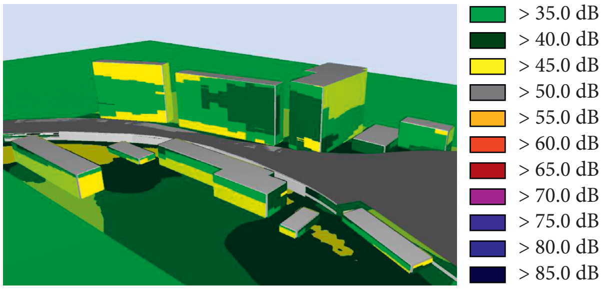


Figure 18: Noise map calculated with mufflers.

noise isolation barriers at the transit path. Therefore, the dissipative splitter muffler was proposed as a potential solution in this project. The sound transit gaps under the cover structure were full filled by splitter muffler which was considering the effective working frequency range and remaining at least 60% ventilation for the fire safety. The detailed parameter for one cell of the splitter muffler is shown in Figure 17.

The performance of proposed mufflers was calculated using the same simulation model of CadnaA. The results showed the A-weighted sound pressure level was obviously reduced to the value under 42 dB (A) (Figure 18).

6. Conclusions

Based on the presented case study in this study, findings could be summarized as follows:

1. Railway-induced noise emerged as the leading environmental nuisance triggering one of the most common public complaints in the TOD development
2. The measurement results indicated that the inside short-term noise level per pass-by event was less than 35 dB (A) when windows were fully closed, while the indicator L_{Amax} was more than 56 dB (A) at outside of buildings. Considering people have good reasons to sleep with their windows open, the outside the noise level exceeded 12.6 dB (A) to 17.7 dB (A) than the sleep disturbance threshold value according to the recommendation of the Night Noise Guidelines for Europe published by the WHO in 2009.
3. The calculation results indicated that even though the direct transit path was cut down, the reflection and diffraction would play a nonnegligible role on the noise influence. Therefore, the noise map evaluation should be necessary taken into consideration in new construct project.
4. The way to install mufflers would be effective for noise reduction for this project

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

H. G. Zhang and Q. Liu conceptualized the study. Z. X. Kang developed methodology, collected resources, and investigated and supervised the study. G. Li. developed software. Q. Liu, Z. X. Kang, and G. Li. validated the study. Q. Liu performed formal analysis and visualized the study. H. G. Zhang wrote, reviewed, and edited the article and acquired fund. R. X. Song administered project.

Acknowledgments

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