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Experimental Study of Airborne Noise Reduction of Concrete Channel Girder Bridge Sections Compared With Box Girder for High-Speed Trains

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Summary

Channel girder is a new type of concrete railway bridge girder section compared with traditional box girder. Channel girder has a U-shaped section with side beams of approximately 2-meter high. In terms of airborne noise, it resembles box girder with sound barriers of the same height, giving it the potential of noise reduction compared with box girder, which may lead to possible cost saving. In this research, the relative noise reduction of channel girder compared with box girder is studied through computer simulation, scale model experiment and full scale model experiment. Additionally, comparisons are made between the relative noise reduction of channel girders with different angles between the deck and side beams, different speed of trains, different train locations, different experimental methods and different receiving points. The results indicate that channel girders can provide effective noise reduction compared with box girder, with a noise level reduction no less than 4 dB at a receiving point of 25 m from the railway midline, 3.5 m above the top of the rail when the side beam angle is 113° and the train is running at 300 km/h on the rail that is closer to the receiver. Increasing the side beam angle is shown to have negative correlation with noise reduction.

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1. Introduction

As a fast and eco-friendly transportation, high-speed trains are getting more and more popular in China and many other countries in the world. In China by the year 2015, the operational length of railways built for train speed over 250 km/h had reached over 19,000 km. However, with train speed increasing over the years, noise is becoming an ever more serious problem [1, 2, 3]. For instance, along the Beijing-Tianjin high-speed railway, the noise level can reach as high as 80 dB(A) at 60 m away from the rail when the train is running [4]. The noise measurement method is specified in ISO 3095: 2013 [5] and GB12525-90 [6], which are the international and Chinese standard respectively, and the latter also gives a maximum Leq limit of 70 dB (A) measured in one hour at 30 m away from the outer rail. In Europe, TSI "Rolling Stock - Noise" gives a Leq limit of 85 dB (A) for pass-by noise of locomotives at the speed of 80 km/h [7]. Numerous experiments have proven that noise from trains on railways had negative physical and psychological effects on people living or working nearby [8, 9, 10]. Therefore, researchers are analyzing and looking for countermeasures for external noise of high-speed railways [11, 12, 13, 14, 15, 16, 17, 18]. Structure-borne noise and airborne noise are the two main aspects of railway noise, and only airborne noise will be considered in this paper. Railway airborne noise emission is found to be coming from multiple sources, and the significant ones includes: 1) wheel/rail rolling noise, which mainly comes from the lower part of the train, 2) traction equipment noise, which also comes from the lower part, 3) aerodynamic noise, which is dominant at train bodies, bogies, inter-car connections and pantographs, 4) train equipment noise, which comes from the train bodies, and 5) pantograph friction and electric discharge noise, which comes from the pantographs at the top of the train [14, 15, 16, 17, 19, 20].

Methods were developed aiming to control each type of noise. Existing methods including decreasing the contact stiffness between wheel and rail, adding rail dampers, applying rail lubricators against curve squeal, installing under-ballast mats, using foamed ballast, installing under-sleeper pads, applying friction modifier for rail brakes and adding insulation plates beside the pantographs [14, 17,

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21, 22, 23, 24, 25], are proven to be partially effective in reducing the external noise of high-speed railways. Among them, noise barriers fixed alongside the rail/road is a very commonly used, well-studied and effective method for reducing airborne traffic noise including railway noise, with noise reduction ranging from less than 5dB to over 15dB [26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41]. The study and use of noise barriers date back to half a century ago, Maekawa [26] and Kurze [27, 28] and numerals successive researchers have calculated the noise reduction of noise barriers, which was found to be relevant to the dimensions and materials of the barriers, and the dimensions and frequency characteristics of the noise sources.

Channel girder, also known as U-girder or trough girder, is a new type of bridge girder cross-section for concrete railway bridges as a variant of box girder (Figure 1). Compared with box girder, its main advantage is the reduction of solid height, thereby saving space and creating higher headroom [42, 43]. Moreover, it has a "U" shaped section that to some extend resembles parallel noise barriers, giving it a great possibility to have the ability of airborne noise reduction. Compared with noise barriers, using channel girders for noise reduction doesn't require extra construction or investment. However, due to the short history of channel girder, limited research or experiment has been found investigating the effect of airborne noise reduction of channel girders compared with box girders. Moreover, the height of channel girder's side beams is strictly limited for structural and construction reasons, and this could restrict the effect of sound attenuation. Therefore, the noise reduction ability of a typical channel girder needs to be verified.

The objective of this research is to quantitatively examine if concrete channel girder bridge section can provide better railway airborne noise reduction compared with box girder, and to provide helpful support for the design of channel girder railway bridge sections.



Figure 1. Examples of channel girder and box girder. a) Channel girder used for Lanzhou-Xinjiang railway. b) Box girder used for 2nd Cross-Sea Bridge in Hangzhou Bay Area.

2. Methodology

Comparison and control variant methodology is used to investigate the relative noise reduction of channel girder compared with box girder instead of the absolute value. That is to say, in every experiment, besides different settings of channel girders, a box girder is tested as a contrast experiment. Three experimental methods are used in this investigation: 1) computer simulation, 2) scale model experiment and 3) full scale model experiment. This section first presents information about the noise source, and then gives details about each experimental method.

2.1. Noise source

The noise of high-speed trains is measured and collected by the Third Railway Survey and Design Institute Group Corporation on multiple high-speed trains in China [4, 44, 45]. Microphone array is used to record the noise and the recorded noise was averaged in the measurement time interval Tp according to ISO 3095:2013 [5]. Then the spacial distribution of sound power is acquired by beamforming and deconvolution technique using B&K Pulse 18.0 software. It is found that the noise of high-speed trains is concentrated in 5 vertical areas: bridge structure, wheel/rail area, train body lower part, train body upper part and pantograph. It is also revealed that these 5 areas account for 17%, 48%, 25%, 6% and 4% of the total noise respectively [44].

Based on the results above, the source of airborne noise is simplified to 3 line sources in this research according to the vertical distribution (Figure 2). The noise in bridge structure is not included as the goal of this research is to study the reduction of airborne noise. The lower part of the body noise is amalgamated with the wheel/rail noise, because the distance between the two sources are very small. Therefore, the 3 line sources used in the experiment are: 1) the bottom noise (shown as Śsource 1' in Figure 2, consisting mainly of wheel/rail rolling noise, traction noise and bottom aerodynamic noise), 2) the body noise (shown as Śsource 2' in Figure 2, consisting mainly of train body aerodynamic noise and train equipment noise) and 3) the pantograph noise (shown as Śsource 3' in Figure 2, consisting mainly of pantograph aerodynamic noise, pantograph friction noise, and electric discharge noise). The sound power of each line source is calculated by summing up the total sound power of all sources within the corre-

sponding area in the spacial distribution. The horizontal locations of the line sources are within the boundary of the projection of the train body, and the vertical locations are at the equivalent heights, which is the sound-power-weighted average height of all sources within the corresponding area (Table A1). However, the directivity patterns of the sources are complicated and cannot be singularly picked out by the analyzing techniques used by the Third Railway Survey and Design Institute Group Corporation [44]. Due to this limitation, the line sources are treated as omni-directional throughout this research. Although the simplified noise sources cannot fully represent the train noise, they capture the main characteristics and thus are used in this research.

The sound power levels of the 3 line sources in 1/3-oct bands (from 250 Hz to 6300 Hz, unweighted spectrum) are presented in Figure 3 (See Table A1 for numerical information). The wheel/rail noise, the aerodynamic noise and other noise sources may change when the train runs at different speeds, and the noise reduction result may also be different consequently. Therefore, the noise sources are measured for two typical train speeds: 300 km/h and 340 km/h. In each measurement, the frequency characteristics and vertical distribution of the noise were measured and simplified to 3 line sources according to the stated method. It can be seen from Figure 3 that at both speeds, the bottom noise has the highest sound power levels among the three line sources for most frequencies (400 Hz and above), and contains mostly mid- and high-frequency noise (500 Hz to 5000 Hz). Body noise and pantograph noise, which respectively have the second and the third largest sound power levels for most frequencies, both have their peak around 500 Hz to 630 Hz at both speeds. It can also be seen that the sound power levels of the three sources increase when the train runs faster (the bottom, body and pantograph noise increase by 1.4 dB, 2.2 dB, and 2.9 dB respectively. See Table A1 for more detail), but the shape of the spectra remains very similar.

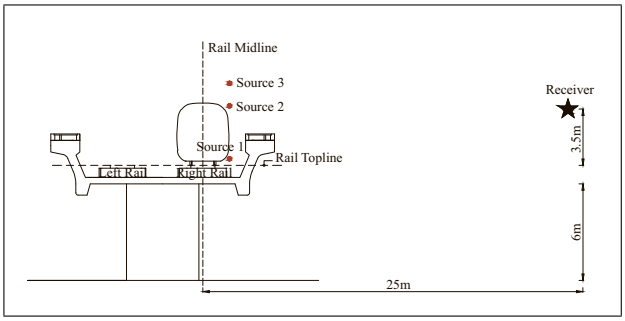

Figure 2. The sound sources in the research and the receiving point for computer simulation.

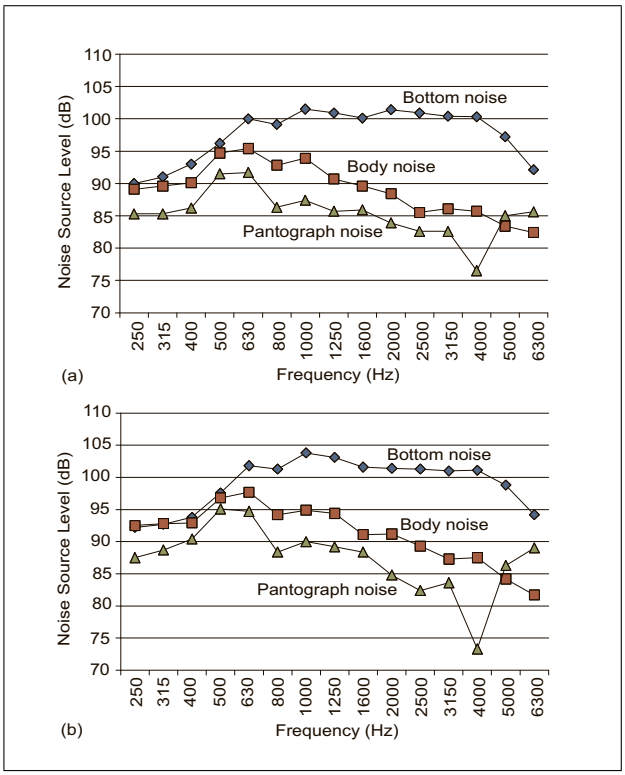

Figure 3. The sound power levels of the 3 line sources in 1/3-oct band. a) 300 km/h, b) 340 km/h.

2.2. Computer simulation

Computer simulation is a widely used method for acoustic experiments that requires no actual construction or costs and can present a visualized simulation [46]. The software SoundPLAN is used in this research to simulate the sound field around a train on a bridge using channel girder or box girder and provides a general understanding about the acoustic environment around the two types of bridges. SoundPLAN is a noise calculation and mapping software for environmental noise prediction. The calculation method used in the software is based on standards including ISO 9613 [47], ISO 3891 [48]. It employs the search angle method to calculate the main reflections between objects (in this case, the train body, the bridge girder, etc.), and the extra path length method for the calculation of diffraction over obstacles (in this case, the side beam) [49]. SoundPLAN simulation requires the following input data: 1) the computer model of physical objects, 2) the material of relevant surfaces, and 3) the information of sound source and location of receiver. The acquisition of the data will be specified respectively in the following paragraphs.

In order to investigate the sound attenuation of channel girder at different situations, three variables are considered in the simulation: a) the angle between the deck and side beams, b) the train speed used for generating the noise source, and c) the position of the train (the variation settings of the variables are explicated in Section 2.2.4). It is clear that the height of side beams is also likely to be an influential factor of the sound attenuation of channel girder, however, the height is mainly determined by structural and construction requirements and can hardly be increased for acoustics. Therefore, the effect of different side beam heights is not investigated in this research.

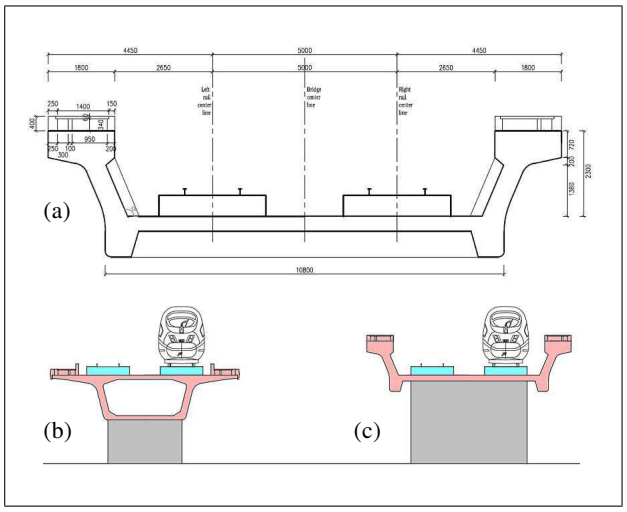

Figure 4. Cross-section models of the box girder and the channel girder. a) Dimensions of the channel girder, b) Cross-section of the box girder, c) Cross-section of the channel girder.

2.2.1. The computer model of physical objects

First the section sizes of channel girder and box girder are chosen according to the *Code for design on reinforced and pre-stressed concrete structure of railway bridge and culvert* (the standard code in China) [50] based on their mechanical properties, ensuring that the channel girder can afford as much load as the box girder. Then the cross-sections of the two kinds of girder are drawn with real dimensional data in the software AutoCAD according to the standards and exported to SoundPLAN to generate 3D models. The dimensions of the channel girder are shown in Figure 4a. This is the standard section in Chinese railway bridge channel girder design, and this experiment only includes the noise reduction of the original structure of the beam without adding extra noise barriers. The side beams of the channel girder are 2.3m high and with top surfaces 1.8m wide. Both the decks of the box girder and channel girder are 10m wide, with 2 sets of rails. The decks of the two girders are set at the same height, in this case 6m as a regular height of railway bridges, to control variable. The length of the model is 50m. Figure 4b and Figure 4c indicates the cross-section models of channel girder and box girder used in this experiment.

Originally 6 values are chosen for the angle between the deck and side beams (shown as α in Figure 4a): 90°, 100°, 110°, 120°, 130° and 140°, to distribute evenly among the normal range of angles for channel girders. Then different angles are considered together with other factors including structural, aerodynamic, economical, etc. As the angel chosen by construction engineers after structural optimization, 113° is also added in the computer simulation.

Also, to take the influence of sound reflection on the train body into consideration, a long cuboid representing the train is added in the model.

2.2.2. The material of relevant surfaces

The material used for actual bridge girders is reinforced concrete and the train body is coated aluminum, both highly reflective materials. Therefore, the input material acoustic characteristics for the girders in the software are simplified highly reflective material, with an absorption coefficient of 0.02 at all frequencies.

Table I. Experiment settings for software simulation. Shape: Section Shape, Angle: Side beam angle, *v*: Train speed (km/h), Position: Train position.

Case No.	Shape	Angle	*v*	Position
C0-1	Box girder	/	300	Right rail
C0-2		/	340	
C0-3		/	300	Left rail
C1-1	Channel girder	90	300	Right rail
C1-2		100		
C1-3		110		
C1-4		113		
C1-5		120		
C1-6		130		
C1-7		140		
C2-1		90	340	Right rail
C2-2		100		
C2-3		110		
C2-4		113		
C2-5		120		
C2-6		130		
C2-7		140		
C3-1		90	300	Left rail
C3-2		100		
C3-3		110		
C3-4		113		
C3-5		120		
C3-6		130		
C3-7		140		

2.2.3. The information of sound source and receiver

The simplified noise source (See Section 2.1 for details) at different height was input in the software as three omni-directional line sources. The receiving point picked for data collection is 25 m from the midline of the rail and 3.5 m above the level of the top of the rail as a standard receiver location [5] (Figure 2).

2.2.4. Test cases

The settings of cases are listed in Table I. It should be noted that the right rail refers to the rail that is closer to the receiver, while the left rail is the further one to the receiver (See Figure 2 for definition).

2.3. Scale model experiment

Scale model is a commonly used method in acoustic experiments [30, 31, 32]. Compared with full-scale model, scale model costs less money and construction work, and is more flexible in the aspects of time and space. Compared with computer simulation, it can take into consideration the fluctuation of the sound waves and thus make better predictions of the real situation.

2.3.1. Experimental environment

The experiment is conducted in a hemi-anechoic chamber, with the floor using reflective material while the walls and roof using highly-absorptive material, to simulate the environment of open space. The background noise in the chamber reaches as low as 14.1 dB(A). Because the chamber is in the basement and is a box-in-box structure, the temperature and humidity of the chamber remain stable during the experiment (the average temperature is 17.1°C, and the average humidity is within 37.6%).

2.3.2. Selection of the scale

In order to best recast the real acoustic environment, the sound wave in the scale model should have a correspondingly scaled wave length [51, 52],

$$\lambda_m = \frac{1}{n}\lambda_r, \quad f_m = nf_r,$$

where $1/n$ is the scale of the model, λ_m and λ_r are the wave length in the model and in reality (in m), f_m and f_r are the frequency in the model and in reality (in Hz).

The frequency range applicable for the microphones and receivers available for this experiment is within 20 kHz. Therefore, if the scale of the model is too small, the high frequency part of train noise cannot be calculated. Considering the energy of train noise mainly distributes within the frequency range of 20–4000 Hz, the scale shouldn't be smaller than 1:5. The laboratory room space and construction cost also restrain the max scale. If the scale is too big, the length of the model (which is 5 m, limited by the room) will be too small compared to the width, resulting in great inaccuracy. Balancing these aspects, 1:5 is the relatively suitable scale in this experiment.

2.3.3. Settings of the model

a) Model construction

The models of the bridge girders are built by 18mm-thick wooden panels with a layer of acrylic resin paint 1 mm thick applied to the surfaces. This material is chosen because it is the standard scale model material to simulate concrete according to Chinese national standard [53]. The material was measured in a model reverberant chamber, and the absorption coefficient stays below 0.1 at all frequencies, therefore can well represent the acoustic characteristics of concrete. Both ends of the bridge model are sealed with 50 mm thick glass wool for absorption to eliminate the influence of propagation from the ends.

One box girder model and one channel girder model are made. The size of the deck is 5 m long, 2 m wide (Figure 5a). The length is determined by the size of the hemi-anechoic chamber and the width is scaled from the approximate width of rail bridge girders. The side beams of channel girder model are 0.46 m high and are fixed on the deck with detachable bolts, enabling adjustment of the angle, for verifying the influence by the angle of the side beams. Due to construction and cost considerations, the number of angles chosen for the scale model experiment must be cut down from 7 in the computer simulation. Although 90° is likely to be the best option for sound attenuation (the computer simulation results also indicate this, see Section 3.1 for details), as the angle approaches 90°, the width of the deck has to be increased or the side beams will affect the running train, and this will cause the cost to increase significantly. Therefore, after taking both acoustic factors and other factors together into consideration, only 2 angles that are most possible options for real construction are tested in the scale model test: 113° and 120° (the angle is defined as α in Figure 4a).

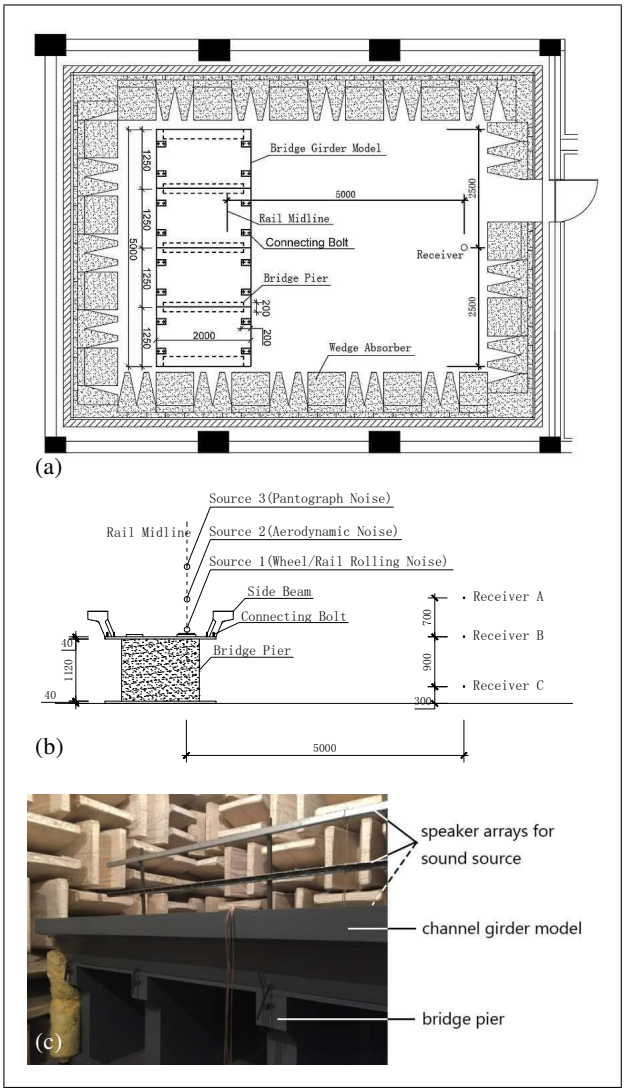

Figure 5. Settings of the scale model experiment. a) Plan of the bridge girder model and the receiver in the hemi-anechoic chamber, b) Section of the bridge girder model, the sound sources and the receiver, c) the sound sources made up with speaker arrays.

The model is placed at the corner of the hemi-anechoic chamber to ensure enough space for the required receiving point (Figure 5a). The cuboid model of train body is also added on the deck in order to take into account the sound reflection on the train, made with the same kind of painted wood as bridge girders.

b) Sound source

Table II. Experiment settings for scale model experiment.

Case No.	Shape	Angle	v	Position
S0-1	Box Girder	/	300	Right Rail
S0-2		/	340	
S1-1	Channel Girder	113	300	
S1-2		120		
S2-1		113	340	
S2-2		120		

Small omni-directional speakers closely arrayed in lines are used in this experiment to simulate the omni-directional line sources. In order to verify the directivity patterns and avoid constructive or destructive interferences between the speakers [54, 55, 56, 57], the emission fields of the sources have been tested and no significant directivity or interference is found (see Appendix for details). Therefore, the speaker arrays are proven to be able to simulate the onmi-directional line sources well. The train noise at the speed of 300 km/h and 340 km/h presented in Section 2.1 is calculated and transformed to frequencies 5 times higher. The generated sound is played in the speaker array in 3 lines to simulate the bottom noise, body noise and pantograph noise respectively (Figure 5c).

c) Receiver

The positions receiving points in the scale model includes the same position in the computer model, which is 25 m (5000 mm in the model) from the midline of the rail and 3.5 m (700 mm in the model) above the top of the rail (receiver A). In addition, 2 heights are added in the same vertical line, which are the level of the rail (6m above ground level, receiver B) and 1.5 m above ground (receiver C), i.e. 1200 mm and 300 mm from the ground in the scale model respectively (Figure 5b). In the direction parallel to the rail, the point is selected at the middle point of the length of the rail model. In each experiment case, the receiving microphone is connected to a real-time analyzer for data analysis.

2.3.4. Test cases

The settings of different cases are shown in Table II.

2.4. Full scale model experiment

In order to verify the experimental findings in the simulations and scale model experiments, a full scale model experiment is conducted to test the sound reduction performance of channel girder compared with box girder. With the material acoustic characteristics and sound source frequency range exactly same as the real situation, full scale tests can provide closest simulations. However, the huge costs and difficulties of full scale model construction and experiment limit its flexibility. Therefore, it is best used as final verification.

2.4.1. Experimental environment

The experiment is conducted in an outdoor open space with an area larger than 100m x 100m clear of any buildings or facilities, simulating the real environment of railway bridges. The ground is covered with greensward and the background noise level is 55dB (A).

2.4.2. Settings of the model

a) Model construction

Full-scale, real-size bridge girder models are made with concrete, the material in real situations. Due to the high costs, construction difficulties and financial limits, only one box girder model and one channel girder model is made and the length of each one is 50 m. For the angle between the deck and side beams in the channel girder model, 113° and 120° both showed good noise reduction abilities in the results of simulation and scale model test (see Section 3: Results and Analysis for details). In the computer simulation, 113° appeared to present better noise reduction but in the scale model test 120° appeared to be better. However, the difference is small compared with the overall noise reduction. Therefore, for the full scale model experiment, the angle is chosen considering other factors, including structural characteristics, financial costs and building process. The angle 113° is chosen.

The side beam of channel girder is built with steel truss and covered with calcium silicate board, which is also a highly reflective material whose absorptive coefficient stays below 0.1 similar to concrete. The model of train body is made with coated steel, which is also highly reflective, to simulate the sound reflection on the steel shell of the train (Figure 6).

b) Sound source

The sound source used in full scale model test is the noise measured from trains running at 300 km/h (see Section 2.1 for details). The measured results of bottom noise, body noise and pantograph noise are played by 3 linear omni-directional speaker arrays, similar to that in the scale model test, to simulate the frequency and location characteristics of train noise. The speakers representing bottom noise and body noise are inserted into pre-perforated holes in the coated steel representing train body and the ones representing pantograph noise are fixed on special made steel supporters on top of the train body model, their locations shown in Figure 7.

c) Receiver

The receiving points chosen for full scale model are the same as in scale model. The horizontal distance between the receivers and the railway midline is 25 m, and the vertical coordinates of the receivers are 1.5 m, 6 m and 9.5 m from the ground, among which 6 m is the level of the top of the rail, and 9.5 m is 3.5 m above the top of the rail. The receiving microphone is also connected to a real-time analyzer. The microphones are fixed on a special made steel supporter (Figure 6).

2.4.3. Test cases

The settings of different cases are shown in Table III.



Figure 6. Photos of full scale model experiment.

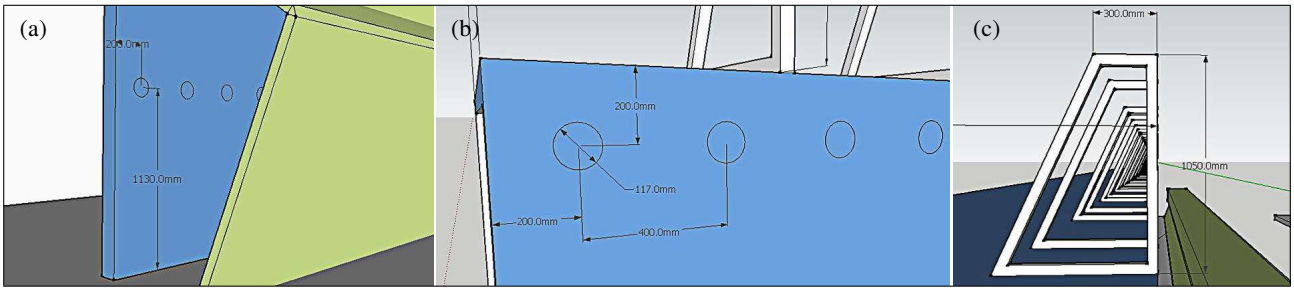

Figure 7. Location of speakers in full scale model experiment. a) Bottom noise, b) Body noise, c) Pantograph noise.

Table III. Experiment settings for scale model experiment.

Case No.	Shape	Angle	v	Position
F0 F1	Box Girder Channel girder	/ 113	300	Right Rail

3. Results and Analysis

3.1. Simulation results

3.1.1. Overall reduction

The relative noise level reduction of channel girders compared with box girders calculated in the computer simulation is presented in Figure 8. For cases numbered C1-1 to C1-7, the noise level reduction is calculated by comparing with C0-1. For cases numbered C2-1 to C2-7, the reduction is calculated by comparing with C0-2, while for case numbered C3-1 to C3-7, the reduction is calculated by comparing with C0-3.

It can be seen from the computer simulation results:

1) The noise level reduction of channel girders compared with box girders stays above 3.9 dB for all the cases conducted in this research. The best noise reduction is reached when the angle is 90°, the speed is 300 km/h and the train runs on the right side rail (the rail that is closer to the receiver), with a reduction of 7.0 dB.

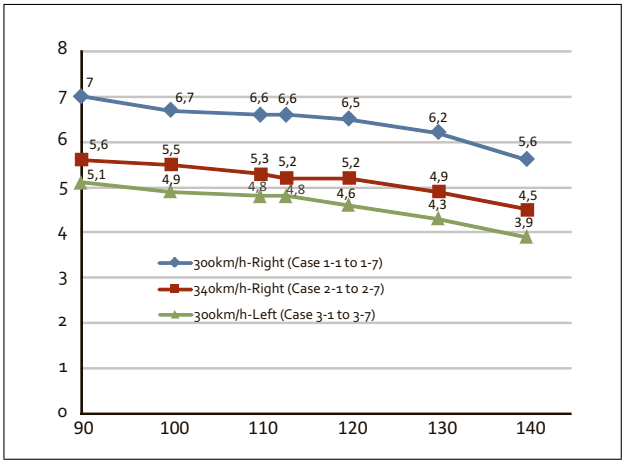

Figure 8. Noise level reduction of different angles and different speeds.

2) For the noise of trains running at different speed, the noise reduction of channel girders compared with box girders is higher when the train is running at 300 km/h

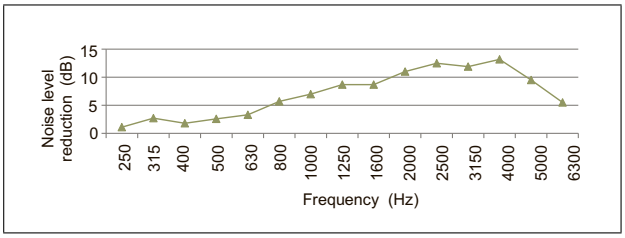

Figure 9. Frequency characteristics of noise reduction in case C1-4.

than at 340 km/h for any angle between the deck and side beams, with an average difference of 1.3 dB when the train runs on the right side rail. This phenomenon could be caused by the difference of the noise sources: As shown in Section 2.1, the sound power levels of all three line sources increase when the train speed increase from 300 km/h to 340 km/h. However, the increment of the bottom noise (1.4 dB) is lower than the body noise (2.2 dB) and the pantograph noise (2.9 dB). Considering that the side beam of the channel girders is more effective in blocking the bottom noise than the body noise and the pantograph noise, the uneven increments of the three line sources are likely to cause the phenomenon that the noise reduction is higher when the train is running at 300 km/h than at 340 km/h.

3) For the noise of trains running at different rails, the noise reduction of channel girders compared with box girders is higher when the train is running on the right rail (the rail that is closer to the receiver) than on the left rail (the rail that is farther to the receiver) for any angle between the deck and side beams, with an average difference of 1.8 dB when the train runs at 300 km/h.

4) When the angle between the deck and side beams increases, the noise reduction decreases. The difference of noise reduction between 90° and 140° is averagely 1.3 dB.

3.1.2. Frequency characteristics

The frequency characteristics of noise level reduction in case C1-4 (113°, 300 km/h) is presented in Figure 9.

It can be seen from the frequency curve that the noise reduction of channel girder increases when frequency increases from 250 Hz to 2500 Hz. The best noise reduction is reached around 2500–4000 Hz where the reduction reaches 12–13 dB, then decreases in higher frequencies. The noise level reduction stays above 10dB between 2000 Hz and 4000 Hz. Noise reduction at low frequencies is weak, with the reduction staying below 5dB when the frequency is below 630 Hz.

3.1.3. Spatial characteristics

In the simulation, computer generates plan and section drawings of the acoustic field. The drawings of box girder and channel girder (113°), both at the speed of 300 km/h, are presented in Figure 10. The drawings provide a visual comparison between the noise reduction of box girder and channel girder. It should be noted that only the noise level on the outside of the extensional line of the train body (i.e., on the right side in the drawings) is valid while the noise level on the inside (i.e., on the left side) is not representative, because the noise sources are only defined on

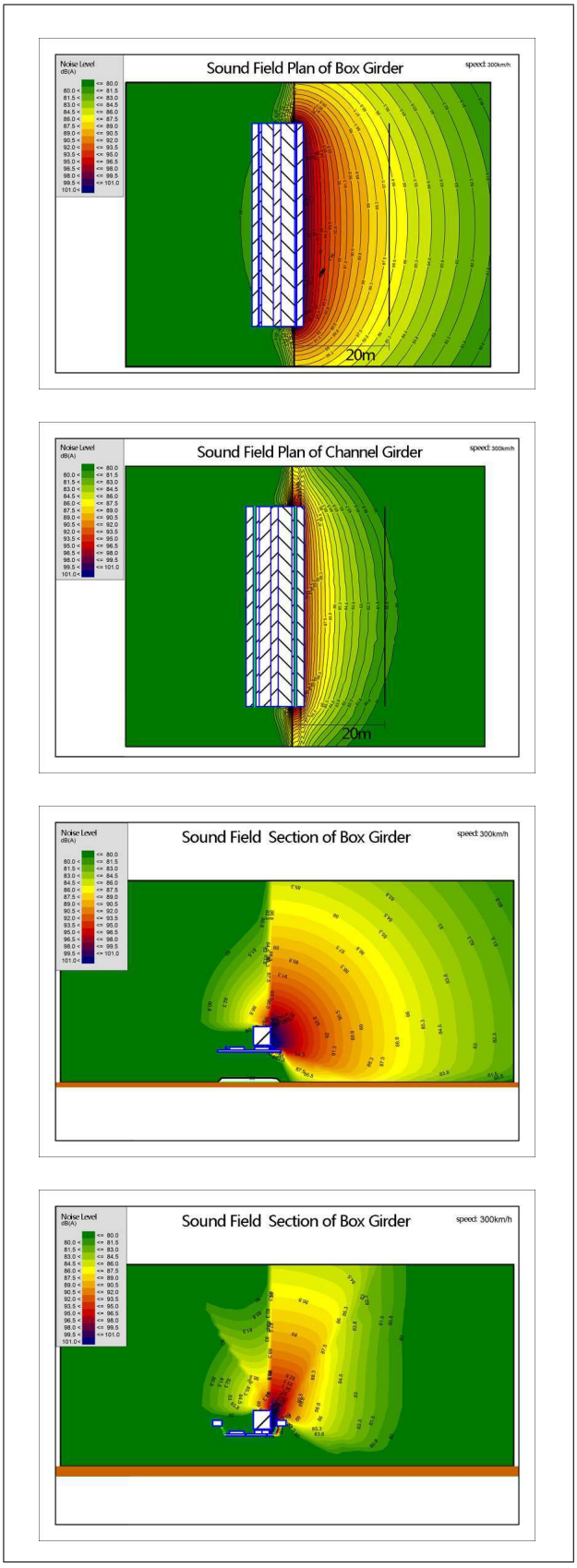

Figure 10. Acoustic plan and section drawings of box girder and channel girder in computer simulation.

the outside of the extension line. It can be seen from Figure 10 that the side beams of the channel girder changed the shape of the sound field of train noise significantly. The noise level on the outside of the extensional line of the side beams of the channel girder is dramatically reduced, with the reduction reaching as high as 7dB, while in the area between the extensional line of the side beams and the extensional line of the side of the train body there's less or even no difference. Therefore, at the level around and below the height of the rail, channel girders can provide effective noise reduction, and the reduction lessens when the angle enlarges. The noise level close to the ground reaches as high as 87.5 dB(A) in the case of box girder, while in the case of channel girder the level stays below 80 dB(A) around ground level. Therefore, except for very few extreme cases where tall buildings are built very close to the railway bridges, channel girders can provide very effective noise reduction for most rail side buildings.

3.2. Scale model results

3.2.1. Overall reduction

The data of relative noise level reduction of channel girders compared with box girders measured in the scale model experiment is presented in Table IV and Figure 11.

It can be seen from the scale model experiment results:

1) The noise level reduction of channel girders with the angle of 113° and 120° between the deck and side beams compared with box girders when the train is running at 300 km/h or 340 km/h stays above 5.4 dB at receiver A (the standard receiving point) and above 4.8 dB at all receivers.

2) Contrary to the results in computer simulations, at receiver A and B, the noise reduction of channel girder with the angle of 120° is better than the angle of 113°, with an average difference of 0.6 dB at receiver A and 1.5 dB at receiver B. The maximum difference of 1.8 dB is reached at receiver B when the noise speed is 300 km/h. At receiver C, 113° provides a better noise reduction than 120° with an average difference of 0.4 dB. Possible explanation can be the wavelike properties of sound in the scale model. The reason for this discordance will be studied in further experiments.

3) For the noise of trains running at different speed, the noise reduction of channel girders compared with box girders is also higher when the train is running at 300 km/h than at 340 km/h for any angle and receiver, with an average difference of 0.7 dB approximately. The difference found here may result from the same reason as in the computer simulation, see Section 3.1.1.2 for details.

4) The measured noise reduction differs at different receivers in the same case. At the angle of 113°, at both speeds the noise level reduction reaches maximum at receiver C and minimum at receiver B, i.e. the noise reduction weakens when the receiving point moves from 3.5 m above the rail to the level of the rail, but goes even better when it reaches 1.5 m above the ground. However, at the angle of 120°, the difference between the results at different receivers is very little and there is no obvious pattern.

Table IV. Relative noise reduction measured in scale experiment at three receiver positions.

Case No.	Contrast Case	Rec. A	Rec. B	Rec. C
S1-1	S0-1	6.0	4.9	7.0
S1-2	S0-1	6.8	6.7	6.7
S2-1	S0-2	5.4	4.8	6.4
S2-2	S0-2	5.7	6.0	5.9

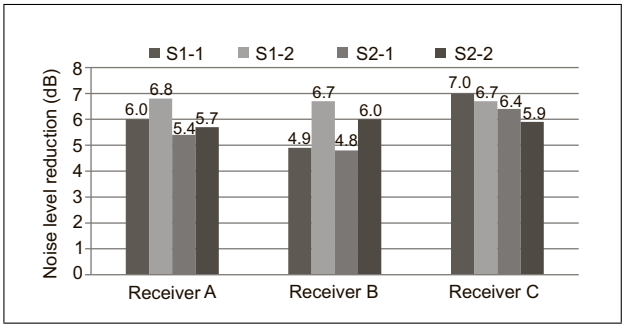

Figure 11. Noise level reduction of different receiver in different cases.

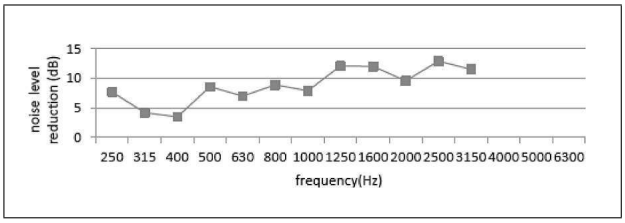

Figure 12. Frequency characteristics of noise reduction in case S1-1.

3.2.2. Frequency characteristics

The frequency characteristics of noise level reduction in case S1-1 (113°, 300 km/h) is converted into full-scale equivalent frequencies and presented in Figure 12.

The frequency curve from the scale model experiment is similar to the one in computer simulation. The noise reduction of channel girder fluctuates when frequency increases but increases from 400 Hz to 2500 Hz in general. The reduction is negatively correlated with frequencies below 400 Hz or above 2500 Hz. The best noise reduction is reached around 1250–2500 Hz, with the reduction around 12 dB. Due to the frequency limit of receiving device, scale model test cannot provide data for frequencies over 3150 Hz.

3.3. Full scale model results

3.3.1. Overall reduction

The data of relative noise level reduction of channel girders compared with box girders measured in the full scale model experiment is presented in Table V.

It can be seen from the full scale model experiment results:

1) The noise reduction of channel girders with the angle of 113° between the deck and side beams compared with box

Table V. Relative noise reduction measured in scale experiment at three receiver positions.

Case No.	Contrast Case	Rec. A	Rec. B	Rec. C
F1	F0	4.2	3.7	5.6

girders when the train is running at 300 km/h is 4.2 dB at receiver A (the standard receiving point) and above 3.7 dB at all receivers.

2) The noise reduction pattern at different receivers is accordant with the findings at the angle of 113° in the scale model experiment, which reaches maximum at receiver C and minimum at receiver B.

3.3.2. Frequency characteristics

The frequency characteristics of noise reduction in case F1 (113°, 300 km/h) is presented in Figure 13.

The frequency curve in the full scale model test is also similar to that in the other 2 methods. The noise reduction is positively correlated with frequencies below 2500 Hz and negatively correlated with frequencies above 2500 Hz. The best noise reduction is reached at the 1/3 octave band of 2500 Hz with the reduction around 13 dB. The noise level reduction stays above 5 dB between 1250 Hz and 3150 Hz.

3.4. Comparison

Cross-frequency bands comparisons are made between results gained from each of the 3 methods used in this experiment in the same situation (Case C1-4, S1-1, and F1), where the angle between the deck and side beams in the channel girder is 113°, the noise source is generated from trains running at 300 km/h and the receiving point is 25 m from the midline of the rail and 3.5 m above the level of the top of the rail. The noise reduction of channel girder compared with box girder in each 1/3-oct frequency band is presented in Figure 14.

Among the 3 methods, full scale model experiment is the closest to real situation, thus the result should be more accurate than computer simulation and scale model experiment. It can be seen from the chart that computer simulation and full scale model experiment can provide quite similar results at bands below 630 Hz and around 1600–2500 Hz, but computer simulation have higher results at other frequencies. Scale model can provide predictions for full-scale model at frequencies between 2000–3150 Hz, but the results are higher than full-scale model experiment at other frequency bands, and cannot provide predictions for frequencies over 3150 Hz. For all 3 methods, the noise reduction generally increases with frequencies until 2500 Hz and drops after.

The overall noise level reduction measured by the 3 methods in the same situation (Case C1-4, S1-1, and F1) is also presented in Figure 14. It can be seen that the noise level reduction in the computer simulation is the highest while in full scale test is the lowest.

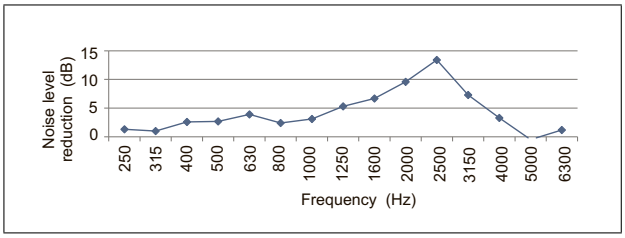

Figure 13. Frequency characteristics of noise reduction in case F1.

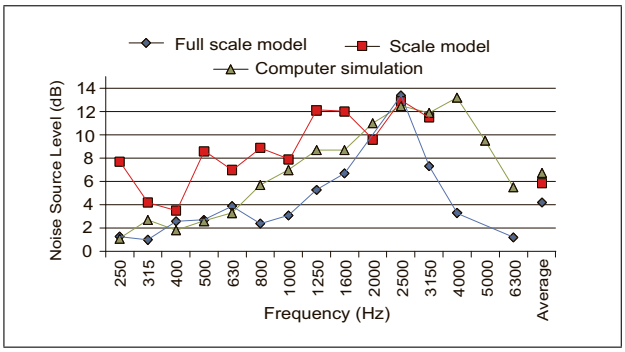

Figure 14. Cross frequency and overall comparison between results from the 3 methods.

4. Discussions

The results in this research can only partially demonstrate the real situation due to the following limitations: a) the noise sources used in the experiments are artificial non-moving, omni-directional line sources simplified from measurements, and therefore cannot fully represent the noise of a moving train with specific directivity; b) the bridge girder and train models used in the experiments are only simplified surfaces instead of real objects with full details; c) each of the 3 methods are only experimental tools and has their limitations of accuracy.

Computer simulation is the easiest and most cost-saving way to predict the noise reduction, it's suitable for the comparison between multiple situations, but differences between computer simulations and a real situation may result due to the following: a) computer simulation can only estimate the wavelike properties of sound in air [58], but the reflections between the train body and the bridge girder can create a complex sound field which the software cannot simulate precisely; b) the input acoustical performances of materials in computer simulations are only idealizations of the real materials; c) the influence of environment on the propagation of sound waves (including wind speed, temperature, ground reflection, etc.) are only estimated by the simulation [59, 60, 61]; d) the calculation accuracy is limited to constrain the calculation time [52].

Scale model test simulate the complexity of the sound field better than computer simulation, and is also more convenient and less costly than full-scale models, but differences between scale model tests and a real situation may result due to the following: a) the length of model is limited by the room size; b) the change of sound propaga-

tion in different frequency range [62]; c) the materials used in the scale model tests can only simulate the acoustical performances of the real materials even after calculation; d) there might still be slight unwanted sound reflections in the hemi-anechoic chamber; e) the air absorption is more significant in the high frequencies. Although the effect is largely neutralized by subtraction in the calculation of the relative sound reduction, it still has certain influence on the results. It is found that the result of the scale model test is higher in most frequency bands than the other two methods, and among the five factors mentioned above, the first one (the length of model is limited by the room size) may be the main reason. The length of the scale model test is 5 m, which is 25 m in full scale, so compared with computer simulation and the full scale model test in which the length is 50 m, less sound from the side can diffract around the edge of the girder side beam. This makes the sound attenuation caused by channel girder more significant and therefore the reduction result is higher.

Full scale model test can recreate the most authentic sound field as the real situation, but differences between full scale model tests and a real situation may result due to the following: a) the limitation of the length of model; b) the difference between the real running train noise source (including vibrations etc.) and the generated audio; b) the difference between the material used for the train body and the real train in motion. The result of the full scale model test is lower than the other two methods in frequency bands over 2500 Hz, the main reason might be because the material of the ground is grass on dirt, and have higher absorption coefficient in high frequencies compared with hard concrete floor in scale model test and reflective ground in computer simulation. It can be seen in the sound field sections in computer simulation that the noise close to the ground is much higher in the situation of box girders than channel girder, therefore with the absorption of the ground the measured noise reduction is lower than the actual reduction.

The results found in this research will be tested in actual construction projects. Further studies will be conducted to investigate effective ways to improve the noise reduction of channel girders. Possible ways include adding absorptive materials, changing the shape of the side beams [63], etc. The discordance found between the results of the same case in different methods and the reason for this will be studied in the future. Also, this research only studied airborne noise. Vibrations and structure-borne noise, which are also very important factors in the propagation of noise from trains on railway bridges [64], will be studied in the future.

5. Conclusions

In this research, the airborne noise reduction of channel girders compared with box girders is studied via 3 methods: computer simulation, scale model experiment and full scale model experiment. Several conclusions can be drawn from this research:

1) For the location of 25 m from the railway midline, 3.5 m above the top of the rail, channel girders can provide effective noise reduction compared with box girders. When the angle between deck and side beams is 113° and the train is running at 300 km/h on the right side rail (the rail that is closer to the receiver), the noise level reduction over box girder stays above 4dB in all 3 methods.

2) The noise reduction varies with the change of angle between the deck and side beams of the channel girder. In the computer simulation results the noise reduction decreases when the angle increases, with an average 1.3 dB difference between 140° and 90°. In the scale model test, contrary to the simulation results, the noise reduction of 120° is better than 113°. The relationships between the noise reduction and the angle will be further studied in the future.

3) The noise reduction varies for trains running at different speed, due to different frequency characteristics of noise source at different speed. The noise level reduction is higher at the speed of 300 km/h than at 340 km/h, with an average difference of 1.3 dB in the computer simulation and 0.7 dB in the scale model test when the train runs on the right rail.

4) The noise reduction varies for trains running on different rails. The noise level reduction is higher when the train runs on the right rail (the rail that is closer to the receiver) than on the left rail (the rail that is farther to the receiver), with a difference of 1.8 dB in the computer simulation when the train speed is 300 km/h.

5) The noise reduction measured at different receiving points has different results. For the height of 1.5 m, 6 m (level of top of railway) and 9.5 m on the vertical surface of 25 m from the railway midline, the highest result is measured at 1.5 m and the lowest is at 6 m. The spatial distribution of sound field will be further studied in the future.

6) The noise reduction measured with different methods has slightly different results. For the average results, the full scale model has the lowest result and the computer simulation has the highest result. The differences between the methods and the cause of that will be furture studied in the future.

Appendix

Emission field test of the speaker array in the scale model test

The emission field of the speaker array in scale model test was tested with microphones in arc arrays at the distance of 20cm and 100cm from the source, and at the angles of 0°, 15°, 30°, 45°, 60°, 75°, 90° from the horizontal plane.

An example is given in Figure A.1, which shows the measured emission field at 20 cm and 100 cm from the source in the 2500 Hz octave band. The results indicate that the emission field of the speaker array can simulate the onmi-directional field of line sources well, and no significant constructive or destructive interference exists. Similar results are found at all other octave bands and for the speakers used in the full scale model test.

Table A1. Sound power levels (dB) of the 3 line sources in 1/3-oct bands. Height: Equivalent height above rail top (m).

	300 km/h			340 km/h		
Frequency (Hz)	Bottom noise	Body noise	Pantograph noise	Bottom noise	Body noise	Pantograph noise
250	90.0	89.1	85.3	92.2	92.5	87.5
315	91.0	89.6	85.3	92.7	92.8	88.7
400	93.0	90.1	86.2	93.8	92.9	90.4
500	96.2	94.7	91.5	97.6	96.8	95.1
630	100.0	95.4	91.7	101.8	97.7	94.7
800	99.1	92.8	86.3	101.3	94.2	88.4
1000	101.5	93.9	87.4	103.8	94.9	90.0
1250	100.9	90.7	85.7	103.1	94.4	89.2
1600	100.1	89.6	85.9	101.6	91.1	88.4
2000	101.4	88.4	83.9	101.4	91.2	84.8
2500	100.9	85.5	82.6	101.3	89.3	82.4
3150	100.4	86.1	82.6	101.0	87.3	83.6
4000	100.3	85.7	76.5	101.1	87.5	73.3
5000	97.2	83.4	85.0	98.8	84.2	86.3
6300	92.1	82.4	85.6	94.2	81.7	89.0
A-Weighted	110.7	102.5	98.5	112.1	104.7	101.4
Height	0.41	3.7	5.1	0.45	3.3	5.1

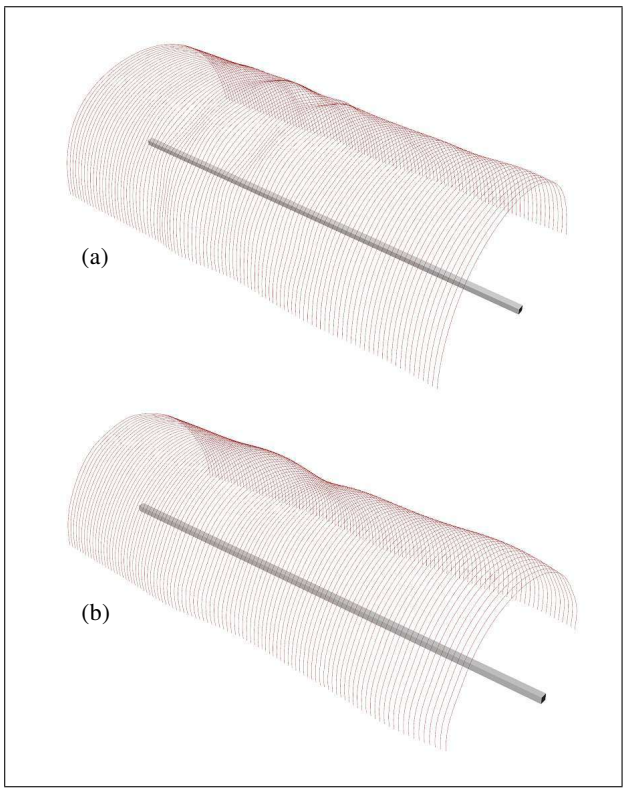

Figure A1. Emission field of the speaker array at 2500 Hz octave band. a) 20 cm from the source, b) 100 cm from the source.

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