Research Article

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Low-frequency cabin noise of rapid transit trains

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Abstract: Rapid transit or mass rapid transit (MRT) is a high-capacity public transport designed to carry a large number of passengers, especially during the peak hours. They are becoming very popular in major cities and some deem the presence of the rapid transit system in a city as a symbol of modern development and essential feature of urban life. As the rapid transit system expands, the traveling time on a rapid transit train may increase due to longer journey and cabin noise has become an environmental concern for the passengers. In the present study, we would attempt to do a more detailed study of the effect of viaduct height, in particular viaducts of different heights on the cabin noise of various rapid transit systems. The present study examined and benchmarked the cabin noise in terms of both dB(A) and dB(C) for four different rapid transit systems, namely part of the East-West line including the Tuas-West extension on elevated tracks with very high viaduct of the Singapore MRT System; part of Paris Line 2 from Anvers to Belleville station including a stretch of elevated track on viaduct; part of the Piccadilly line of London from Heathrow Airport to Green Park station with a stretch on surface ground; and finally part of Chongqing Line 3 from Gongmao to Lianglukou station across the Yangtze river. It was found that the cabin noise would be dominated by low-frequency content and would be better reflected if the measurements were presented in dB(C), especially for trains running on elevated tracks of greater height.

Keywords: rapid transit systems, cabin noise, low-frequency noise, viaduct

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1 Introduction

Rapid transit or mass rapid transit (MRT), also known as heavy rail, metro, subway, tube, U-Bahn or underground in different parts of the world, is a high-capacity public transport designed to carry a large number of passengers, especially during the peak hours. They are becoming very popular in major cities and some deem the presence of the rapid transit system in a city as a symbol of modern development and essential feature of urban life to travel around without getting stuck in traffic jams. Unlike buses or trams, rapid transit systems are electric railways that operate on an exclusive track, which cannot be accessed by pedestrians or other vehicles of any sort. They are typically in tunnels in a densely crowded city center and on elevated tracks at the outskirts of a city. As the rapid transit system expands, the traveling time on a rapid transit train may increase due to longer journey and cabin noise has become an environmental and health concern for the passengers. However, there are no specific hearing protection regulations in place for passengers using public transport, in particular the rapid transit trains. In a recent study by Singh *et al.* [1], the sound pressure levels (SPLs) of the cabin noise between Euston and South Wimbledon station on the Northern Line, between Euston and Vauxhall station on the Victoria Line and within Zone 1 of the London Underground were found to exceed 80 dB(A), with levels sometimes reaching above 100 dB(A). Yan *et al.* [2] reported an overnight field experiments of the interior noise and vibration of a standard B-type metro train running on a viaduct for metro line 14 of Guangzhou, China. They found that the interior noise was in the low-to-middle frequency range. While increased train speeds (20, 40, 50, 60, 80, and 115 km/h) would have significant effects on cabin noise, two frequency ranges (125–250 and 400–1,000 Hz) with respective corresponding center frequencies (160 and 800 Hz) of the cabin noise were found to be nearly independent of train speed. The low-frequency noise was found to be associated with the vibration of the floors and the side walls of the train. In a conference paper presented by the authors [3], the cabin noise of the rapid transit systems in five cities where London, Prague, Paris, Singapore and Taipei were benchmarked and compared. The average noise levels for all metros were found to be well below 85 dB(A) and therefore traveling on these metro systems for 8 h was not likely to exceed the maximum duration of occupational noise exposure under the National Institute for Occupational Safety and Health (NIOSH) guidelines. It was also found that the average SPL in dB(C) was about 6 dB higher when compared to dB(A). This indicated the presence of low-frequency components below 200 Hz. However, in that study, the authors only benchmarked the equivalent SPL for the line and did not look into the specific features for the constituent segments such as the presence of viaduct and the height of the viaduct. In this study, a more detailed examination of the effect of viaduct was investigated, in particular viaducts of different heights on the cabin noise of various rapid transit systems. The present study examined and benchmarked the cabin noise in terms of both dB(A) and dB(C) for four different rapid transit systems, namely part of the East-West line including the Tuas-West extension (TWE) on elevated tracks with very high viaduct of the Singapore MRT system; part of Paris Line 2 from Anvers to Belleville station including a stretch of elevated track on viaduct; part of the Piccadilly line of London from Heathrow Airport to Green Park station with a stretch on surface ground and finally part of Chongqing Line 3 from Gongmao to Lianglukou station across the Yangtze river.

First announced on 11 January 2011, the TWE was an extension of the East-West line of the Singapore MRT system from Joo Koon to Tuas Link via a 7.5 km long MRT viaduct. The extension added four new stations, namely Gul Circle, Tuas Crescent, Tuas West Road and Tuas Link as shown in Figure 1. As it was designed to be integrated with the Tuas viaduct for normal traffic flow, one can see that the height of the viaduct of the original East-West line (Figure 2) is much lower than the height of the viaduct of the extension (Figure 3). The exact height of the viaduct was not reported in open literature. The original East-West line terminated at Boon Lay station (Figure 2(a)). The Boon Lay Extension, which was completed on 28 February 2009, consisted of Pioneer and Joo Koon stations as shown in Figures 1 and 4. The exact heights of these stations were not reported in open literature. This stretch of the viaduct will enable the study of the effect of the height of viaduct on the cabin noise where its rolling stock has six cars per train-set running at a service speed of 80 km/h.

Paris Metro Line 2 (French: Ligne 2 du métro de Paris) is one of the 16 lines of the Paris Metro, running between Porte Dauphine and Nation. Line 2 is 12.4 km in length and slightly over 2 km of the line is built on an elevated viaduct. For the present study, the cabin noise was measured between Anvers and Belleville stations as shown in Figure 5, inclusive of the elevated viaduct between Barbès-Rochechouart and Jaurès stations (Figure 6(a)). The rolling stock is MF 01 (or MF2000) with five cars per train set and a maximum speed of 70 km/h. For this stretch of the line, we can study the effect on the cabin noise when a train leaves a tunnel to an elevated track and then back to the tunnel.

The Piccadilly line in London is a London Underground line running from the north to the west of London. It has two branches, which split at Acton Town station and serve 53 stations as shown in Figure 7. The line is known for serving Heathrow Airport and is near popular attractions such as Buckingham Palace. For the Heathrow branch of the Piccadilly line, the section from Heathrow airport to Hounslow West station is inside a tunnel. The aboveground section is from Hounslow West station to Barons Court station and thereafter the train enters into a tunnel again. For this study, the cabin noise measurements were carried out from Heathrow station to Green Park station. However, there is no viaduct for the track for this stretch of Piccadilly line from Heathrow to Green Park stations. The train runs on the surface track before entering the central London.

The subway lines at the City of Chongqing, China offer a unique example of a subway viaduct at a great height above the ground. The extreme difference in elevation between the river valleys and the hilly plateaus of Chongqing poses a unique challenge in designing alignments for conventional rail transit lines. In this study, we would examine the subway cabin noise for line 3 across the Yangtze river as shown in Figure 8. There was no reported height for the Tongyuanju station (Figure 9).

Figure 1: Stations from Jurong East to Tuas Link for East West Line of Singapore [4].

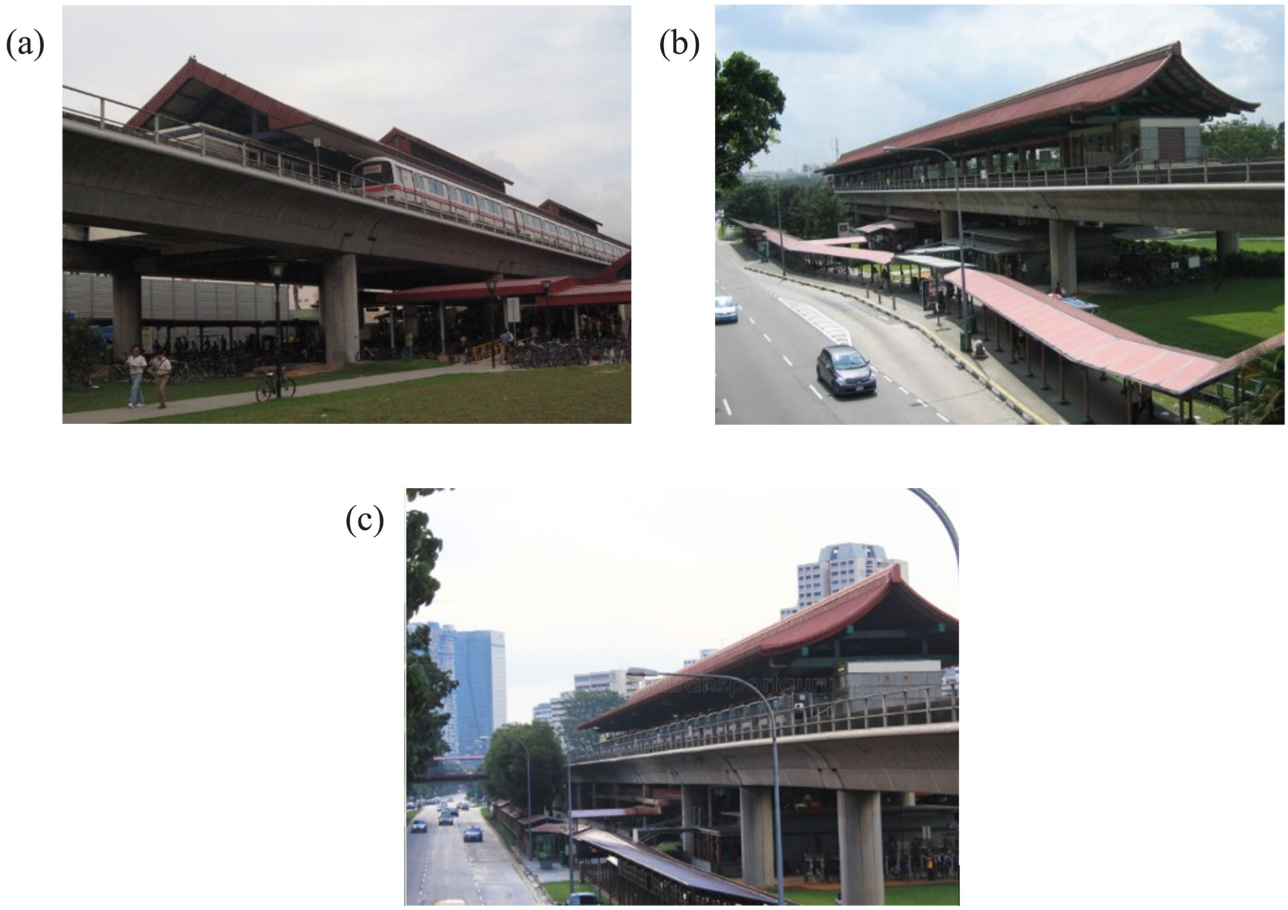

Figure 2: The three MRT stations at the original East-West Line of Singapore: (a) Boon Lay [5], (b) Lakeside [6] and (c) Chinese Gardens [7].

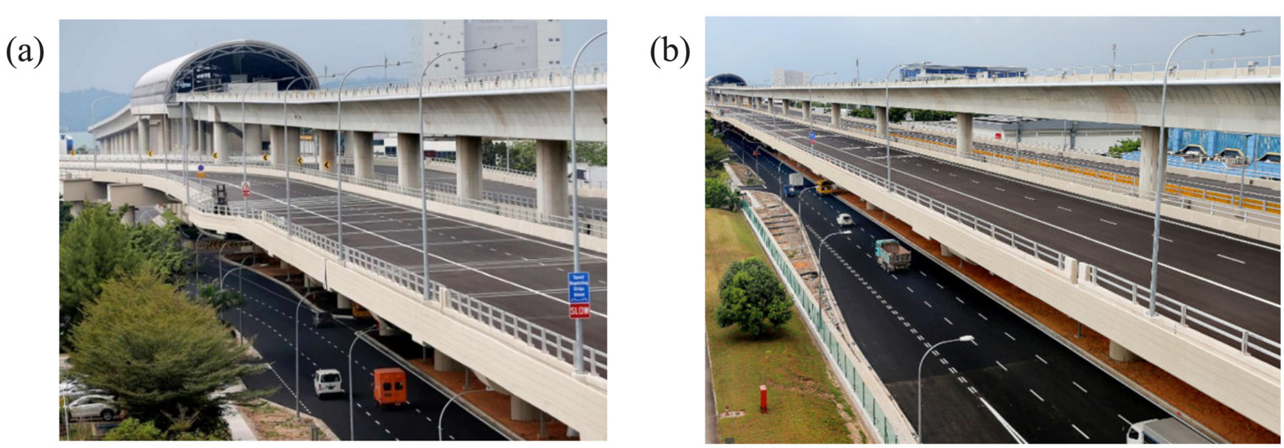

Figure 3: (a) The Tuas viaduct [8] and (b) the integrated TWE [9] for the MRT line of Singapore.

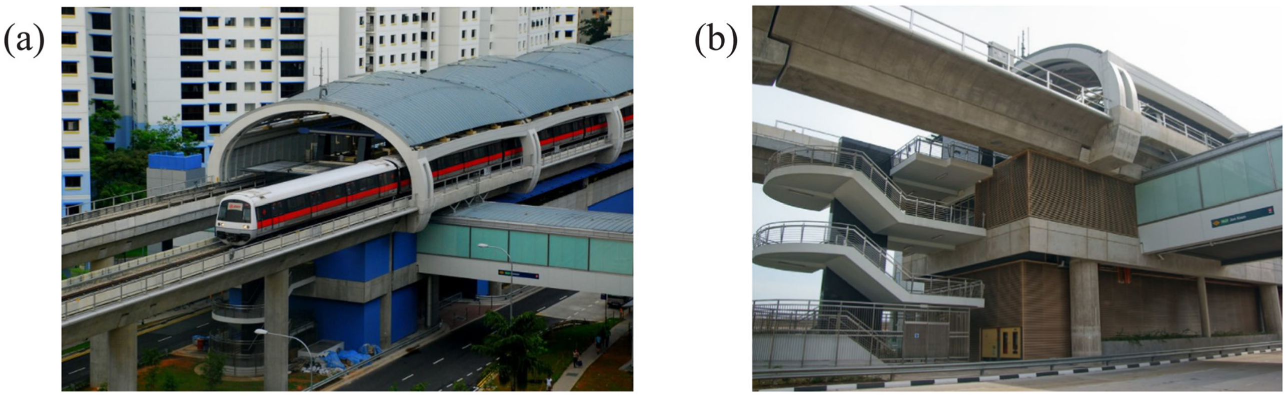

Figure 4: (a) Pioneer [11] and (b) Joo Koon stations [12] of the East-West line of Singapore.

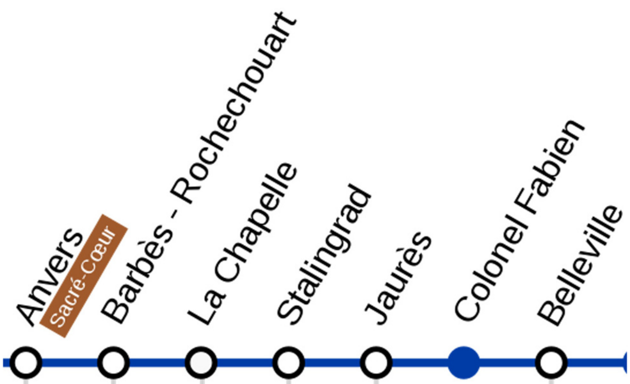

Figure 5: Part of Paris metro line 2 [13].

2 Methodology

The noise measurement in the train cabins was performed using an in-house developed app known as Noise-Explorer [10] with the microphones of the smartphone calibrated against a typical type 1 sound level meter. Details of the calibration process can be found in a recently reported work by Garg *et al.* [10]. The app would allow for the computation of the A-weighted equivalent continuous SPL (LA_{eq}), A-weighted maximum SPL (LA_{max}) and A-weighted minimum SPL (LA_{min}). Recording for each section of the train journey started after the door was closed and stopped before the opening of the door. Only one measurement was carried out for each journey. All measurements were conducted in the cabin just behind the control room of the train. The measurement durations of all journeys were different and are presented in Tables 1–5. Most of the reported studies on cabin noise of MRT system were still based on A-weighted SPL (dB(A)). For this study, the noise levels were computed and presented in both dB(A) and dB (C) (C-weighted decibel scale). The dB(A) sound level applies to the mid range frequencies as opposed to the dB(C) sound level that measures low and high frequencies. The sound level in terms of dB(C) could be significantly higher than dB (A) when there is significant low-frequency content. The dB (C) was originally developed to reflect the frequency

Figure 6: Viaduct of Paris metro line 2 near (a) Jaures station [15] and (b) Stalingred station [16].

Figure 7: Part of the Piccadilly line from Heathrow Airport to Green Park station, London [17].

Figure 8: Chongqing line 3 from Gongmao to Lianglukou stations across Yangtze river, China [18].

sensitivity of the human ear to high sound levels in access of 85 dB [14]. However, the C-weighting is almost exclusively used to assess the low-frequency content of sound in more recent time, often in combination with the A-weighted scale. C-weighting is generally flat with respect to frequency, and thus includes more of the low-frequency range of noise. For example, in a recent article by Lee *et al.* [19] for the measurement of noise profiles emitted from construction equipment and processes commonly done in construction industry, it highlighted the significant presence of low-frequency noise at construction sites for some construction equipment and processes, especially for large construction equipment. However, the existing legal requirements in terms of noise exposure are typically defined in terms of dB(A) only but not dB(C). There were also some reported works in the use of dB(C) for the study of noise from the large offshore wind turbine due to the presence of significant low-frequency noise [20].

3 Results and discussion

3.1 Singapore East West line

The cabin noise for the journey from Tuas Crescent to Jurong East stations for the East-West line is shown in Table 1. The LA_{eq} shows a distinct difference between the first three sections from Tuas Crescent to Pioneer stations with an average LA_{eq} value of 80.9 dB(A) compared to the average LA_{eq} value of 75.6 dB(A) for the remaining four sections from Pioneer to Jurong East stations. On the other hand, the difference in terms of dB(C) is not that distinctive. The LC_{eq} for the first three sections from Tuas Crescent to Pioneer stations has an average value of 85.2 dB(C) compared to the average value of 83.4 dB(C) for the

(a) (b)

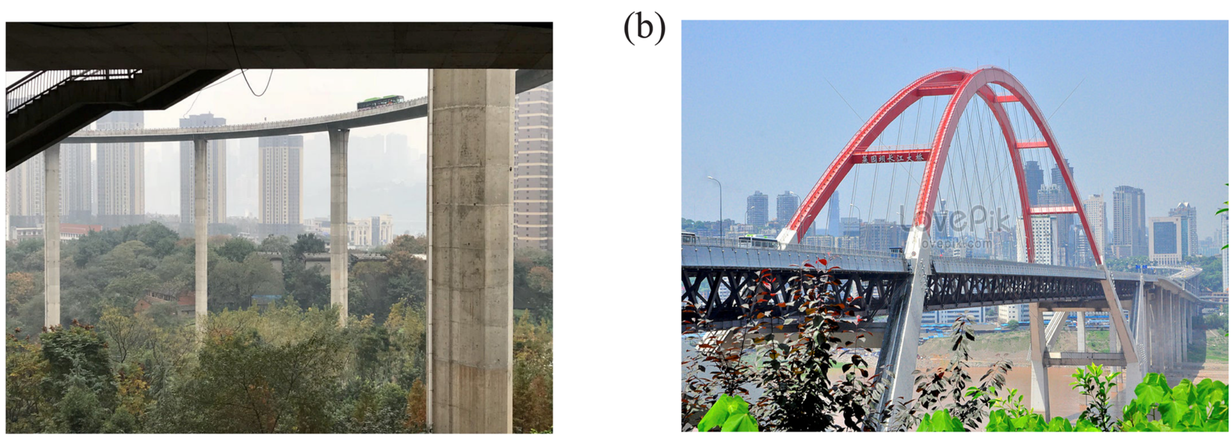

Figure 9: (a) The Tongyuanju subway station [21] and (b) the Caiyuanba bridge [22] of Chongqing Line 3, China.

Table 1: Cabin noise, measurement duration and average viaduct height for the journey from Tuas crescent to Jurong East for the East-west line, Singapore

Section	Duration (min)	Viaduct height (m)	LA_{eq} (dB(A))	LA_{max} (dB(A))	LC_{eq} (dB(C))	LC_{max} (dB(C))
Tuas Crescent to Gul Circle	2	15.9	81.4	87.7	85.5	91.6
Gul Circle to Joo Koon	3	–12	80.8	88.4	85.1	91.2
Joo Koon to Pioneer	4	8.4	80.6	88.6	85.0	91.2
Pioneer to Boon Lay	2	8.4	76.5	83.0	83.2	85.6
Boon Lay to Lakeside	2	8.5	76.8	86.5	85.3	94.8
Lakeside to Chinese Garden	3	8.8	74.6	81.1	82.5	87.0
Chinese Garden to Jurong East	4	+10.7	74.4	81.1	82.6	88.7

The signs of + and − represent the increment and decrement of the viaduct height from the first station to the second station, respectively.

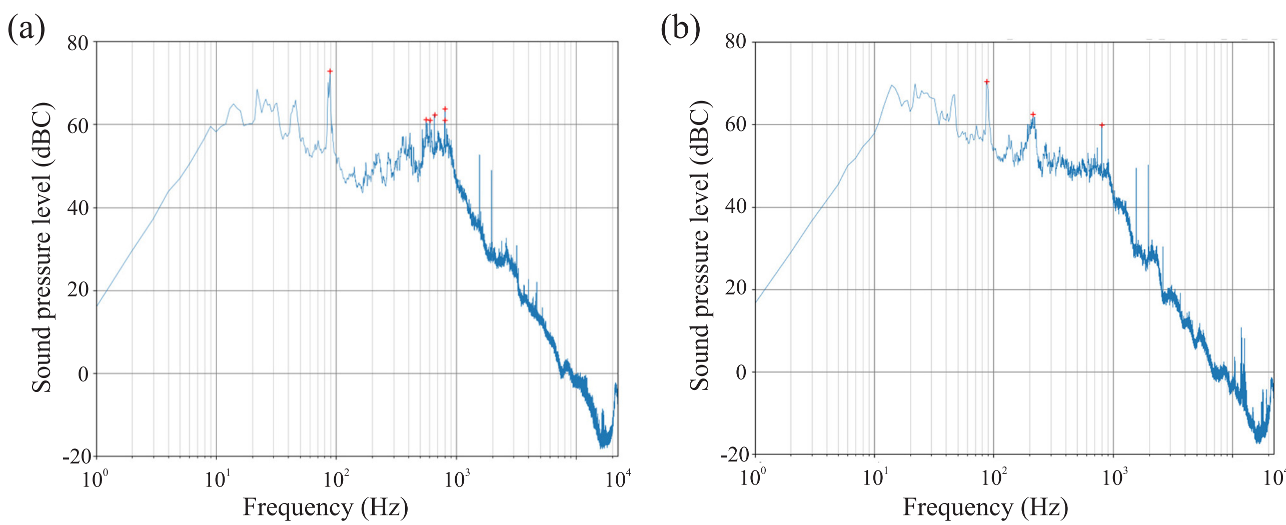

Figure 10: Spectrum of the cabin noise in terms of dB(C) for (a) Tuas Crescent to Gul Circle and (b) Boon Lay to Lakeside stations.

remaining four sections from Pioneer to Jurong East stations. The viaduct has a gradual increase in height from Pioneer to Gul circle stations and the height of the viaduct from Jurong East to Pioneer stations is much lower than the height of the viaduct at Gul Circle station. Figure 10 shows the spectra of the cabin noise in terms of dB(C) for Tuas Crescent to Gul Circle stations and for Boon Lay to Lakeside stations. The difference between the two spectra, presented in Figure 11 for dB(A), shows less significance. Comparing the spectra between dB(A) and dB(C), there is a significant peak at about 90 Hz which was not reflected in the spectra in terms of dB(A). For the spectrogram in terms of dB(A) for the same two segments as shown in Figure 12, we can see that the spectrogram for the section from Tuas Crescent to Gul Circle has more significant lower frequency content compared to the spectrogram for the section from Boon Lay to Lakeside. This could explain the more than 5 dB difference in terms of LA_{eq} for dB(A). The higher cabin noise could be due to the low-frequency vibration of the floor and walls of the train as reported in the Guangzhou study by Yan *et al.* [2]. The higher level of vibration may impose more stringent requirement for the electronic circuitries and equipment on board the train. The lower frequency noise could be caused by the vibration of the more slander supporting columns of the viaduct.

3.2 Paris metro line 2

The cabin noise for part of Paris metro line 2 is presented in Table 2. There is elevated viaduct between Barbès-Rochechouart and Jaurès stations. There is no clear pattern between the cabin noise for the elevated track and underground track for both dB(A) and dB(C). However, the average LA_{eq} of 72.3 dB(A) is lower than the average LC_{eq}

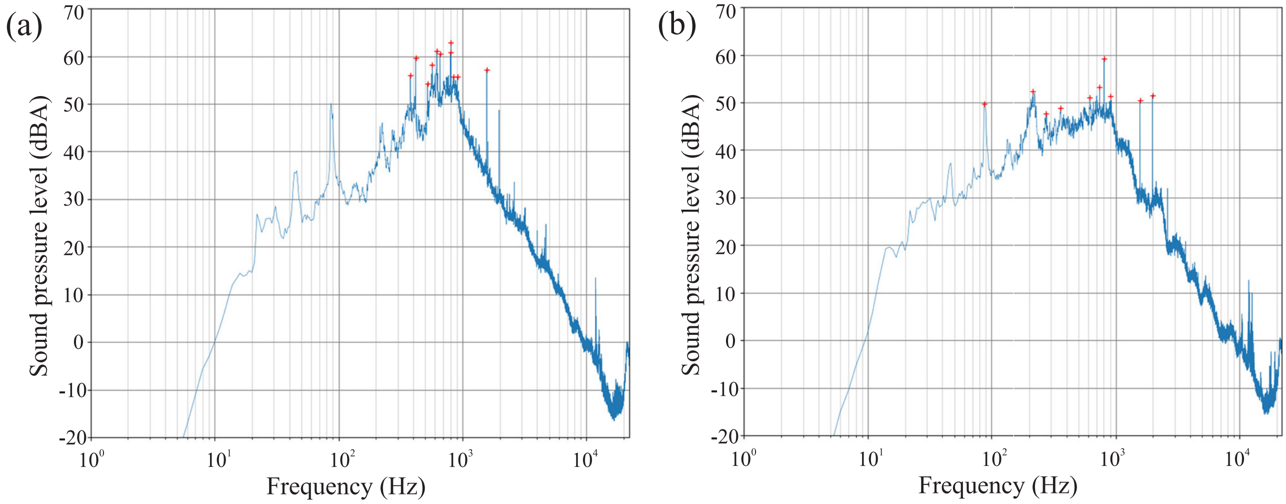

Figure 11: Spectrum of the cabin noise in terms of dB(A) for (a) Tuas Crescent to Gul Circle and (b) Boon Lay to Lakeside stations.

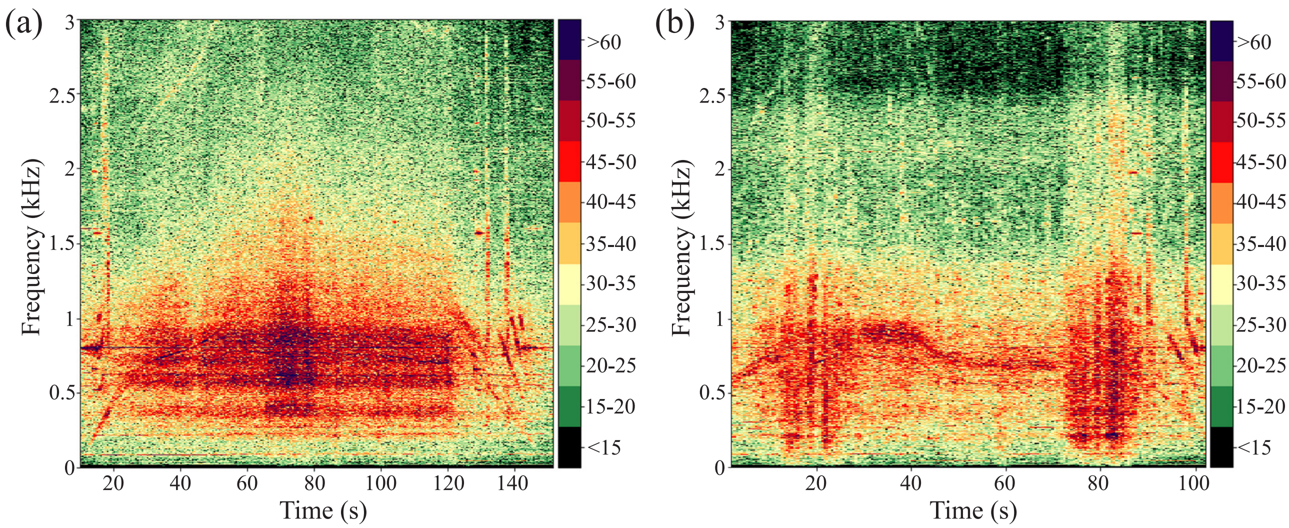

Figure 12: Spectrogram of the cabin noise in terms of dB(A) for (a) Tuas Crescent to Gul Circle and (b) Boon Lay to Lake side stations.

Table 2: Cabin noise, measurement duration and average viaduct height for the journey from Anvers to Belleville stations for Paris metro line 2, France

Section	Duration (min)	Viaduct height (m)	LA_{eq} (dB(A))	LA_{max} (dB(A))	LC_{eq} (dB(C))	LC_{max} (dB(C))
Anvers to Barbès Rochechouart	1	+6.5	64.8	71.2	81.5	88.5
Barbès Rochechouart to La Chapelle	1	9.8	69.3	73.7	87.5	93.8
La Chapelle to Stalingrad	1	9.8	70.9	79.7	83.8	89.8
Stalingrad to Jaurès	1	10.2	75.1	86.6	87.4	92.8
Jaurès to Colonel Fabien	1	−6.1	80.6	91.3	88.0	96.2
Colonel Fabien to Belleville	1	Underground	73.0	83.6	86.2	98.0

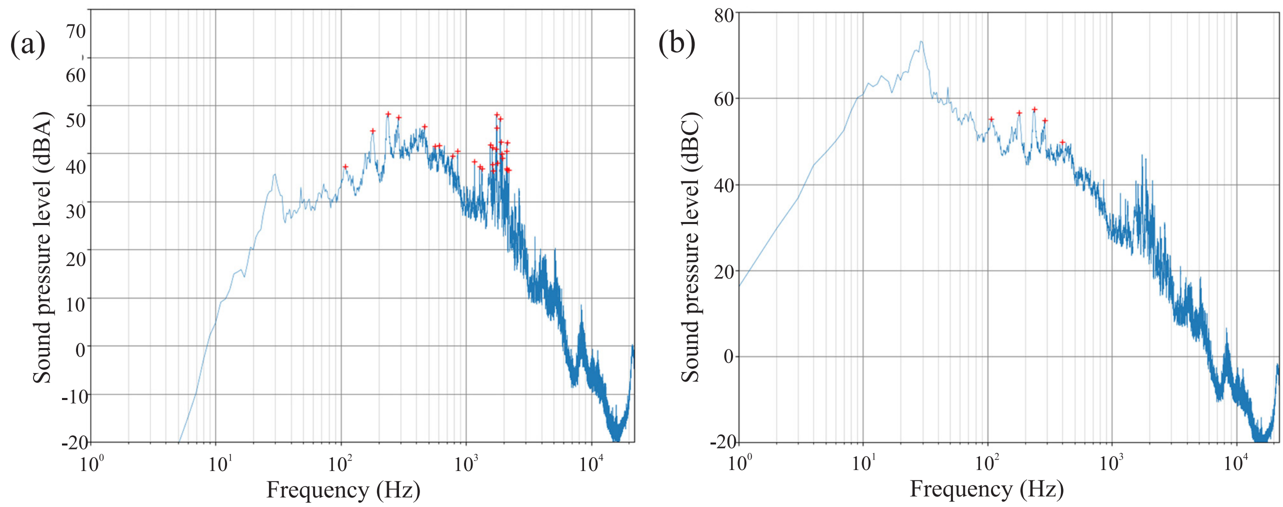

Figure 13: Spectrum of the cabin noise from La Chapelle to Stalingrad metro station in (a) dB(A) and (b) dB(C).

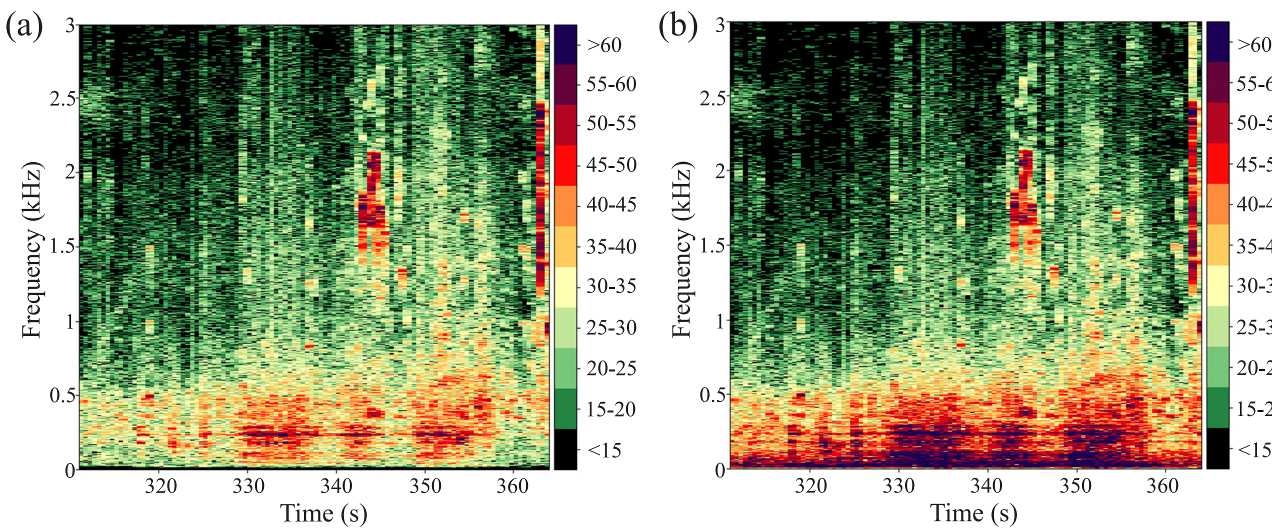

Figure 14: Spectrogram of the cabin noise from Stalingrad to Jaurès metro station in (a) dB(A) and (b) dB(C).

of 85.7 dB(C). The spectra of the cabin noise from La Chapelle to Stalingrad metro station in dB(A) and dB(C) are shown in Figure 13. It can be seen that there is a significant presence of low-frequency noise below 100 Hz which is not captured in the measurement in terms of dB(A). The spectrograms of the cabin noise from Stalingrad to Jaurès metro station in db(A) and db(C) are shown in Figure 14. It can be seen that there is a lot of low-frequency content in the spectrogram in terms of dB(C). It should be noted that the two underground stations connected to the elevated track are not very deep as many of the underground stations are deemed to be too shallow to be used as bomb shelters.

3.3 London Piccadilly line

The cabin noise for the Piccadilly line from Heathrow airport to Green Park station is shown in Table 3. On the day of the measurement, there was a diversion from Osterly to Boston Manor station via another intermediate stop due to railway maintenance work. The average LA_{eq} for all sections was 77.3 dB(A) compared to the average LC_{eq} of 86.5 dB(C). As an illustration, the spectrogram for the cabin noise from Hounslow West to Hounslow Central station is shown in Figure 15. It showed the train leaving the tunnel and entering onto a surface track. The spectrogram in dB (A) did not capture the very low-frequency content on the

Table 3: Cabin noise, measurement duration and average viaduct height for the journey from Heathrow Airport to Green park station for Piccadilly line, London

Section	Duration (min)	Viaduct height (m)	LA_{eq} (dB(A))	LA_{max} (dB(A))	LC_{eq} (dB(C))	LC_{max} (dB(C))
Heathrow terminals 1-2-3 to Hatton cross	3	Underground	86.3	90.9	93.1	95.7
Hatton cross to Hounslow West	3	Underground	82.5	88.8	93.2	99.8
Hounslow West to Hounslow central	3	+3.9	74.1	80.6	83.0	87.6
Hounslow central to Hounslow East	1	+6.6	69.9	76.4	82.0	90.8
Hounslow East to Osterly	2	–3.8	70.4	78.3	83.3	92.9
Osterly to intermediate stop (diversion)	2	+4.9	71.5	78.7	83.7	88.2
Intermediate stop to Boston Manor (diversion)	2	–4.7	74.9	85.1	86.5	96.1
Boston Manor to Northfields	3	0	73.0	82.1	81.3	89.9
Northfields to South Ealing	3	0	73.4	82.0	82.3	91.3
South ealing to acton town	2	0	75.3	84.6	83.5	92.0
Acton town to Turnham Green	3	4.8	73.0	82.9	84.5	92.0
Turnham Green to Stamford Brook	2	5	70.4	79.6	82.7	89.9
Stamford Brook to Ravenscourt Park	1	4.8	72.2	80.5	83.9	89.6
Ravenscourt park to Hammersmith	2	−3.2	72.7	83.0	83.5	91.0
Hammersmith to Barons court	2	Underground	76.6	83.6	87.9	93.6
Barons court to Earl's court	3	Underground	86.7	97.6	91.0	101.1
Earl's court to Gloucester road	2	Underground	87.4	94.3	91.8	97.7
Gloucester road to South Kensington	1	Underground	82.7	90.5	89.1	94.9
South Kensington to Knightsbridge	3	Underground	84.3	92.4	90.6	97.8
Knightsbridge to Hyde park corner	2	Underground	82.2	92.1	89.2	96.8
Hyde park corner to Green park	2	Underground	84.3	91.3	90.7	97.2

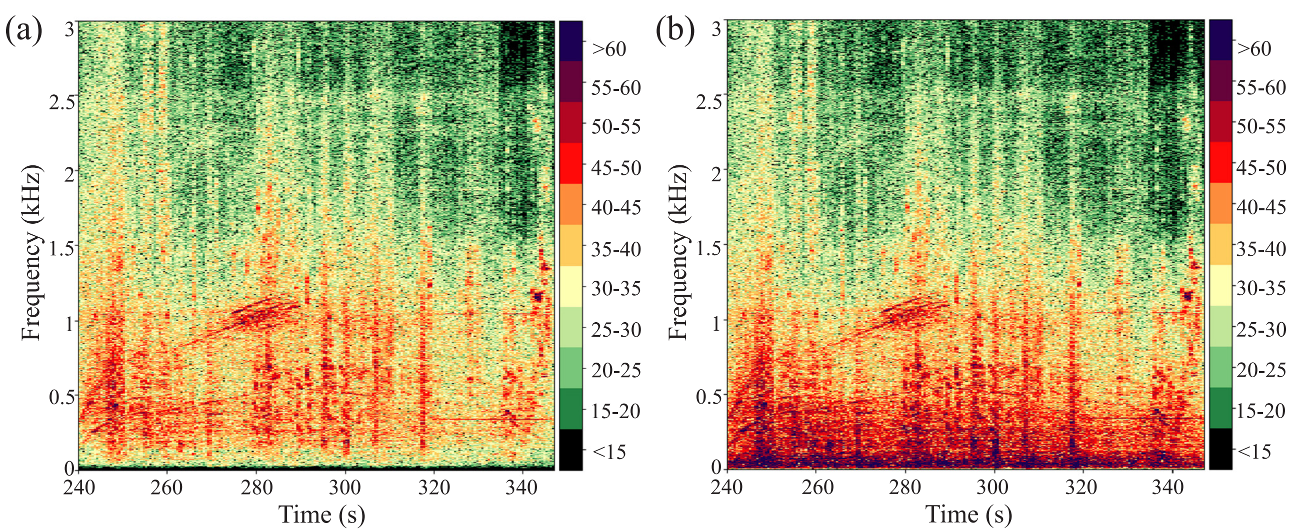

Figure 15: Spectrogram of the cabin noise from Hounslow West to Hounslow Central station in (a) dB(A) and (b) dB(C).

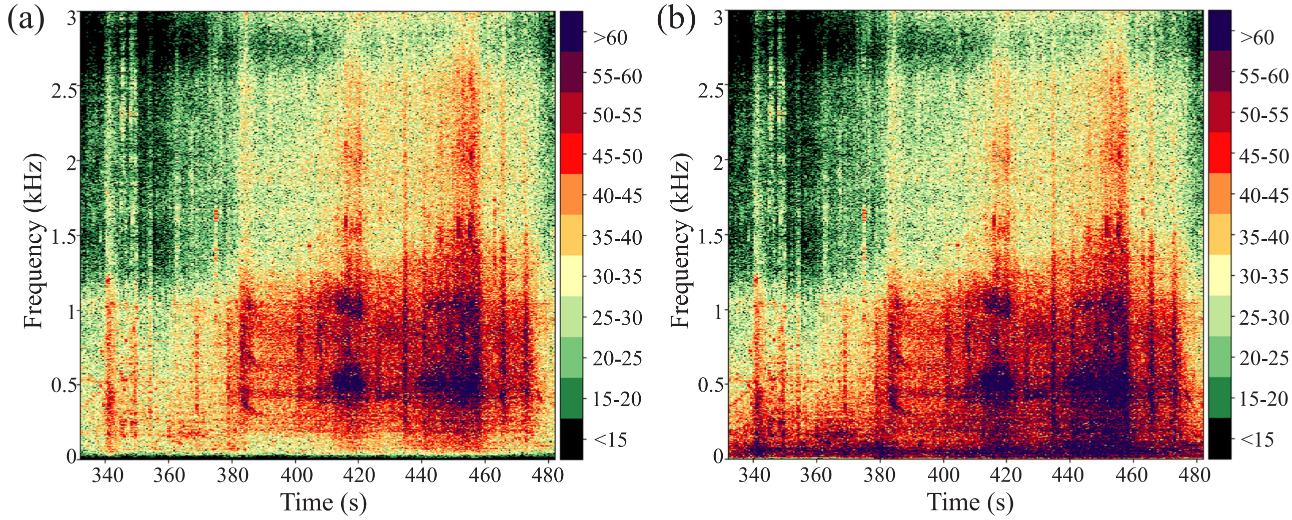

Figure 16: Spectrogram of the cabin noise from Barons Court to Earl's Court station in (a) dB(A) and (b) dB(C).

Table 4: Cabin noise, measurement duration and average viaduct height for the journey from Gongmao to Lianglukou stations of Chongqing Line 3, China

Section	Duration (min)	Viaduct height (m)	LA_{eq} (dB(A))	LA_{max} (dB(A))	LC_{eq} (dB(C))	LC_{max} (dB(C))
Gongmao to Tongyuanju	2	35.8	73.7	78.3	84.1	86.4
Tonguanju to Lianglukou	3	35.8	74.1	81.2	85.7	92.4

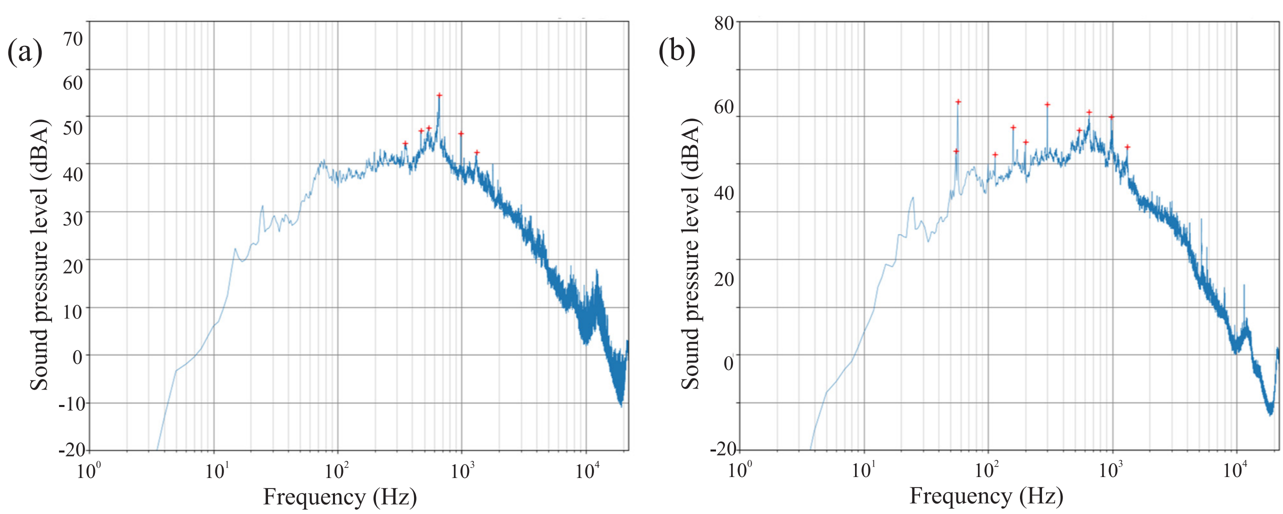

Figure 17: Spectrum in dB(A) for (a) Gongmao to Tongyuanju and (b) from Tongyuanju to Lianglukou.

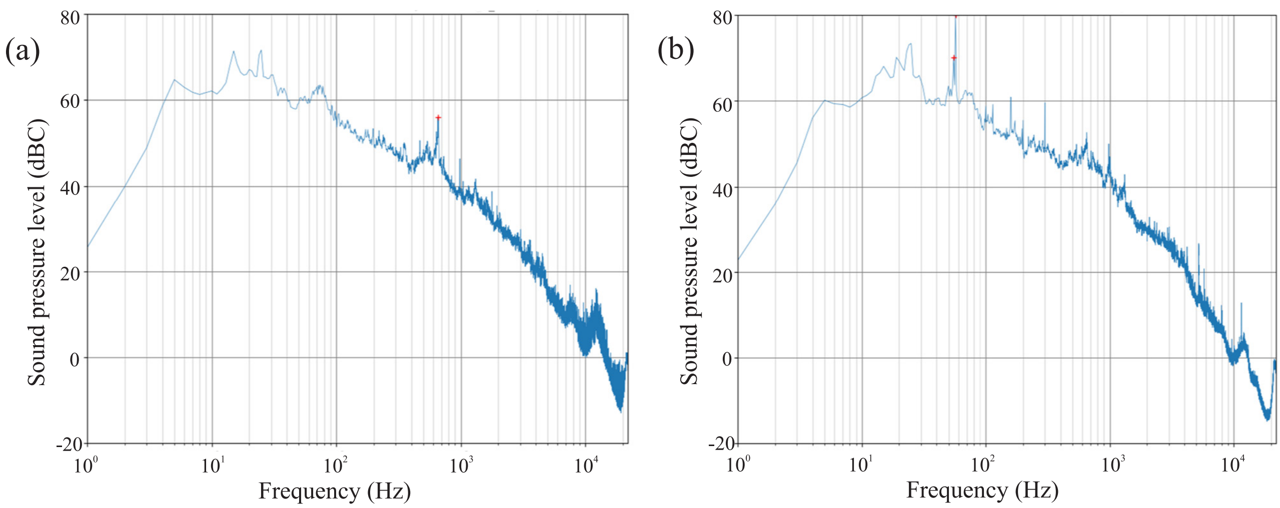

Figure 18: Spectrum in dB(C) for (a) Gongmao to Tongyuanju and (b) from Tongyuanju to Lianglukou.

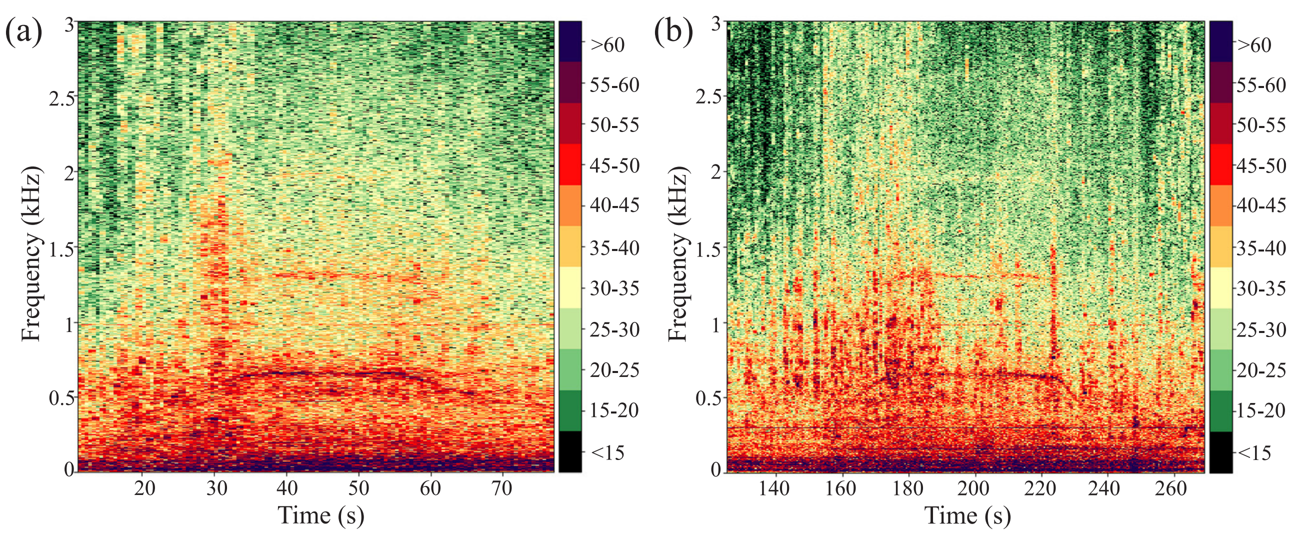

Figure 19: Spectrogram in dB(C) for (a) Gongmao to Tongyuanju and (b) from Tongyuanju to Lianglukou.

surface track. For identifying the low-frequency noise, one would need to present in dB(C). The spectrogram for the cabin noise from Barons Court to Earl's Court station is shown in Figure 16. It showed the train leaving the surface track and entering into the tunnel. Once again, the spectrogram in dB(A) did not capture the very low-frequency content.

3.4 Chongqing line 3

The cabin noise for the journey from Gongmao to Lianglukou stations for line 3 of Chongqing subway system is shown in Table 4. The Gongmao station is an underground station and from Figure 8, the section from Tongyuanju to Lianglukou stations spans across the Yangtze river below the bridge deck of the Caiyuanba Bridge. The Lianglukou station is also an underground station. The cabin noise for this stretch has interesting geometrical features from underground, under the bridge deck to an elevated track and then back to underground. The spectra in dB(A) for Gongmao to Tongyuanju stations and from Tongyuanju to Lianglukou stations are shown in Figure 17. Even for dB(A), there is a significant peak below 60 Hz. In terms of dB(C) as shown in Figure 18, the cabin noise is all dominated by low-frequency noise. For the stretch below the bridge deck, there is a dominating frequency of close to 60 Hz. The spectrograms as shown in

Table 5: Comparison of cabin noise for the four rapid transit systems

Rapid transit system	Duration (min)	Average LA_{eq} (dB(A))	Average LC_{eq} (dB(C))
Tuas Crescent to Jurong East station of East West line, Singapore	20	66.2	84.2
Anvers to Belleville station of Paris Metro line 2	6	72.3	85.7
Heathrow terminals 1-2-3 to Green Park station of Piccadilly line	47	77.3	86.5
Gongmao to Lianglukou station of Chongqing line 3	5	73.9	84.9

Figure 19 confirm the intense low-frequency content of the cabin noise. The differences between L_{eq} in dB(A) and dB(C) for both sections are all slightly above 10 dB.

3.5 Comparison of cabin noise for the four rapid transit systems

A summary of the findings from these four different rapid transit systems are presented in Table 5. It can be seen from the findings that the cabin noise of the four rapid transit systems in terms of dB(C) is quite close to each other from 84 to 87 dB(C) although the difference in terms of dB (A) is much wider from 66 to 78 dB(A). The reason for the wide difference in dB(A) is because of the low-frequency content, which may not be accounted for A-weighted noise measurement. As the average LA_{eq} for cabin noise is found to be well below 85 dB(A), there is no risk of exceeding the daily exposure to noise of 85 dB(A) for 8 h under the NIOSH regulation for the four rapid transit systems. However, as many reported studies have shown that prolonged exposure to low-frequency noise may lead to disorders, discomfort, sensitivity to and irritability from noise, annoyance, hearing loss and cardiovascular diseases [23], there may be a need to carry out a more detailed study of the effect of low-frequency noise on passengers. The low-frequency noise is most likely caused by the vibration of the floor and walls of the train, influenced by the coupled vibration of the supporting structures besides the motion of the train. If the supporting structures in the form of viaducts or bridges are slender or large with low natural frequencies, they will likely to cause much more significant low-frequency content for the cabin noise. It may be prudent to carry out a more detailed vibroacoustic analysis of the train for the prediction of the cabin noise.

Cabin noise of a vehicle is influenced by the aerodynamics noise as well as the complex coupled vibroacoustic of a train. The problem is to some extent similar to the prediction of aircraft cabin noise although some of the input forces are different. Jognescu [24] reported that commercial airplane had used test-based methods to improve the accuracy of an acoustic aircraft cabin model that can save engineering time by predicting acoustic properties of new cabin configurations prior to physical testing. The reason was due to the cost of physical testing, the traditional method for evaluating aircraft cabin acoustics and any potential changes to the design during the prototyping phase would be expensive. Atmaja *et al.* [25] reported that the cabin noise of a train could be predicted as a function of the train velocity, taking into consideration the noise of wheel, track and the friction of both. Other components such as electrical instruments, mechanical equipment and structure construction add the noise level of the train. The cabin noise of a train in a tunnel or a high-speed train is more likely to be dominated by the aerodynamic noise [26]. For a rapid transit train moving at relatively slower speed in comparison to high speed train and aircraft, the low-frequency cabin noise is more likely caused by the coupled vibration of the train and the supporting structures. Detailed simulations could be complex and costly but it may be worthwhile to investigate via modeling and simulation at the initial stage of design before deciding on the shape and structure of the train to avoid the unlikely coupled resonance of the train and the supporting structure, which may result in excessive low-frequency cabin noise. The changing of the design of the train such as the cabin shape and also the supporting structures at a later stage would be costly and time-consuming.

4 Conclusions

In the present study, we would attempt to carry out a more detailed study of the effect of viaduct height, in particular viaducts of different heights on the cabin noise of various rapid transit systems. The present study examined and benchmarked the cabin noise in terms of both dB(A) and dB(C) for four different rapid transit systems, namely part of the East-West line including the TWE on elevated tracks with very high viaduct based on reinforced concrete of the Singapore MRT System; part of Paris line 2 from Anvers to Belleville stations including a stretch of elevated track on viaduct based on more traditional steel-frame structures; part of the Piccadilly line of London from Heathrow Airport to Green Park stations with a stretch on surface ground; and finally, part of Chongqing line 3 from Gongmao to Lianglukou stations across the magnificent Yangtze river. It can be concluded from the data of the Singapore MRT system and Paris line 2 where the noise levels in terms of both dB(A) and dB(C) increase with the increase in the viaduct height. However, no similar trend is found for Piccadilly line of London.

These four rapid transit systems have different features but a surprised finding is that the cabin noise in terms of dB(C) is very close to each other within 3 dB. All the four rapid transit systems showed significant low-frequency content as reflected by the significant difference between the average L_{eq} in terms of dB(A) and dB(C). As the average LA_{eq} for cabin noise is found to be well below 85 dB(A), there is no risk of exceeding the daily exposure to noise of 85 dB(A) for 8 h under NIOSH regulation for the four rapid transit systems. However, the significant presence of low-frequency noise as manifested by the average LC_{eq} in dB(C) is worthy of further study to investigate the potential health effect, especially for passengers and crews who spend a long duration on the train. Modeling and simulation could also be used during the early design stage to investigate the potential coupled vibration of the train and the supporting structures, which may lead to excessive low-frequency noise in the cabin. This is an area with limited reported studies and there are potentials for future research.

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