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Evaluation of Speech Privacy in Passenger Cars of High-Speed Trains Based on Room Acoustic Parameters

Jin Yong Jeon, Hyung Suk Jang, Joo Young Hong
Department of Architectural Engineering, Hanyang University, Seoul 133-791, Korea. janghyungs@gmail.com

Summary

Speech privacy is important for improving the quality of the acoustic environment in high-speed train compartments because the conversation of other passengers is a major source of disturbing noises in high-speed trains. In order to provide an acoustic environment amenable to speech privacy, it is necessary to explore the room acoustic conditions of passenger cars in high-speed trains. The present study investigates speech privacy in the passenger cars of a high-speed train using the room acoustic parameters suggested in ISO 3382-3. Single-number quantities ($D_{2,\mathrm{S}}$, $L_{p,\mathrm{A,S,4m}}$, r_D and r_P) were measured in an example passenger car to evaluate the spatial decay of the sound pressure level and sound transmission index (STI). Computer simulations were also conducted to explore the effects of changing absorption coefficients and background noise levels on the single-number quantities. We found that $D_{2,\mathrm{S}}$ and $L_{p,\mathrm{A,S,4m}}$ values changed significantly with variation in average absorption coefficients, but that these parameters did not depend on the background noise levels. It was also found the privacy distance (r_P), rather than the distraction distance (r_D), to be a useful parameter for designing speech privacy in a passenger car, due to high background noise levels. The effect of absorption coefficients on r_P was less than that of the background noise levels. In addition, regression models to predict the single-number quantities based on average absorption coefficients and background noise levels are suggested, and these can be used in practice to help with the design of acoustic environments promoting speech privacy in the passenger cars of a high-speed train.

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1. Introduction

High-speed train systems in Europe and Asia have provided not only efficient transport service but also socioeconomic benefits. The Korea Train eXpress (KTX) line began operating in Korea in 2004, and a high-speed domestic line, the KTX-Sancheon, began operation in 2010. Recently, test runs of a second high-speed line with a documented maximum speed of 430 km/h, the HEMU-430X, have begun. As the technologies for high-speed trains develop, considering the environmental qualities in the passenger cars of high-speed trains in order to enhance passenger comfort will be essential. In particular, the sound environment in the interior of a train plays an important role in evaluating its overall comfort.

Many studies on the sound quality of interior noise in trains have been conducted based on acceptance and annoyance [1, 2, 3]. Hardy [1] evaluated internal train noise based on various noise criteria used in building acoustics and showed that room criteria (RC) are in good agreement with subjective responses in terms of acceptability. Parizet *et al.* [2] found that among psychoacoustic metrics, loudness is the dominant factor for noise assessment. Patsouras *et al.* [3] examined the perception of noise tonality in a high-speed train by manipulating synthesized noise. In addition, Iachini *et al.* [4] investigated the effect of noise in metros on acoustic comfort under laboratory conditions, and showed that noise negatively affects passengers' annoyance levels and cognitive performance.

There are two main noise sources in a passenger car: compartment noise consisting of rolling, engine, and aerodynamic noise; and sounds from other passengers [5, 6, 7, 8]. Kuwano [5] found that compartment noise of the Shinkansen train itself may not be annoying, whereas conversation could cause disturbance. Khan [6] also showed that noise from fellow passengers was one of the annoying sounds in trains, from a questionnaire. Several previous studies on the interior noise of trains, with attention to speech privacy and intelligibility, have been conducted in order to address this problem. Patsouras *et al.* [9] explored the relationship between speech privacy and sound quality in a high-speed train. Khan [7] evaluated the masking effects of background noise levels on enhancing acoustic comfort with listening tests inside train passenger cars. Masking sounds enhanced acoustical comfort for the sake of activities like reading, writing, and

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conversation, however, cellular phone conversations and cellular phone signals were still annoying due to the frequency characteristics. Kuwano *et al.* [5] investigated annoyance levels resulting from sounds combined with conversation (C) and background interior noises (N) of the Shinkansen train in Japan. They found that annoyance due to the combined sound increases as the conversation-to-noise ratio (C/N) decreases, and suggested that the optimal background noise level concerning conversation levels in the compartment was between 50 and 60 dBA. Maffei *et al.* [10] conducted laboratory experiments to measure speech intelligibility in metro trains taking into account driving conditions, genders of the speakers, and four different voice levels. They found that 80% of speech intelligibility scores occurred for a signal-to-noise ratio (SNR) values between -6 dB and -3 dB.

Previous studies [5, 9, 10] have often focused on the subjective evaluation of speech privacy regarding SNR. However, investigations of the spatial acoustic characteristics of a passenger car in high-speed trains are necessary for the design of such passenger cars. Even though Shimokura and Soeta [11] measured room acoustic parameters, including early decay time (EDT), clarity (C50), relative levels (RL), interaural cross correlation coefficient (IACC) and speech transmission index (STI), in passenger train compartments to evaluate the acoustic conditions for speech intelligibility, their work did not provide practical criteria for room acoustic conditions in order to design an acoustic environment for speech privacy in a passenger car.

An improved analysis could benefit from using ISO/TC 43/SC 2/WG 19, which are new, single-number quantities that describe both the spatial distribution of the sound pressure level and the STI as a function of distance in order to evaluate speech privacy in open-plan offices; the measurement procedures for these single-number quantities are specified in the new standard ISO 3382-3 [12]. The single-number quantities include 1) $D_{2,\mathrm{S}}$, the rate of spatial decay of A-weighted sound pressure level per distance doubling, 2) $L_{p,\mathrm{A,S,4m}}$, the A-weighted sound pressure level of speech at a distance of 4 m, 3) STI, 4) r_D, the distraction distance where STI falls below 0.5, and 5) r_P, the privacy distance where STI falls below 0.2. Previous studies have adopted these parameters in order to assess speech privacy in open-plan offices [13, 14, 15, 16].

The present study aims to use the parameters specified in ISO 3382-3 to evaluate speech privacy in the passenger cars of a high-speed train using the single-number quantities in order to explore useful room acoustic design parameters for encouraging speech privacy in a passenger car. A preliminary survey and measurements were performed in order to identify the acoustic conditions in existing passenger cars of high-speed trains. The single-number quantities were then measured in passenger cars of the KTX train, and computer simulations were then conducted to investigate the behavior of the single-number quantities with variation of absorption and background noise levels in such a passenger car.

2. Preliminary study on acoustic comfort in passenger cars

2.1. Surveys on acoustic comfort in passenger car

2.1.1. Questionnaire survey

In order to evaluate acoustic comfort in passenger cars, questionnaire surveys were conducted. In the first part of questionnaire, environmental amenities were assessed in the passenger cars of high-speed trains. Participants were asked to rate their satisfaction on interior environmental factors including air, lighting, thermal, and acoustic conditions using a seven-point scale (with '-3' signifying not at all satisfied and '$+3$' signifying extremely satisfied). In the second section, respondents were asked to specify the most annoying noise generally and the most annoying speech noise while they were in the trains.

2.1.2. Participants

The surveys were performed on board the KTX during various times of the day, including rush hour, for two days in January 2012. In total, 91 passengers in high-speed trains participated in the survey. 41 males and 50 females participated, with 41% of respondents over the age of 50, 19% in their 40s, 13% in their 30s, and 24% in their 20s. Most participants were using the high-speed trains for business or travel.

2.1.3. Results

Among the environmental conditions in passenger cars, respondents were most satisfied with the lighting conditions, with 1.1 mean satisfaction score (standard deviation, SD: 1.3), while the acoustic environment was judged as the least satisfying, with -0.2 mean satisfaction score (SD: 1.6). Thermal and air quality conditions received mean satisfaction scores of 0.5 (SD: 1.8) and 0.3 (SD: 1.5), respectively. Independent T-tests were conducted to examine the mean differences between satisfaction with acoustic comfort and that with other environmental conditions. The mean satisfaction with acoustic comfort was significantly less than that with other environmental conditions ($p < 0.05$). This indicates that recently, the acoustic environment in passenger cars has been less satisfying for users than other environmental conditions.

As listed in Table I, 31.8% of respondents specifically indicated that noise from other passengers was the most annoying noise on the high-speed train. Respondents also selected low-frequency engine noise (19.1%) or aerodynamic noise (15.3%) as one of the most annoying noises on high-speed trains. In particular, the respondents that selected noise from other passengers as the most annoying noise indicated that sounds from ambient conversation (43.5% of respondents), cellular phones (23.5%), and children (14.1%) were the most annoying sounds from other passengers. This demonstrates that conversations from other passengers are one of the main noise sources affecting the overall environmental quality in the passenger cars of a high-speed train.

Table I. Summary of the survey responses about acoustic comfort in passenger cars in high-speed train.

Types of sounds	Percentage
Question: Which sound annoys you?	
Noises from passengers	31.8%
Low-frequency engine noise	19.1%
Aerodynamic noise	15.3%
Noise from opening and shutting the door	12.7%
Noise from breaking	8.3%
Running noise in tunnel	8.3%
Announcements	3.2%
Other	1.3%
Total	100%
Question: Among sounds made by humans, what is the most annoying sound?	
Speech sounds	43.5%
Cellular phone calls	23.5%
Sound of children	14.1%
Speech sounds from the aisle	4.7%
Sound of ticket inspector	1.2%
Footsteps	1.2%
Other	12.9%
Total	100%

2.2. Speech privacy in running trains

2.2.1. Measurement setup

As described in the previous section, surveys about the acoustic environment showed that speech was found to be a deteriorating noise source in the passenger cars of trains. In this section, field measurements using an example speech source are presented in order to examine the acoustic conditions for speech privacy in the passenger cars of high-speed trains.

Both male and female speech sources (4 s) recorded in an anechoic chamber were used as test signals; the frequency characteristics of the sources were also measured in an anechoic chamber. The speech sample was one phonetically balanced Korean sentence. The sentence consisted of ten syllables. The speech source was produced by a portable speaker (Drumbass II, Lifetrons) and recorded by a binaural microphone (Type 4101, B&K) at a distance of 1 m from the speaker. The mean sound pressure levels of the male and female speech in the one- third-octave frequency band from 400 Hz to 8 kHz are shown in Figure 1. The L_{Aeq} of the source was 59.5 dBA. The spectral characteristics of the speech sources were dominated by 630 Hz and 4 kHz components, while the sound pressure levels from 800 Hz to 3.15 kHz were relatively lower than those of the other frequency ranges. Sound pressure levels over 4 kHz somewhat were greater for the female voice than are those of the male voice.

The in situ measurements of the speech transmission were conducted in a passenger car of the KTX while the high-speed train was running at 100 or 300 km/h. The portable speaker was positioned at a height of 1.05 m to mimic a passenger sitting on a seat. Only background noise and combined noise with the speech source were recorded using a binaural microphone (Type 4101, B&K) at 1.1 m, which approximates ear height, to examine speech transmission in running trains. As shown in Figure 2, the source (white circle, S) and two receiver (black circle, R1 and R2) positions were selected in the passenger car. The source-to-receiver distances were 5.6 m (d_1) for R1 and 8.7 m (d_2) for R2. The source and receiver positions were in seats facing in opposite directions.

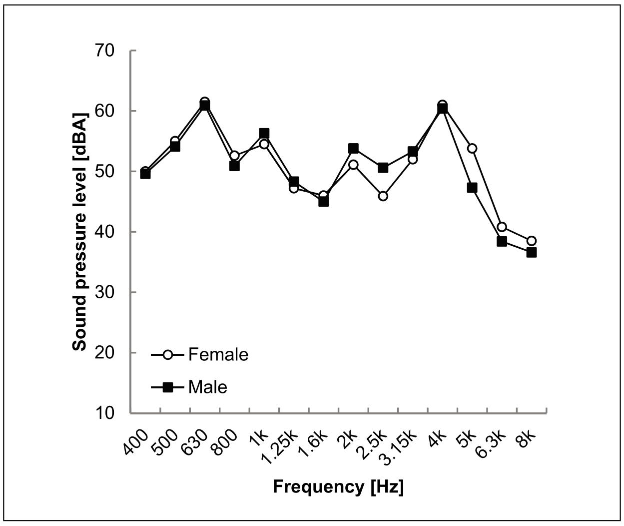

Figure 1. One-third-octave band sound pressure levels of the male and female speech measured in anechoic chamber in the range 400 Hz to 8 kHz.

2.2.2. Speech transmission

Figure 3 shows a comparison of the A-weighted equivalent sound pressure levels (L_{Aeq}) of the background noise with background noise and speech noise at the receiver point R1 in the passenger cars of KTX at speeds of 100 and 300 km/h. Even though the measurements were conducted when trains were running at constant speeds, background noise levels in a passenger car may be influenced by other environmental conditions on the rails. Seven audio samples of background noises (4 s duration) were taken when trains were running at speeds of 100 and 300 km/h, to compare the variance of background noises. Figure 3a shows that the difference of sound pressure levels at 63 Hz to 1 kHz between background noise alone and combined noise was within standard deviation at 100 km/h; the standard deviation at 63 Hz to 1 kHz was 1.1 dB. As shown in Figure 3b, the train noise at 300 km/h was relatively constant and the standard deviation was smaller than that at 100 km/h. The difference of sound pressure levels within 63 Hz to 3.15 kHz between background noise alone and combined noise was within a standard deviation; the standard deviation within 63 Hz to 3.15 kHz was less than 3.9 dB. Thus, when combined noise was within a standard deviation in a frequency band, speech was masked by the background noise, and higher-level sounds falling outside the range of the standard deviation in high fre-

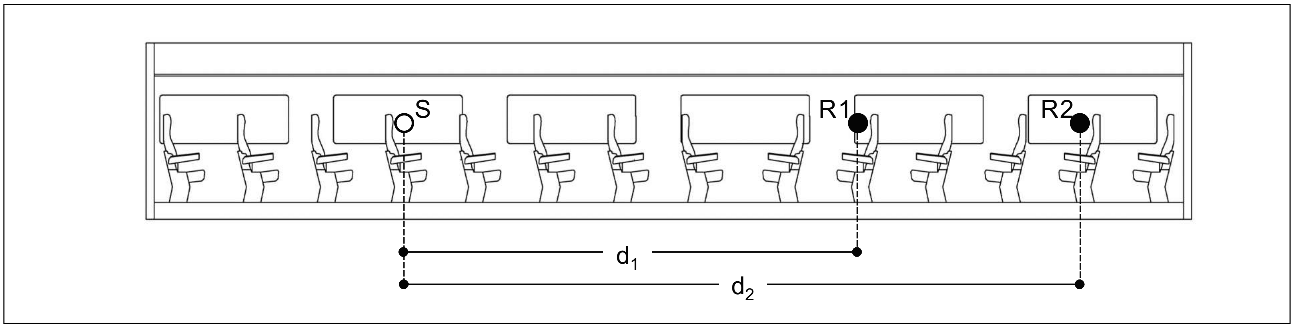

Figure 2. The source (white circle, S) and receiver (black circles, R1 and R2) positions in the passenger car. The source-to-receiver distances were d_1 =5.6 m (between S and R1) and d_2=8.7 m (between S and R2), respectively.

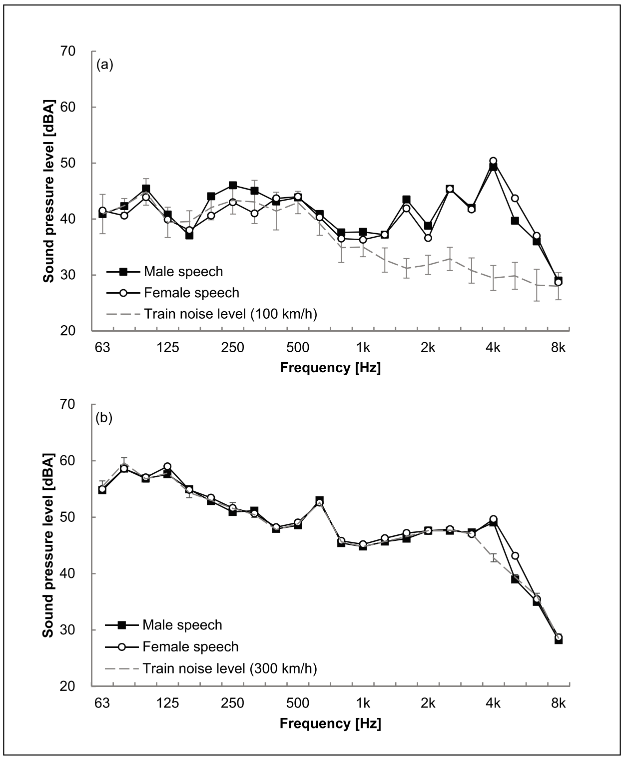

Figure 3. Speech transmission in a passenger car of the KTX; symbols indicate the SPL of the background noise (grey line), the combined noise with the male (black squares) and female (white circles) speech sources at (a) 100 km/h and (b) 300 km/h. Error bars denote standard deviation of background noises.

quency bands were speech-source influences. In addition, harmonic components were not found in the background noise samples, so that the change of combined noise could be caused by the speech source. Since each speech sound was entirely masked by background noise at R2 due to the sound attenuation of the increased distance, only the measurement results at R1 were plotted. The combined background noise and speech at a speed of 100 km/h increased in energy at high frequencies, above 1.6 kHz, due to the spectral characteristics of speech, as shown in Figure 3a; speech levels at 100 km/h increased to a maximum of 17 dBA at 5 kHz. However, when the train speed was 300 km/h, the increase of SPL caused by the speech source was only found between 4 kHz to 5 kHz, as shown in Figure 3b.

3. Room acoustic parameters

3.1. Measurement setup

In the present study, the single-number quantities for evaluation of speech privacy in an open-plan office were used to measure the acoustic properties in the 2nd class KTX passenger car of a stopped high-speed train according to ISO 3382-3 [12]. Reverberation time (T20) and early/late sound ratio for 50 ms (C50) were also measured simultaneously, according to ISO 3382-1 [17]. These measurements were conducted in an empty passenger car with the ventilation system operating which was in the Korail garage. Figure 4 illustrates the dimensions, the source position, and the receiver positions in the passenger car. The width, length, and height of the passenger car were 2.7 m, 13.0 m and 2.2 m, respectively, and the volume of the passenger car was approximately 77.2 m^3. The floor finish was vinyl tile and the ceiling covering consisted of fabric and plastic. The passenger car was furnished with 56 heavily upholstered chairs. The width and height of the chairs were 0.54 m and 1.1 m, respectively.

An omni-directional loudspeaker (Type DO12, AVM) and half-inch omni-directional microphones (Type 4189, B&K) were used for measurements to evaluate the room acoustic parameters. The sound source and the microphones were placed at a height of 1.2 m above the floor. Measurements were performed in three groups of positions: two along the seats and one along the aisle. The eight successive measurement positions in each line are shown in Figure 4.

A swept-sine signal was used as a sound source to measure impulse responses to calculate T20 and C50 in the passenger car. The signal-to-noise ratio was 35 dB in all frequency ranges at the farthest position from the speaker, which is sufficient to calculate T20. Pink noise was produced to measure the $L_{p,\mathrm{A,S,4m}}$, $D_{2,\mathrm{S}}$ and STI. The speech levels in each position were determined according to ISO 3382-3. ISO specified that SNR between the pink noise and the background noise was higher than 6 dB at all the distant measurement positions. The pink noise level at the farthest position was 70.5 dBA and the background noise level was 43.5 dBA. The sound pressure levels (SPL) were measured at a distance of 1 m from an omni-directional

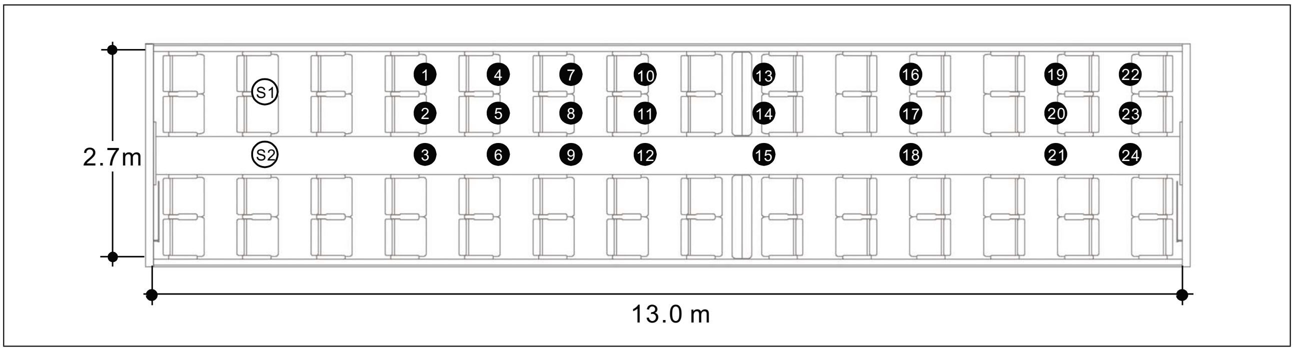

Figure 4. The source (white circle) and the receiver (black circles) positions diagrammed on the plan of the passenger car (KTX).

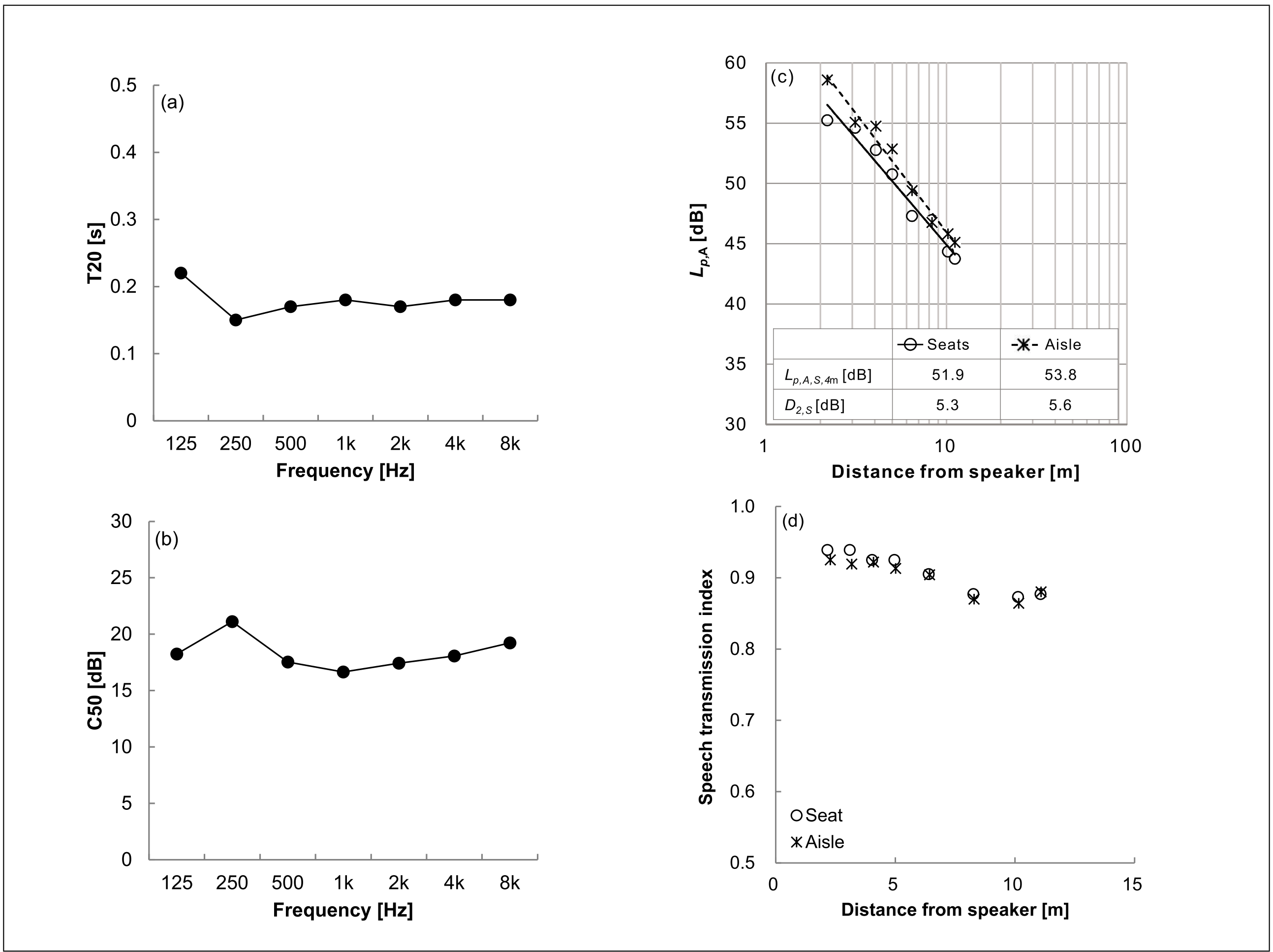

Figure 5. The frequency characteristics of (a) T20 and (b) C50. Spatial distribution of (c) A-weighted sound pressure level of speech ($L_{p,\mathrm{A,S}}$) with $L_{p,\mathrm{A,S,4m}}$ and $D_{2,\mathrm{S}}$, and (b) STI in the passenger car; black circles indicate the averaged values over all measurement positions, and white circles and stars indicate measurement points along the seats and aisle, respectively.

loudspeaker in a free field ($L_{p,\mathrm{S,1m}}$) in order to calculate the sound attenuation at each measurement position.

3.2. Results

The room acoustic parameters calculated from the acoustic measurements are shown in Figure 5a-d. The T20 and C50 are averaged values over all the measurement positions, and averaged from 125 Hz to 8 kHz. As shown in Figure 5a, the average T20 was 0.18 and the values in each frequency band in the passenger car were smaller than 0.22, indicating that the passenger car was an acoustically dry space, owing to its small volume and highly absorptive surfaces. In Figure 5b, C50 was 17.1 dB, indicating that a passenger could hear sounds with high clarity.

Figure 5c shows the spatial distribution curves of the A-weighted sound pressure level of speech ($L_{p,\mathrm{A,S}}$) as a function of the distance from the loudspeaker. The spatial decay rates in terms of the lines along the seats and the aisle were different; the $D_{2,\mathrm{S}}$ of the line in the seats was 5.3 dB, while that of the line in the aisle was 5.6 dB. In addition, $L_{p,\mathrm{A,S,4m}}$ obtained using a linear regression line from the measurement points along the seats was relatively smaller than that of the measurement points along the aisle; the values of $L_{p,\mathrm{A,S,4m}}$ in the lines along the seats and the aisle were 51.9 and 53.8 dB, respectively. This indicates that seats increased the spatial decay rate and sound reduction.

The STI values in the seat and aisle lines are shown as functions of the distance from the loudspeaker in Figure 5d. Background noise, $L_{p,\mathrm{A,B}}$ was 43.5 dBA with the ventilation system in operation for the calculation of STI. No significant difference was found in STI between the seats and the aisle. Overall, the STI values were calculated to be above 0.8 at all measurement points, showing that the speech intelligibility would be excellent even though the source-to-receiver distance is more than 10 m. Hence, distraction and privacy distances could not be obtained because STI values were above 0.5. According to the acoustic classification of open-plan offices for speech privacy based on the single number quantities including $D_{2,\mathrm{S}}$, $L_{p,\mathrm{A,S,4m}}$, and r_D from a previous study [13], the acoustic condition in the stopped passenger car was evaluated as the poor acoustic environment for speech privacy. This implies that the objective acoustic conditions with regards to speech privacy in the passenger car of high-speed train noise are not satisfactory when the train is stopped.

4. Computer simulation of speech privacy

4.1. Computer modeling

As the speed of the train increased, the background noise levels in the passenger cars of the high-speed train increased, and the STI became significantly influenced by the background noise. In this context, the speech privacy in a passenger car can change depending on the background noise levels due to changes in the speed of the train. However, it is difficult to measure the room acoustic parameters specified in ISO 3382-3 [12] when the train is running because of lower signal-to-noise ratio due to high levels of background noises in the cabins. Therefore, it is necessary to use computer simulation methods to predict the behaviors of the room acoustic parameters in terms of absorption and the background noise levels. This section reports computer simulations that were carried out in order to investigate effects of absorption and background noise levels on room acoustic parameters in a passenger car.

The room acoustic software ODEON version 11.23 was used to construct simulation models for the passenger car; the configuration of the simulated passenger car was modeled to be the same as the dimensions of the real passenger car measured in Section 3. The absorption coefficients and the scattering coefficients of the materials in such a passenger car were determined to reproduce the acoustical conditions of the passenger car. The absorption coefficients data measured in the reverberation chamber according to ISO 354 [18] are required for the ODEON simulation. Thus, in order to select the appropriate absorption coefficients of the materials in the passenger car, the relative absorption differences among the materials such as the ceiling, floor door, window, etc. were measured by using a P-U probe (PU regular, Microflown Technologies). The absorption coefficients were then selected from the ODEON database, with consideration of the results of the P-U probe and comparing the absorption coefficients of similar materials based on the previous data [19, 20, 21]. The scattering coefficients at mid-frequency, around 700 Hz, were selected with attention to the surface characteristics of the materials [21, 22]. The selected absorption and scattering coefficients are listed in Table II.

As illustrated in Figure 4, two speech sources and twenty-four receivers were positioned following the in-situ measurements conducted in section 3. The transition order was set to '2' by using 7000 rays and 3000 ms impulse response lengths for the computer simulation. Table III compares the room acoustic parameters obtained from the in-situ measurements and the simulation; the in-situ measurements and the simulation show good agreement in terms of averaged T20, C50, $L_{p,\mathrm{A,S}}$ and STI over all measurement positions, within just noticeable difference (JND) values [23, 24]. In addition, the spatial distributions of $L_{p,\mathrm{A,S}}$ and STI for simulation showed smaller differences with measurement results in Figure 5c-d than JND values. This indicates that the simulation fitting represented the acoustic environment of the stopped passenger car appropriately.

4.2. Absorptions and background noise levels of a passenger car

In order to examine the relationship between absorption coefficients and the single-number quantities, average absorption coefficients were varied from 0.18 to 0.44 in increments of 15% in octave bands of 125 Hz to 4 kHz. The average absorption coefficients were calculated by varying the absorption coefficients of chairs, side walls, and ceiling in the simulated passenger car according to equation (1). The reference average absorption coefficient, representing the reference passenger car, was 0.26.

$$\overline{\alpha} = \frac{\sum_{i=1}^{n} S_i \alpha_i}{\sum_{i=1}^{n} S_i}, \qquad (1)$$

where $\overline{\alpha}$ represents the average room absorption coefficient, S_i is the interior surface area of the surfaces, and α_i is the absorption coefficient of the surfaces.

Different background noise levels were determined depending on the conditions, e.g. whether the train was stopped or running at a speed of 100, 200, or 300 km/h. The speed was selected by considering the minimum (at rest) and maximum (300 km/h) speeds of the train. The background noise for each train speed was recorded, and the L_{Aeq} and the frequency characteristics of the selected background noises were calculated, as listed in Figure 6. Case 1 represents the condition when the train is stopped in the station so that not only the ventilation noise but also the noise from the engine can be heard, giving 56.7 dBA. Cases 2 to 4 represent the situation where the train is running at different speeds. As the train speed increased in

Table II. Absorption and scattering coefficients of materials in the passenger car.

Material	Absorption coefficients						Scattering coefficients
	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	
Floor (vinyl tile)	0.05	0.05	0.05	0.05	0.05	0.05	0.10
Chair seats	0.14	0.36	0.63	0.50	0.48	0.36	0.30
Chair back	0.42	0.38	0.68	0.66	0.65	0.64	0.30
Chair frame	0.45	0.07	0.17	0.17	0.01	0.01	0.20
Table	0.15	0.15	0.15	0.10	0.10	0.10	0.20
Door	0.20	0.13	0.07	0.08	0.06	0.06	0.10
Windows	0.17	0.11	0.05	0.08	0.06	0.12	0.05
Wall and curtain	0.03	0.04	0.11	0.17	0.24	0.35	0.50
Fabric wall	0.23	0.30	0.35	0.40	0.45	0.47	0.30
Plastic wall	0.44	0.30	0.10	0.10	0.10	0.10	0.20
Tray	0.30	0.20	0.16	0.12	0.15	0.20	0.20
Fabric ceiling	0.23	0.30	0.35	0.40	0.45	0.47	0.30
Plastic ceiling	0.28	0.12	0.10	0.17	0.13	0.09	0.20
Video screen	0.20	0.20	0.20	0.20	0.20	0.20	0.15

Table III. Measurement and simulation results of room acoustic parameters in a passenger car to describe the accuracy of the simulation model.

Acoustical parameter JND	T20 [s], 5% rel.	C50 [dB], 1.1 dB abs.	$L_{p,\mathrm{A,S}}$ [dB], 1.0 dB abs.	STI, 0.03 abs.
Measurement (M)	0.18	17.1	43.8	0.88
Simulation (S)	0.17	17.3	44.4	0.87
Difference (S-M)	0.01 (−5%)	0.2	0.6	−0.01

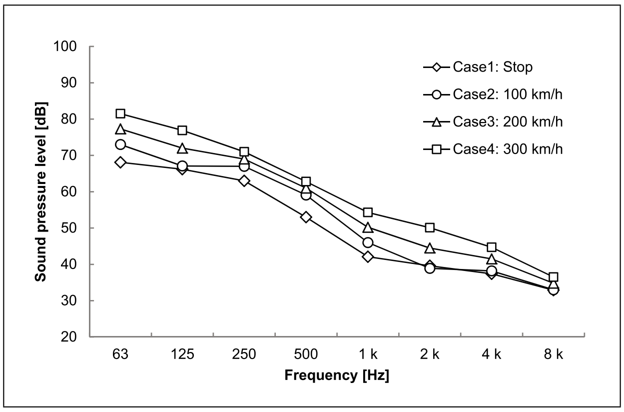

Figure 6. Variation of background noise levels in a passenger car.

steps of 100 km/h, the noise level increased by approximately 3 dBA with each step. Background noises when the train was running at 100, 200 and 300 km/h were 60.9, 63.5 and 66.0 dBA, respectively. The engine noise caused increments of low frequency noise from 63 Hz to 125 Hz, while the aerodynamic noise increased the sound pressure levels above 1 kHz. Compared with the high and low frequency levels, the sound energy at the mid- frequencies from 250 Hz to 500 Hz did not increase significantly as the speed increased.

4.3. Results

Figures 7a and 7b show the predicted $L_{p,\mathrm{A,S,4m}}$ and $D_{2,\mathrm{S}}$ values as a function of absorption coefficient. As shown in Figure 7a, $L_{p,\mathrm{A,S,4m}}$ decreased from 54.9 to 49.0 dB, as the average absorption coefficient increased from 0.18 to 044. In contrast, Figure 7b shows that $D_{2,\mathrm{S}}$ increased with increased when increasing the absorption coefficients, but the variation in $D_{2,\mathrm{S}}$ was smaller than that in $L_{p,\mathrm{A,S,4m}}$; $D_{2,\mathrm{S}}$ varied in the range between 5.0 and 5.8 dB as a function of the average absorption coefficient. There were no changes in $L_{p,\mathrm{A,S,4m}}$ and $D_{2,\mathrm{S}}$ in terms of background noise levels.

The spatial distributions of predicted STI with variation in the background noise levels in the reference case are shown in Figure 8. The STI values changed significantly with variations in the background noise levels; as the background noise level increased, the STI decreased dramatically. All the STI values as a function of the distance were below 0.5, so that neither of the distraction distances could be calculated. The difference of background noise levels between the STI values plotted in Figure 5d and Figure 8 was more than 13.2 dBA. This difference of background noise levels caused the great variation in STI values. When the average noise level in a passenger car exceeds 55 dBA, the distraction distance, r_D, is not useful for evaluating speech privacy because STI values are below 0.5. Similarly, Rindel [16] concluded that the distraction distance is not a relevant parameter for speech privacy in cases where the background noise level in an open-plan office is over 45 dB. This indicates that the privacy distance, r_P, can be a useful single-number quantity for evaluating and designing the room acoustic conditions for speech privacy in a passenger car. The privacy distance was calculated from the linear part of the STI distribution, and

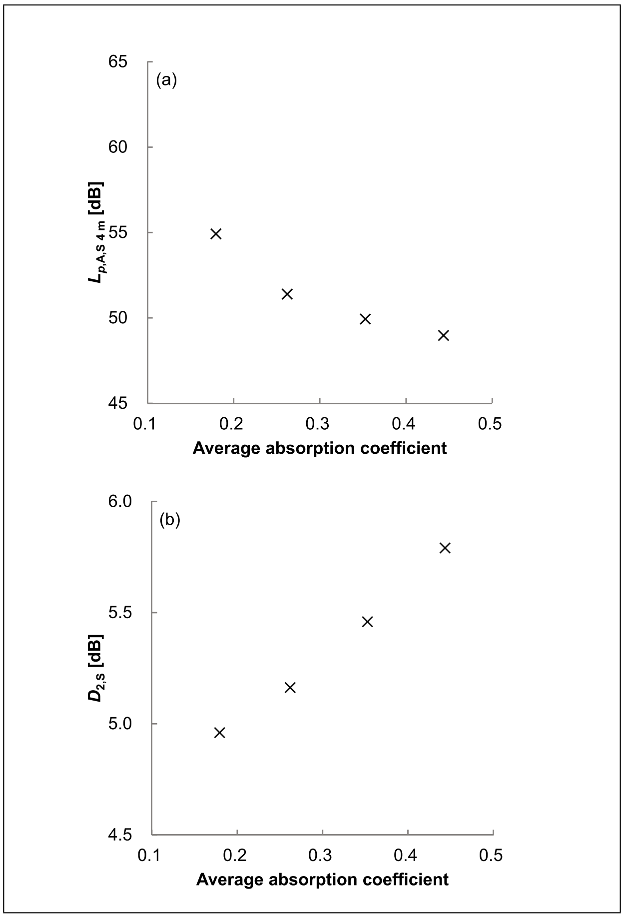

Figure 7. Relationship between average absorption coefficient and (a) $L_{p,\mathrm{A,S,4m}}$ and (b) $D_{2,\mathrm{S}}$.

Figure 9 shows the relationship between r_P and absorption coefficients and background noise levels. r_P ranged from 2.2 to 10.3 m. In contrast to $L_{p,\mathrm{A,S,4m}}$ and $D_{2,\mathrm{S}}$, we found that both average absorption coefficients and background noise levels influenced the privacy distance, r_P, as shown in Figure 9. r_P decreased with increasing average absorption and background noise levels. r_P changed approximately 2.5 m and 5.6 m with the variation in average absorption coefficients and background noise levels.

5. Discussion

Speech privacy and intelligibility are both mainly influenced by the amount of absorption and the background noise level. In this context, the room acoustic parameters suggested in ISO 3382-3 [12] can be classified into two groups: $D_{2,\mathrm{S}}$ and $L_{p,\mathrm{A,S,4m}}$ are based on the spatial decay of the A-weighted sound pressure level, and depend on the absorption, while the distraction distance and the privacy distance are obtained from the spatial distribution of STI and are sensitive to the signal-to-noise ratio [16].

The $L_{p,\mathrm{A,S,4m}}$ value in the reference passenger car was 51.4 dB. According to the acoustic classification for open plan offices [13], $L_{p,\mathrm{A,S,4m}}$ values over 50.0 dB were classified as being poor acoustic conditions for speech privacy. When increasing average absorption coefficients by 30% in the passenger car, $L_{p,\mathrm{A,S,4m}}$ values decreased by 49.0 dB, indicating rather good acoustic conditions for speech privacy. Annex A in ISO 3382-3 [12] suggests that good acoustic conditions in open plan offices require a $D_{2,\mathrm{S}}$ value above 7.0 dB. The $D_{2,\mathrm{S}}$, in the reference passenger car was 5.2 dB. Even though the average absorption coefficient increased by up to 30%, $D_{2,\mathrm{S}}$ increased to 5.8 dB, which is still evaluated as being poor for speech privacy. A similar tendency was found, that $L_{p,\mathrm{A,S,4m}}$ varied twice as much as $D_{2,\mathrm{S}}$ when floor and ceiling absorption in open plan office were varied [15]. Keränen and Hongisto [25] also revealed that $L_{p,\mathrm{A,S,4m}}$ values were chiefly influenced by absorptions of nearby surfaces including ceiling and side walls, whereas $D_{2,\mathrm{S}}$ values largely depended upon the screen height / room height ratio compared with absorptions of ceiling and furniture in an open-plan office. These conclusions support our finding that $L_{p,\mathrm{A,S,4m}}$ values were

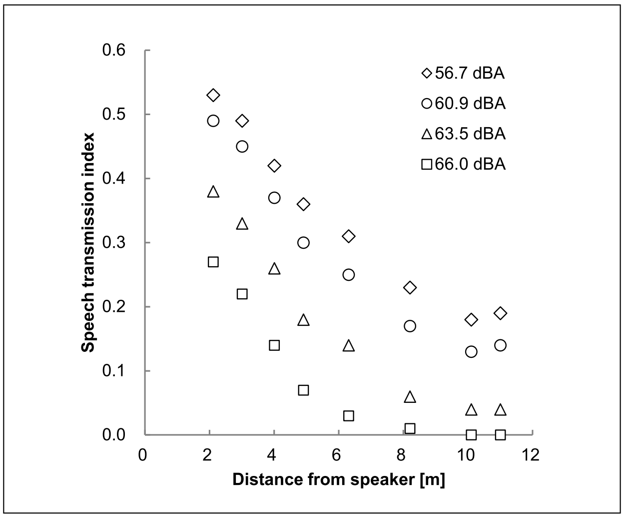

Figure 8. Spatial distribution of STI with different background noise levels. ◇: 56.7 dBA, ○: 60.9 dBA, △: 63.6 dBA, □: 66.0 dBA.

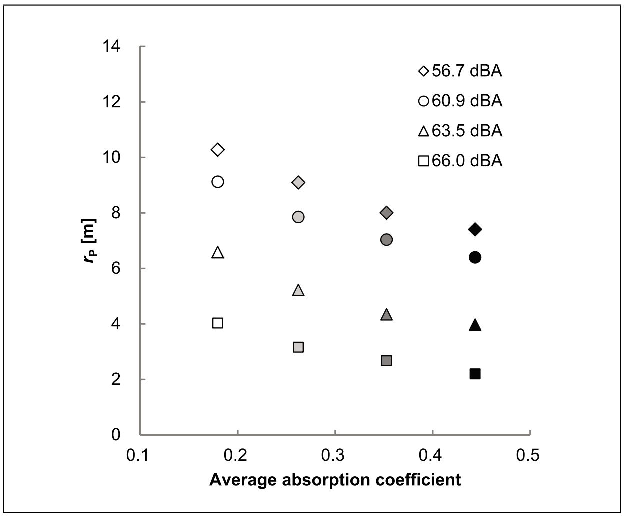

Figure 9. Relationship among r_P and (a) average absorption coefficient and (a) background noise levels. ◇: 56.7 dBA, ○: 60.9 dBA, △: 63.6 dBA, □: 66.0 dBA.

Table IV. Distances for speech privacy in a passenger car in terms of the background noise levels.

Background noise level	56.7 dBA (Stopped)	60.9 dBA (100 km)	63.5 dBA (200 km/h)	66.0 dBA (300 km/h)
Privacy distance (STI ≤ 0.2)	9.1 m	7.9 m	5.2 m	3.2 m
Transitional distance (AI ≤ 0.2)	8.0 m	6.9 m	4.4 m	1.3 m
Normal distance (AI ≤ 0.1)	10.2 m	9.1 m	6.4 m	3.7 m

more sensitive than $D_{2,\mathrm{S}}$ when average absorption coefficients of a passenger car were changed in the simulation. Eq. (2) and (3) were drawn from simple regression analyses to predict $L_{p,\mathrm{A,S,4m}}$ and $D_{2,\mathrm{S}}$ using average absorptions ($\overline{\alpha}$) of a passenger car. The determination coefficients (R^2) for equatins (2) and (3) were greater than 0.9 (p<0.01). These equations can be used to design speech privacy in a passenger car based on average absorption. For instance, it can be said that a variation of 0.05 and 0.32 of average absorption coefficients in a passenger car is required to change 1 dB of $L_{p,\mathrm{A,S,4m}}$ and $D_{2,\mathrm{S}}$ values. The prediction model for r_P was obtained from multiple regression analysis using a linear combination of average absorption coefficients and background noise levels, as shown in equation (4). The standardized regression coefficients of average absorption coefficients and background noise levels in equation (4) were −0.39 and −0.91, respectively. This indicates that the contribution of background noise to r_P is much greater than that of the absorption coefficient.

$$L_{p,\mathrm{A,S,4m}} = -21.9\overline{\alpha} + 58.0, \tag{2}$$

$$D_{2,\mathrm{S}} = 3.1\overline{\alpha} + 4.4, \tag{3}$$

$$r_P = -9.5\overline{\alpha} - 0.65 L_{p,\mathrm{A,B}} + 49.2, \tag{4}$$

where $\overline{\alpha}$ is the average room absorption coefficient, and $L_{p,\mathrm{A,B}}$ represent the background noise levels.

In previous studies [13, 25] background noise levels in open plan offices, ranging from 34 and 45 dBA, were fixed at certain levels. In contrast to open-plan offices, it is important to consider that the background noise levels of a passenger car change as the train's speed changes. In fact, $L_{p,\mathrm{A,S,4m}}$ and $D_{2,\mathrm{S}}$ are independent from the background noise levels so that those two single-number quantities could not fully describe the acoustic conditions for speech privacy in a passenger car of a high speed train. For instance, although speech privacy in a passenger car is evaluated as not satisfactory in terms of $L_{p,\mathrm{A,S,4m}}$ and $D_{2,\mathrm{S}}$, speech privacy could be improved when the train is running with increasing background noise levels. Therefore, determination of the distances based on STI could be more useful to evaluate speech privacy in a passenger car due to variation of background noise levels. Although ISO 3382-3 [12] does not suggest the range of privacy distances for an open plan office, ANSI S3.5 [26] describes the relationship between the articulation index (AI) and the degree of speech privacy. According to ANSI S3.5, the AI value should be below 0.1 for achieving normal privacy. Similar to the calculation of the privacy distance, the distances when AI is below 0.1 (normal distance) and 0.2 (transitional distance) at each background noise level were calculated using linear regression lines with the reference passenger car. We found that similar results to the privacy distance were obtained, and these are listed in Table VI. At all background noise levels, normal distances (AI < 0.1) were longer than the privacy distances, while the difference between the transitional distances (AI < 0.2) and the privacy distances were not significant. The privacy distances and the transitional distances, which ranged from 1.3 to 8.0 m, could be more practical for the design of acoustic conditions for speech privacy because the length of the passenger car was 13.0 m.

Increasing the background noise level could be a design approach for the improving the acoustic environment in a passenger car. However, high levels of background noise in a passenger car might negatively affect acoustic comfort for users. Therefore, in the future, optimal background noise levels should be investigated by considering both acoustic comfort and speech privacy in order to design adequate interior acoustic environments for high-speed trains. In addition, the Lombard effect and speech effort should be also considered: speakers tend to increase their speech levels when loud background noise levels are present [25, 27]. Although ISO 3382-3 specifies the sound pressure level at a distance of 1.0 m from unisex speech as 57.4 dB, high background noise levels in a passenger car could cause speech levels to increase. This could lead to overestimation of the privacy distance. Thus, studies on the relevant speech level for the measurement of speech privacy in a passenger car are also needed for future investigations.

6. Conclusion

In the present study, the acoustical conditions in a high-speed train passenger car were examined using room acoustic parameters described in ISO 3382-3 to explain speech privacy through in situ measurements. Parametric studies were then performed using a computer simulation to investigate the effect of absorption and background noise levels on speech privacy in a passenger car of a high-speed train. We found that the effect of average absorption in a passenger car on $L_{p,\mathrm{A,S,4m}}$ and $D_{2,\mathrm{S}}$ values was significant, while $L_{p,\mathrm{A,S,4m}}$ were relatively more sensitive than $D_{2,\mathrm{S}}$ values to absorption in a passenger car. We also found that r_P was a useful single-number quantity, as compared with r_D, due to the relatively higher background noise levels in a passenger car. Variation of average absorption and background noise levels in a passenger car caused significant changes in r_P, and the effect of background noise levels on r_P values was more significant than that of absorption in a passenger car. Regression models to predict the single number quantities using average absorption coefficients and background noise levels were suggested, and can be used in practice for the design of speech privacy in a passenger car of high-speed train using the room acoustic parameters. This study is limited by how average absorption coefficients were used to estimate the behaviors of the single number quantities, while various individual design factors in a passenger car, such as the heights of the chairs and the absorption of the ceiling and floor finishes, might affect the variation of these quantities. Therefore, more research on how design factors influence single-number quantities is required in the near future.

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