Room acoustic design to improve speech privacy in passenger cars of high-speed trains

Jin Yong Jeon (1), Hyung Suk Jang (1)

(1) Department of Architectural Engineering, Hanyang University, Seoul, Republic of Korea

ABSTRACT

In the present study, room acoustic environments in high-speed trains were investigated to identify design elements for passenger cars. Absorption coefficients of the interior finish materials were tested, and reverberation time (RT) and sound pressure level (SPL) were measured at the ear height of passengers. A room acoustic simulation model for the passenger cars was constructed from actual measurements carried out at different positions in the passenger cars. Design elements were identified and classified through computer modelling of different interior surfaces with different absorption coefficients. It was found that appropriate absorptive material and ceiling shape help improve speech privacy inside passenger cars. The privacy distance (rP) improved by 2.7 m by increasing the absorption coefficients and by 1.8 m by adding ceiling banners.

INTRODUCTION

In many countries, technology has been used to develop high-speed trains having maximum speeds above 300 km/h. With the introduction of these high-speed trains, it has become essential to develop technologies to increase passenger comfort. Noise in passenger cars is one of the main causes of passenger discomfort that need to be eliminated. Korea Train eXpress (KTX) has been operating since 2004 in Korea. It has succeeded in developing a high-speed domestic train, KTX-Sancheon, in 2010. Recently, test runs of HEMU-430X have been carried out, and its maximum speed has been documented as 430 km/h.

Studies on noise annoyance of train passenger cars (Vernet, 1977) and psychoacoustic metrics and subjective evaluation in passenger cars (Patsouras *et al.*, 2002) have been carried out since the 1970s. However, few studies have considered the acoustic distribution and speech privacy inside the passenger cars. The purpose of the present study is to suggest room acoustic design guidelines for train passenger cars improve passenger comfort in high-speed trains.

Sound recording and room acoustic measurements were carried out in the passenger cars and computer simulations were carried out to investigate the current acoustics in order to improve the speech privacy and acoustic comfort in the KTX. Based on these investigations, the design guidelines for high-speed train interiors will be presented.

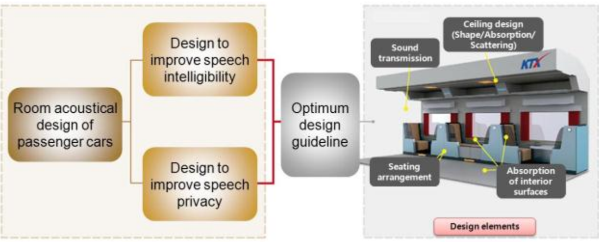

Figure 1. Research target and design elements in the high-speed train passenger cars

MEASUREMENT IN PASSENGER CARS

Noise recording on board

Noise recording was performed on board three high-speed trains in Europe and two high-speed trains in Korea. The recording was conducted using a field recorder and a binaural microphone (Type 4101, B&K). Measurements were carried out from the middle seat near the left window in the trains.

The noise characteristics in the passenger car were recorded while the trains were moving and when stationary. The noise was recorded for different train speeds and when passing through open fields and tunnels. The noise characteristics were different for the different conditions. The recording conditions during the maximum speed and in the open fields were selected as reference for analysing the L_{Aeq}.

(a) KTX (b) KTX-Sancheon
Figure 2. Photographs of Korea Train eXpress (KTX)

Train noise level

Figure 3 shows a plot of the train noise levels in the frequency band of L_{Aeq} measured in the passenger cars of the different trains. Train A showed the lowest recorded noise level in the overall frequency band. The maximum speed of Train A was 200 km/h, in contrast to the maximum speeds of the other trains, which were 300 km/h.

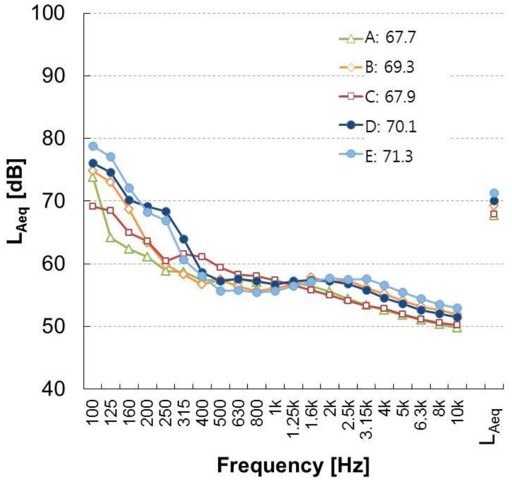

Figure 3. Train noise level for different trains in the frequency band

The low frequency noise depended on the type of train, and the noise level of Trains D and E in the low frequency band was higher than that of the other trains in the 200–250 Hz frequency band. Noise with frequency greater than 2 kHz can be generated by aerodynamic interactions; however, during measurement, it was found that the high-frequency noise in Train E was caused by the vibration of the baggage rack. In the acoustic designing process of passenger cars, maintaining the noise level below 400 Hz may be critical because the noise level at this frequency was different for different trains.

Acoustic measurement setup

Acoustic measurements were carried out in 2nd class passenger cars of KTX. The measurement setup used to investigate sound field characteristics in the passenger cars conformed to the standards defined by ISO 3382-1 and 3382-3. Dodecahedron omnidirectional sources were placed 1.1 m high on the seats and 1.6 m high in the aisle. The receiver in the passenger cars were placed along three lines passing over the window seats, aisle seats, and aisle, as shown in Figure 4. Half-inch microphones and a ear microphone, and a figure-of-eight microphone were used to evaluate the room's acoustic parameters, namely, reverberation time (RT, T20), early decay time (EDT), clarity (C50), interaural cross-correlation (IACC), and lateral energy fraction (LF). The absorption coefficients of the chairs in the 2nd class cars were measured with in situ absorption measurements.

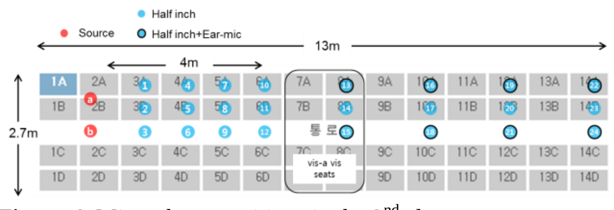

Figure 4. Microphone positions in the 2nd class passenger car of KTX

Results

In such a small volume (74.4 m^3), the reverberation time was very short, 0.17 s, and the early decay time was 0.19 s. The reverberation time rose to 0.22 s at 125 Hz. Clarity (C50) was measured in three bands (500 Hz, 1 kHz, 2 kHz), and an average value of 17 dB was obtained in this dry space. Interaural cross-correlation was calculated to be 0.33 for 500 Hz, 1 kHz, 2 kHz averages.

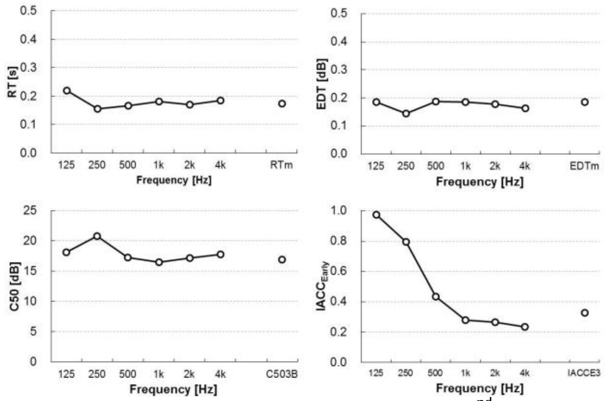

Figure 5. Acoustic measurement results in the 2nd class passenger car

COMPUTER SIMULATION

Computer modelling

Computer simulation was carried out using the measurement data to investigate the effects of the dimensions of and materials in the passenger car on the room acoustic characteristics. The in situ absorption coefficients of surface materials in the passenger cars were measured with a PU probe. Figure 5 shows the acoustic parameter values from the computer simulation fitted to the measurement data. The red squares indicate computer simulation values and the blue crosses shows the measurement values from the KTX car.

Table 1. In situ absorption coefficients of surfaces inside the KTX car as measured with a PU probe

	SC	α					
		125	*250*	*500*	*1000*	*2000*	*4000*
floor	0.1	0.44	0.24	0.10	0.10	0.15	0.10
chair_seats	0.3	0.14	0.36	0.63	0.50	0.48	0.36
chair_back	0.3	0.42	0.38	0.68	0.66	0.65	0.64
chair_iron	0.2	0.45	0.07	0.17	0.17	0.01	0.01
windows	0.05	0.17	0.11	0.05	0.08	0.06	0.12
curtain	0.4	0.71	0.43	0.30	0.36	0.63	0.91
fabric wall	0.3	0.23	0.30	0.35	0.40	0.45	0.47

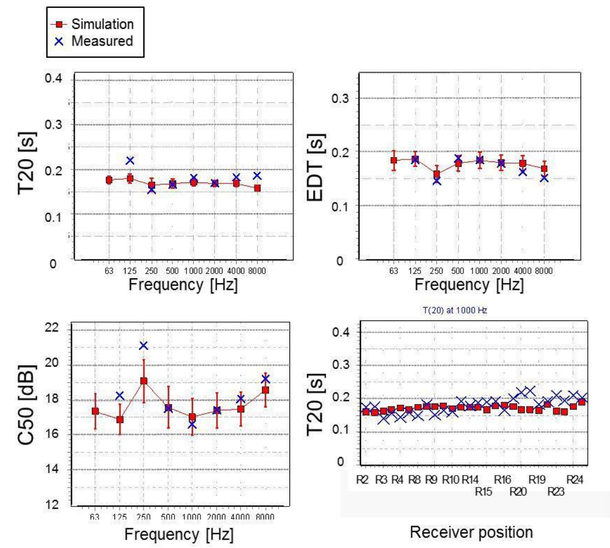

Figure 6. Comparison between measurements and simulation results

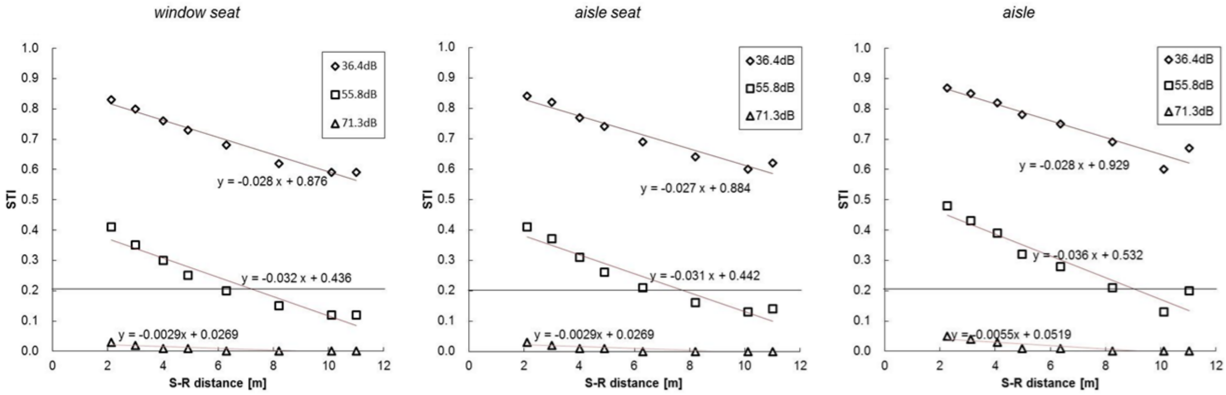

Figure 7. STI values of three receiver lines under three background conditions

Table 2. Average STI and rP for three background noise levels (WS: window seat, AS: aisle seat, A: aisle)

BG noise	*36.4 dB*			*55.8 dB*			*71.3 dB*		
Seat	*WS*	*AS*	*A*	*WS*	*AS*	*A*	*WS*	*AS*	*A*
STI	0.70	0.72	0.75	0.24	0.25	0.31	0.01	0.01	0.02
r_P[m]				7.4	7.8	9.2			

Variation of STI with background noise level

The speech transmission index (STI) is a physical quantity representing the transmission quality of speech with respect to intelligibility. STI is affected by background noise. Background noise in the high-speed train was determined under three conditions: no HVAC (36.4 dB), train stops with HVAC (55.8 dB), and train travelling at 300 km/h (71.3 dB). Speech privacy was evaluated in terms of the STI. The privacy distance (r_P) is defined by ISO 3382-3 as the distance from the speaker where the speech transmission index falls below 0.20.

The background noise levels were controlled in the computer simulation for the purpose of STI calculation. Figure 7 shows STI results for the three receiver lines: window seats, aisle seats, and aisle. When the background noise was as low as 36.4dB, the STI was over 0.6. Higher STI values indicated that speech would transmit well in this long and narrow space. In the stopped train with HVAC noise levels at 55.8 dB, STI values were below 0.50 at the distraction distance (r_D). Under this condition, the privacy distance (r_P) was calculated as shown in Table 2. The r_P value in the aisle was around 2 m greater than that in the seating area. In the 300 km/h run, the background noises were louder than the source noises, so the STI values were close to zero.

r_P was altered to improve speech privacy by changing interior surfaces in high-speed trains. Speech privacy evaluation by changing design components was conducted at aisle seats at a 55.8 dB background noise level during train stops.

Improvement of speech privacy by changing absorption

The reverberation time under initial conditions was 0.17 s. The effects of changing the absorption coefficients of materials on speech privacy were evaluated. When the absorption coefficients of the fabric ceiling, wall, and chairs were varied from -15% to +30%, RT changed to 0.30, 0.17, 0.15, and 0.14, as shown in Table 3. -15% was defined as a reflective condition and +30% was defined as a highly absorptive condition. Increasing the absorption coefficients of the interior surfaces decreased the average STI values. The use of highly absorptive surfaces could obtain a speech privacy area of 5.1 m (r_P). On the other hand, reflective surfaces transmitted speech sound to 9.8 m at 0.2 STI.

Table 3. RT, STI, and r_P results for different absorption coefficients of interior surfaces

	Change of absorption coefficients			
	-15%	*0*	*+15%*	*+30%*
RT [s]	0.30	0.17	0.15	0.14
STI	0.32	0.25	0.21	0.17
r_P [m]	9.8	7.8	6.4	5.1

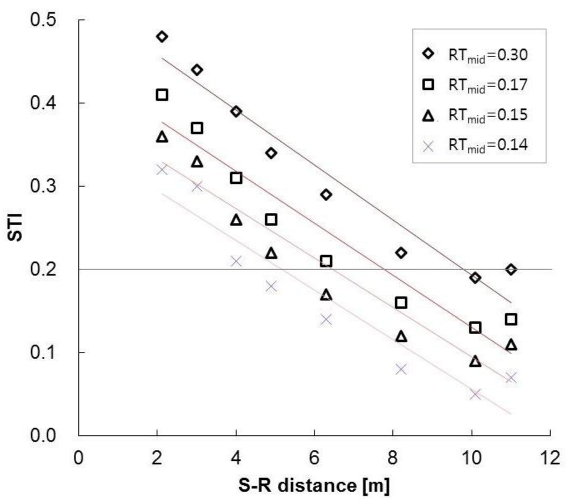

Figure 8. STI values with changes in absorption coefficients of interior surfaces

Improving speech privacy by adding ceiling banners

The evaluation condition in this case was the same as that in the previous evaluation, that is, at aisle seats at a 55.8 dB background noise level during train stops.

Ceiling banners were installed in the passenger cars to improve speech privacy. The banner heights were raised up to 500 mm in 100 mm steps except at the baggage rack tray and ceiling of the aisle, as shown in Figure 9. In Table 4, The reverberation times changed slightly; however, the speech privacy improved in terms of STI and r_P. The r_P with a banner at 500 mm was about two rows shorter than that without a banner as shown in Figure 10.

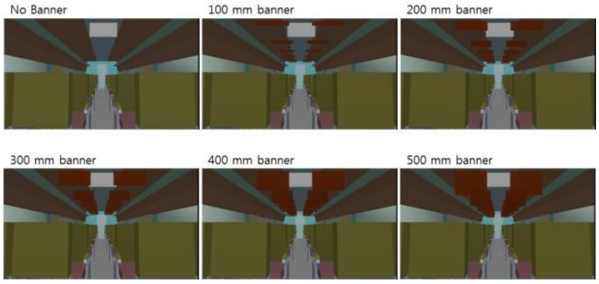

Figure 9. Adding ceiling banners to improve speech privacy

Table 4. RT, STI, and r_P results with installation of ceiling banners in passenger cars

	banner heights [mm]					
	0	*100*	*200*	*300*	*400*	*500*
RT [s]	0.17	0.17	0.17	0.16	0.15	0.16
STI	0.25	0.23	0.22	0.21	0.20	0.19
r_P [m]	7.8	7.0	6.7	6.5	6.1	6.0

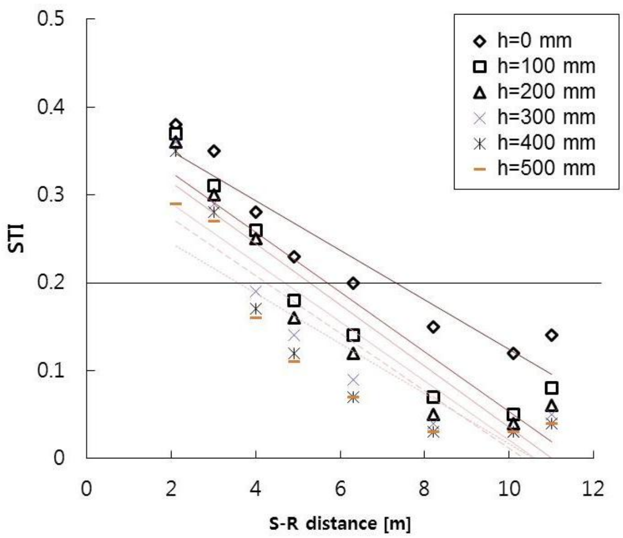

Figure 10. STI values with addition of ceiling banners to improve speech privacy

SUMMARY

Noise characteristics in high-speed trains were investigated by comparing different types of high-speed trains in Europe and Korea. The noise levels at frequencies below 400 Hz were different for different trains.

Acoustic measurements were carried out in a high-speed train depot. The reverberation time was 0.17 s and the C50 was 17 dB. Computer simulation modelling results were fitted to the measurement results. The STI values significantly depended on background noise. The STI values were calculated at train stops under background noise of 55.8 dB, and the privacy distance was 7.4–9.2 m in the window seats and aisle.

The effect of changing the interior design materials in the passenger cars on speech privacy was investigated by the changing the materials. In addition, the effect of adding ceiling banner was evaluated. Both measures were found to improve the speech privacy in the passenger cars, although changing the absorption of interior surfaces was more found to be the more effective one. An r_P of 9.8 m obtained when reflective materials were used and that of 5.1 m was obtained when highly absorptive materials were used.

In the future, subjective evaluations are planned to investigate the relationship between objective parameters and subjective preferences for evaluating speech privacy and speech intelligibility. From these results, optimum design guidelines could be proposed for the acoustic design of passenger cars of high-speed trains.

REFERENCES

Farina, A & Bozzoli, F 2002, ‘Measurement of the Speech Intelligibility Inside Cars’, *Proceeding of the 113th AES Convention*, Audio Engineering Society, Los Angeles, pp. 5-8.

International Organization for Standardization 2009, *Acoustics - Measurement of room acoustic parameters - Part 1: Performance space*, ISO 3382-1:2009, International Organization for Standardization, Geneva.

Keränen, J, Hongisto, V, Oliva, D & Hakala, J 2012, ‘The effect of different room acoustic elements on spatial decay of speech – a laboratory experiment’, *Proceedings of Euronoise*, European Acoustics Association, Prague, pp.624-629.

Patsouras, C, Fastl, H, Widmann, U & Holzl, G 2002, ‘Psychoacoustic evaluation of tonal components in view of sound quality design for high-speed train interior noise’, *Acoustical Science and Technology*. vol. 23, no.2, pp.113-116.

Rindel, JH & Christensen, CL 2012, ‘Acoustical simulation of open-plan offices according to ISO 3382-3’, *Proceedings of Euronoise*, European Acoustics Association, Prague, pp. 630-635.

The British Standards Institution 2012, *Acoustics — Measurement of room acoustic parameters Part 3: Open plan offices (ISO 3382-3:2012)*, BS EN ISO 3382-3:2012, The British Standards Institution, London.

Vernet, M & Vallet, M 1977, ‘Noisiness of high speed Trains’, *Journal of Sound and Vibration*, vol. 51, no.3, pp. 359-361.

Vernet, M 1977, ‘Effect of train noise on sleep for people living in houses bordering the railway line’, *Journal of Sound and Vibration,* vol. 66, no.3, pp. 483-492.