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A PRELIMINARY STUDY OF NOISE IN A TUNNEL DUE TO A MOVING TRAIN

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ABSTRACT

Citizens travelling between cities and towns rely heavily on a mass transport system in many developed countries. In recent years, many more of these underground railway systems are constructed and expanded in many different cities. Though there have been significant reductions in the acoustical environment in automobiles and aircraft, train passengers are only recently starting to see improvements. The prime purpose of this preliminary study is to estimate the noise levels due to an underground train operating at different speeds in a tunnel. A simple experimental method is explored for measuring noise levels of a passenger train travelling in a tunnel in urban areas. This paper also attempts to study the reverberant sound fields when a train operates inside a tunnel - a long enclosed space. The result of the current study provides a guideline for design engineers in their future planning for constructing a new railway line and assists in supporting realistic contractual specifications. The experimental results can also be used as a guide to direct future efforts for reducing noise levels transmitted into the passenger compartments for an existing railway line.

1. INTRODUCTION

Railway noise is a very complex problem [1-3] especially when it is coupled with the vibration of railway vehicles. Sources of railway noise and their control have been discussed widely [4,5]. It is well known that noise levels are generally higher when trains travel in tunnels than in open fields. This is because the sound energy is trapped in the tunnel between the walls and railway vehicles. A reverberation sound field is excited resulting in a higher noise level inside a tunnel than in an open field with comparable operating conditions. This higher noise levels in train compartments could contribute to passengers' discomfort in their journeys. The current study investigates the rolling (wheel/rail) noise and mechanical equipment noise of a railway car in tunnels and compares the relative noise levels at different operating environments: in a tunnel and in an open field. We also examine the contribution of noise levels from AC alternator, air-conditioning, and traction in long enclosures, e.g. tunnels and underground stations. The contribution of aerodynamic noise from the train profile is not considered here because the maximum travelling speed does not normally exceed 90 km/h in a typical underground mass transit railway line.

Most of the earlier studies in this area are mainly focused for the transmission of train noise into an open space and its adverse impact on the neighbourhood communities [6,7] There are relatively less attentions devoted for improving the acoustic environment in train compartments [8]. Indeed, a recent study [9] showed that the equivalent noise level in the interior of a typical train falls within the range from 75 to 85 dBA. There are even fewer published data for the noise levels measured at the interior and exterior of a train which is operated in a tunnel. This is probably reflected in the fact that there are generally lack of detail specifications and contractual requirements to set an acceptable comfort criterion for train passengers. Nevertheless, we remark that Hardy [10] discussed the importance of an acceptable acoustic environment for the passengers' comfort in railway vehicles. Railway operators in Hong Kong have become more aware of this issue and have purchased newer rail fleets with vastly improved internal noise performance [11].

Noise levels inside train compartments will certainly become a more important factor for design engineers because of an increased awareness of general public who demands a more pleasant journey at reduced levels of noise and vibrations and the more widespread use of mobile telephones. This will provide a motivation for railway manufacturers to develop quieter railway carriages. The current paper describes an experimental study to examine the sound fields inside and outside a railway compartment when the train travels in a tunnel. The measured data forms a database focusing future efforts to reduce noise levels transmitted into the passenger compartments for an existing railway line.

2. METHODOLODY AND EXPERIMENTAL SET-UP

The underground mass transport system is one of the most important traffic networks in Hong Kong. Currently, it operates with well over 1,050 railway cars, rail tracks of 91 km in length, and 53 railway stations with most of them sited underground. It carries over 2.6 million passengers daily with each traveller stays an average of less than a half-hour per day during their journeys.

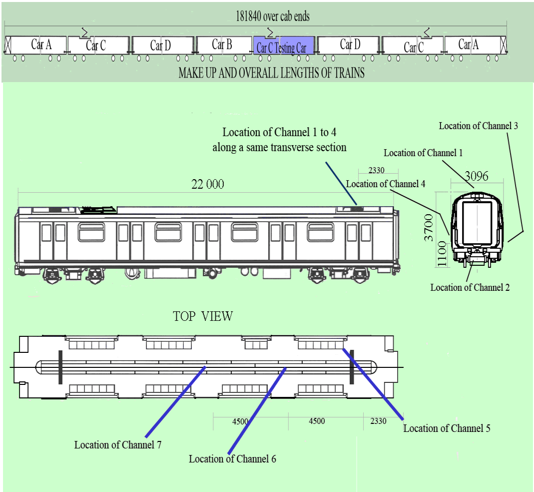

Figure 1 Typical layout of a eight-cars train and details of Car-C train car

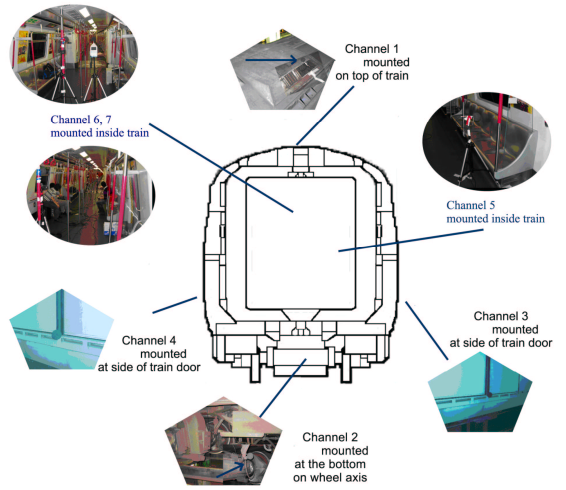

Figure 2 Locations of Channel 1 to 7 mounted on Train and within Train Vehicle

This study investigates the noise levels of a passenger train which was travelled inside an underground tunnel in routine operation conditions. We measured the noise levels when the train was stationary and also when it was operated in an open space. Field measurements were conducted in late 2005 where the level of train services was reduced because of the decrease in the number of passengers during the off-peak periods in weekends. The experimental measurements, which were conducted in an empty 8-car train with a total length of over 180 m, were completed in 3 different weekends over a period of 6 weeks. The same passenger train was used in all measurements. Each measurement period lasted for over 4 hours. The passenger train was powered by three C-Cars which was installed with electric motors. Though recently refurbished, the railway cars studied are the oldest in the fleet which first started operations in 1979. Each of these 3 C-cars was also housed with equipment for power supply and a pantograph connecting to the 1500 kV overhead power lines. It was expected that the conditions of rail tracks and train wheels did not change appreciably within this 6-week period. Figure 1 shows the schematic diagram of the train that was used for experimental measurements. The centre C-car (shaded in Figure 1) was chosen as the monitoring station. All noise measurements were conducted in the mid-car monitoring station where the end effect of the passenger train was minimized

Seven B&K Type 4942 ½" condenser microphones fitted with matching pre-amplifiers were used as receivers to measure the noise levels both inside and outside the monitoring station. The microphones were connected directly to a Sony SIR-1000i 16-channel digital tape recorder via standard BNC cables. Prior to and after each period of measurements, all microphones were calibrated with a B&K Type 4231 calibrator. The measured data were digitized and stored (Channel 1 to 7) in magnetic tapes for subsequent signal processing and data analyzes. In conducting the experimental measurements, we followed the relevant procedures of the international standards [12] as far as they were practicable.

Figure.3 Experimental set-up inside the train compartment

	ASI	Comp.	Air Cond.
Stage 1	off	off	Off
Stage 2	on	off	Off
Stage 3	on	on	Off
Stage 4	on	on	On

Table 1 Parameters for train equipments in 4 conditions

ASI – Alternator for AC supply and Static Inverter (DC to AC)
Comp – Air Compressor
Air Cond. (AC) – Air Conditioning

Figure 2 shows the experimental set-up at the monitoring station. Four microphones are mounted outside the train compartment and 3 microphones are mounted inside (only 2 microphone positions are shown in Fig. 2). Specifically, Channel 1 is connected to a microphone mounted on the roof outside the train. Channel 2 is used to monitor the noise levels at the under-carriage of the train. Channels 3 and 4 were connected respectively to 2 external microphones which were held in place at the floor level by the closing doors at the left and right sides of the passenger train. Channel 5 – 7 were used to record the interior noise levels at various locations as shown in Fig. 1. Channel 5 was connected to a microphone close to a passenger seat at an entrance of the monitoring station. It was set at a height of 1.0 m above the floor level simulating the position of a seating passenger. Channel 6 and 7 were connected to two microphones which were located 1.2 m above floor level and at the centre-line of the train compartment. See Table 2 for a list of the microphone locations. All microphones were fitted with windscreens to reduce the effect of wind noise. Figure 3 displays the monitoring station that experimental measurements were conducted.

The primary objective of the present study was to explore experimentally the noise levels in the tunnels due to a moving train. During the experimental measurements, the train was operated under normal conditions travelling from east to west in an underground railway line with an approximate distance of 8 km in length and an approximate journey time of 40 minutes. During its west-bound (up-track) journey between the stations at either ends, the passenger train passed through 8 underground stations and it was also required to slow down at some particular locations for safety reasons. The passenger train started at the terminal in the up-track platform. It stopped at each of the 8 stations according to the normal operation procedures except that passengers were not permitted to board the test train. The positions and speeds of the passenger train were stored in its computerized system that was subsequently downloaded after each measurement period for future analysis. We remark that the built-in timer provided by the Sony digital recorder was synchronized with that of the train throughout the measurement periods. As a result of this careful procedure, the measured noise levels can then used to correlate with the positions and speeds of the passenger train. The trackform traversed in these studies was mixed with sections of directly supported concrete track, base-plated track and floating track slab, with a number of points and crossings. The surface of the rails in normal service is maintained to a low degree of roughness with regular rail grinding.

Generally speaking, the rolling noise is the dominant source in most situations. However, it is also of interest to quantify the respective noise levels radiated from major equipments like alternator, air-conditioners, the traction and ancillary equipment of a train in tunnels. This is achieved by conducting the noise measurements of the passenger train stationed in the tunnel and at an open ground in the depot. As shown Tab1e 1, four stages of test procedures were conducted with a combination of different equipment turning on/off in a sequence. This allows examination of noise levels contributing from each of these components.

3. MEASUREMENT RESULTS

3.1 Equipment Noise

To examine the contribution of noise levels from train equipment in long enclosures, measurements were conducted at two separate locations with the passenger train stationed at an open ground in the depot, and inside a tunnel siding (branch) of the rail track. The tunnel siding was constructed for parking and reversing the travel direction of a train. Four different combinations of train equipment were turned on; see Table 1 for a sequence of operating condition of the train equipment. The noise level from the auxiliary equipment (lighting and small power supply equipment) is small and they do not contribute significantly the overall noise levels. As a result, they are not considered in the study. It is reasonable to assume that noise levels generated by different train equipment are independent of each other. The total sound field can then be estimated by summing each of these components incoherently. It is apparent that the equipment noise levels outside the train compartment did not affect the acoustic conditions in the train compartment. The alternator for AC supply and static inverter were turned on most of the time except for the condition of Stage 1 (see Table 1) when all equipments were shut down for measuring the background noise levels. It was found that background noise levels were below 45 dB throughout the periods of measurements at both locations. The measurements were initially conducted at the depot’s open ground and then C-car of the test train was operated and stopped in a tunnel siding for the same measurement procedures as in the open ground.

3.1.1 Measured noise levels in the open ground of the depot

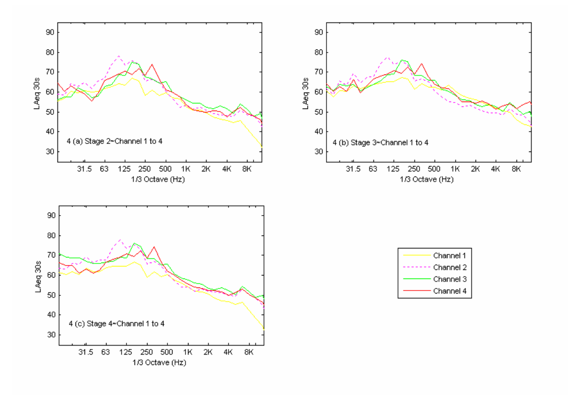

Figure 4 Exterior A-weighted noise levels radiated from train equipment measured at the depot.

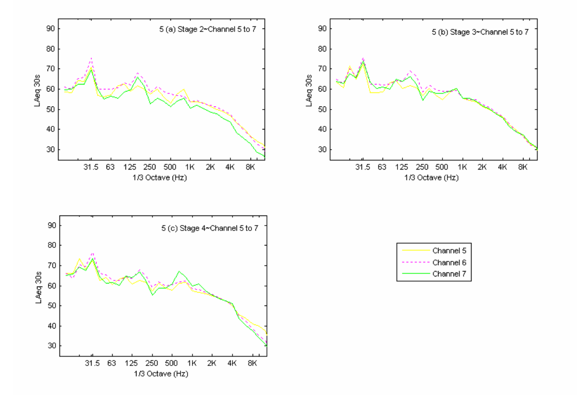

Figure 5 Interior A-weighted noise levels radiated from train equipment measured at the depot.

Figures 4 and 5 showed, respectively, the measured data in the open ground at the depot for the exterior and interior noise levels recorded at the 7 microphone positions. Figures 4 (a) – (d) correspond to the respective conditions for Stage 2 – 4 as listed in Table 1 and Figures 5 (a) – (c) corresponds to the conditions of Stages 2 – 4. From the recorded data for different microphone locations, equivalent A-weight noise levels in one-third octave bands were obtained for duration of 30 seconds. Channels 1 to 4 were dedicated for external locations. Channels 5 to 7 were used to connect to internal microphone positions. Table 2 show a summary of the microphone channels and their locations. By powering up different equipment of the passenger train at different stages, it was possible to estimate the contribution of the noise levels from different equipment and the overall noise levels. Figures 4 (a) – (c) show the exterior noise levels recorded at Channel 1 to 4 respectively. The dominant noise level is slightly above 70 dBA for frequency between 63 Hz and 300 Hz. For frequency above 500 Hz, the difference in noise levels at the right and left side of the monitoring station (Channels 3 and 4) is only about 2 dB. The noise levels when all the equipments were switched on, was about 3 dB higher than the noise levels for the other measuring conditions. It is also of interest to mention that the shape of noise spectra for different equipment have a rather similar pattern.

Microphones		Estimated (dBA) noise level Of equipment				Measured Overall Value
Channel No.	Location reference to train car	ASI	Comp.	Air. Cond.	Overall	
1	Roof Top	65.1	68.2	65.8	71.3	70.6
2	Undercarriage	69.9	59.7	58.4	70.6	70.2
3	Right side	70.7	65.7	59.2	72.1	71.5
4	Left side	71.2	67.4	61.0	73.0	72.7
5	Interior Seat	65.0	56.7	64.6	68.1	67.8
6	Interior A	65.6	60.6	66.2	69.5	68.9
7	Interior B	62.3	63.8	69.8	71.3	70.5

Table 2 – Estimated noise level of the train equipment measured in open ground

In the open field, the measured results at external receiver locations were essentially the near-field data because the microphones were placed quite close to the exterior of the train compartment. These results may not give a good assessment of the sound power of the sources because the shape of the passenger train can shield certain microphone from the equipment noise. Nevertheless, these noise data will be used in conjunction with the measured results at tunnel sidings in order to give a better estimation of the equipment noise for a train operating in

a tunnel. For the interior noise levels recorded at Channels 5 to 7, the measured results are shown in Figure 5(a) to (c). It is remarkable that the spectral shapes recorded at different receiver positions show similar patterns for frequency between 800 Hz and 4 kHz.
The estimated A-weighted noise levels measured at each microphone location are summarized in Table 2. It can be seen from the measured results that the alternator for AC supply and the static inverter (ASI) are the dominant noise sources for the C-car train.
As shown in Table 2, the estimated overall noise levels agree reasonably well (to within 0.3~0.8 dB) with the measured data at all receiver positions.

3.1.2 Measured noise levels at a tunnel siding

The same procedures were carried out when the train was stationed in a tunnel siding. The background noise level was measured and it was below 40dB. The measured noise levels are illustrated in Figures 6 and 7 respectively for the exterior and interior microphone locations.

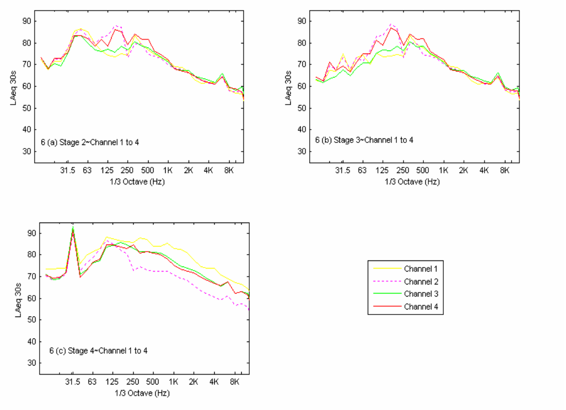

Figure 6 Exterior A-weighted noise levels radiated from train equipment at a tunnel siding

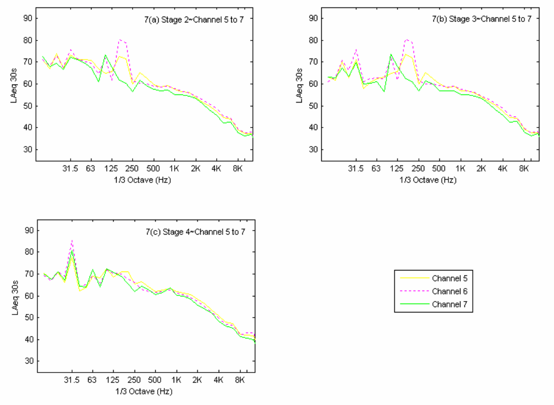

Figure 7 Interior A-weighted noise levels radiated from train equipment at a tunnel siding

In this set of results, it is expected that the reverberant sound field dominates the overall noise levels in a tunnel. When compared with the measured results at the open ground, the overall noise levels at both sides of the passenger train increased by 20 dB for the frequency ranging from 400 Hz to 1 kHz. The measured noise levels at the roof top (Channel 1) were the loudest with an increase of 25 dB. This level was 10 dB higher than the measured results at the undercarriage (Channel 2). This is probably due to the fact that the microphone of Channel 1 was placed close to the air conditioner which was mounted on the roof top of the train.

The spectral patterns for the noise radiated from the alternator and compressor were similar for both experimental locations but the noise levels measured at the tunnel siding were about 15 dB higher than those measured at the depot, see Figures 6(a) and (b). There is an apparent change in the spectral pattern for the noise radiated by the air-conditioner – a spectral peak was observed at the frequency band of 31.5 Hz for the measurement at the tunnel siding.

Microphones		Estimated (dBA) noise level of equipment				Measured Overall Value
Channel No.	**Location reference to train car**	**ASI**	**Comp.**	**Air. Cond.**	**Overall**	
1	Roof Top	82.8	72.5	92.3	92.8	92.5
2	Undercarriage	83.4	73.9	81.6	85.9	84.8
3	Right side	82.6	64.3	86.2	87.8	86.7
4	Left side	85.2	68.9	86.7	89.0	88.5
5	Interior Seat	68.8	52.6	70.4	72.7	71.6
6	Interior A	72.2	53.6	69.6	71.6	70.6
7	Interior B	65.9	54.2	69.8	71.4	70.7

Table 3 – Estimated noise level of the train equipment measured in a tunnel siding

As shown in Figures 7 (a) to 7 (c), a similar phenomenon was also observed in the interior positions. The noise levels were 3 dB higher when measurements were conducted in the tunnel than those obtained in the open ground.

Compared with Figures 6 (a) to 6 (c), the average interior noise levels were about 15 dB lower than the exterior noise levels. This reduction in the noise levels may be regarded as the transmission loss of the train body's.

The estimated A-weighted noise levels at the different microphone locations are listed in Table 3 above. Again, the alternator was the dominant noise source but contribution of noise from the air-conditioner become more important in a tunnel because of the significant increase in the reverberant field.

3.2 Wheel/rail rolling noise in tunnels

The noise radiated from the wheel/rail interaction was measured for the passenger train travelled in a tunnel. The travel time between two consecutive stations was about 80 seconds in the first 5 stations. The travel time extended to 120 s for the next 3 stations. Typically, the train was in a standstill at each station for an average of 30 to 40 seconds during the period of measurements. The test arrangement followed closely the normal train operation procedure during its daily routine. The results are presented in this section with the microphones placing at the same locations as described in Section 3.1. The measured noise levels were analyzed by sampling the recorded data to obtain a time history of 2 second equivalent A-weighted noise levels ($L_{\mathrm{eq},\,2\,\mathrm{s}}$). The time histories of the measured noise data are presented in Figures 8 and 9 as follows.

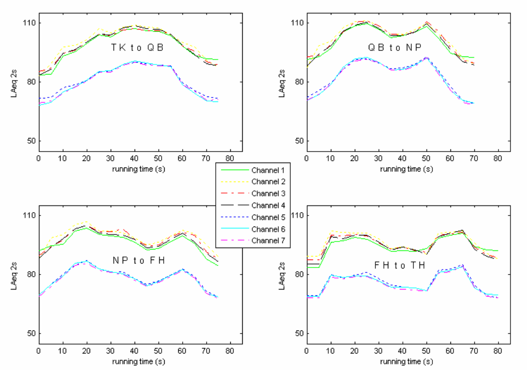

Figure 8: Time histories of the equivalent noise levels for Channels 1 to 7 for the first 5 stations.

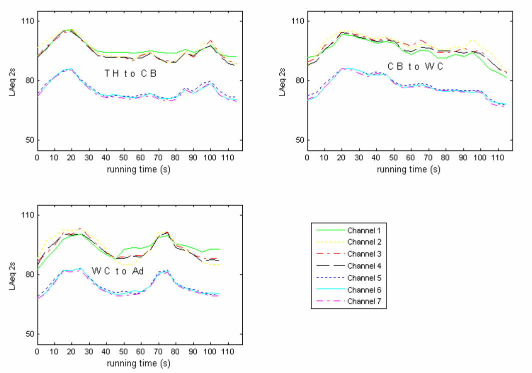

Figure 9: Time histories of the equivalent noise levels for Channels 1 to 7 for the next 3 stations.

Figure 8 shows the time histories of the noise levels measured at different channels for the first 5 consecutive stations. Figure 9 shows the measured results for the next 3 consecutive stations. The noise levels increased with the increase of the speed of train. The maximum noise level was reached when the train travelled at the maximum speed of about 69 km/hr. At the maximum speed, the noise was at a level of 26 dB higher than the situation when the train was stationary.

As shown in Figures 8 and 9, it is clearly indicated that the levels of the wheel/rail noise were quite uniform both inside and outside of the monitoring stations. There was also a clear correlation [13, 14] between the interior and exterior noise levels that was dependent on the transmission loss of the train's body. The results have suggested that a fairly uniform diffused sound field was generated within the tunnel and the train compartments because of the effect of multiple reflections of sound in a long enclosure.

4. DISCUSSIONS AND CONCLUDING REMARKS

A set of preliminary measured results has been presented which demonstrates that there is a significant increase in noise levels when a train is operated in a tunnel. The noise level inside the passenger compartment is dependent on the exterior noise levels inside the tunnel which, in turn, is proportional to the speed of train. Further studies will be conducted to establish an empirical formula for predicting the noise levels in tunnels and in passenger compartments for different operating conditions of trains. The information will be used to focus future efforts for the reduction of noise levels into the passenger compartments when a train travels in tunnels.

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