Applied Acoustics 97 (2015) 46–53

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Short-term noise annoyance assessment in passenger compartments of high-speed trains under sudden variation

Buhm Park [a], Jin-Yong Jeon [b], Sunghoon Choi [c], Junhong Park [a,*]

[a] Department of Mechanical Engineering, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul 133-791, South Korea
[b] Department of Architectural Engineering, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul 133-791, South Korea
[c] Korea Railroad Research Institute, Woulam-dong, Uiwang-city, Kyunggi-do 437-757, South Korea

A R T I C L E I N F O

Article history:
Received 2 September 2014
Received in revised form 31 March 2015
Accepted 10 April 2015
Available online 22 April 2015

Keywords:
High-speed train
Transient noise
Short-term annoyance
Acoustic comfort of passenger compartments

A B S T R A C T

The sounds in passenger compartments of high-speed trains operating in Korea under various conditions were measured, and its evaluation method for annoyance is presented. The stationary noise was measured for trains operating on ballast, concrete, open, or tunneled tracks at different speeds. The unsteady sudden variation of sound resulting from the entrance or exit of a tunnel, or passing another train traveling in the opposite direction was also measured. The sound pressure level and sound quality metrics such as loudness, sharpness and roughness were calculated for different conditions, and their variations were compared. The short-term annoyance was evaluated for various sounds using a paired comparison method. The loudness exhibited a closer correlation to the annoyance resulting from many different noise sources in the passenger compartment for stationary sounds but was not sufficient in rating noises under sudden variation. To evaluate the annoyance caused by the unsteady sound, a parameter adopting moving average filter to reflect the rate of change in sound quality metrics was proposed. Using statistical analysis, a sound index for estimating the annoyance using independent variables was developed, and its accuracy was compared to existing psychoacoustic annoyance model proposed by Zwicker and Fastl.

1. Introduction

Tracks for high-speed trains are expanding rapidly as green transport systems in Korea. More and more people are using this form of transport for its advantages in terms of speed, safety, and comfort. To satisfy the needs of passengers and to design spaces with high-quality acoustic comfort, the sound environment must be characterized and evaluated accurately to reflect the annoyance perceived by passengers. Current technical specifications are based on the A-weighted sound pressure level (dBA) only [1], and do not accurately account for human perception of interior noise. Most recent studies were directed toward understanding the effects of noise from high-speed trains on nearby residential areas, and little is known about the acoustic characteristics of passenger compartments [2–4]. To explain subjective responses to startling train noise, De Coensel et al. [5] introduced indicators such as increase in sound pressure level due to train's passing-by. Since the interior noise comes from many different sources such as the engine, aerodynamic and rolling noise, the contribution of noise from each source on the short-term annoyance (hereinafter referred to as 'annoyance', which means short-term judgments of listeners to short-term sounds provided under controlled conditions in a laboratory) need to be identified to determine optimal noise control strategies when designing tracks and trains.

Parizet [6] and Poisson et al. [7,8] measured the interior noise and investigated the sound quality factors that influenced passenger perception. Among many parameters, loudness had the most significant influence on annoyance from stationary sounds. Hardy [9] used parameters for indoor sound environments, such as noise criteria (NC), preferred noise criteria (PNC), noise rating (NR), and room criterion (RC) to evaluate the acoustic characteristics. These factors were required to reflect many different operating variables such as the operating speeds and type of tracks. Patsouras [10] studied the effects of tonal components from electric motors and rail on annoyance. Lowering the amplitudes of these tonal components significantly reduced the noise level. Kuwano [11] measured the interior noise for different trains, and investigated the effects of its loudness on speech communication. Khan [12,13] studied the effects of various noise sources on the total loudness perceived by passengers. These studies were limited to stationary noise, and did not include various situations involving time-dependent change of noise encountered during travel. Many studies focused

* Corresponding author. Tel.: +82 2 2220 0424; fax: +82 2 2298 4634.
E-mail address: parkj@hanyang.ac.kr (J. Park).

http://dx.doi.org/10.1016/j.apacoust.2015.04.007
0003-682X/

on understanding the effects of interior noise on passenger activities.

In Korea, the track is constructed through tunnels in mountains to minimize the curvature of the line, which is essential for the operation of high-speed trains. The tunneled section comprises 44% of the 414 km track from Seoul to Busan in Korea. It was built with various types of tracks, such as concrete or ballast tracks fastened with different clamping devices. The sound pressure level in passenger compartments increases significantly and decreases to the normal level when the train runs through a tunnel. This sudden change depends on the shape of the tunnel and train nose shapes. Also, the noise level increases severely when two trains pass each other. These sudden changes in sound pressure influence the perception characteristics significantly, and must be investigated to facilitate increased acoustic comfort. These transient noise variations were investigated in several previous studies, but were not applied to trains. Auweraer [14] analyzed impact sound during vehicle door closure using wavelet analysis. Kim [15] measured the sound emitted when road vehicles go over speed bumps and suggested an evaluation method based on continuous wavelet transform, and subject tests were performed to find the evaluation accuracy. Wang [16] used wavelet transforms and sound quality metrics to analyze the transient variation of sounds in vehicle interior noise, and suggested that it is also useful for evaluating stationary noise. They also suggested the use of statistical characteristics in addition to wavelet transform to analyze the time-dependent variation of sound. Previous studies were applied to evaluation of stationary noise after averaging. In addition, radiation of railway noise into residential areas adjacent to the railway was main focus of previous studies. Thus, it is required to determine an evaluation method of high-speed train interior noise for transient noise encountered for trains passing through a tunnel or by another train.

In this study, the acoustic environment of high-speed trains operating in Korea was investigated by assessing sound pressure level and psychoacoustic metrics for entire railway tracks run by two currently running trains. Transient and spectral characteristics were obtained from measured noises under similar operating conditions (running speed, track types, and existence of tunnel) repeatedly more than 10 times to distinguish sound samples showing spectral characteristics of each circumstance. Subjective tests were performed to evaluate the passenger annoyance by sound pressure level and psychoacoustic metrics. The metrics that have the greatest influence on the annoyance were determined for stationary sounds measured for trains operating at constant velocity on different tracks. Sound pressures measured in the tunneled section and while passing another train traveling in the opposite direction showed different trends compared to stationary sounds. Based on the objective and subjective evaluation of the sounds measured under various operating conditions, the psychoacoustic metrics and their rate of change with time of sound that significantly influence the passenger perception of annoyance were identified. The method used to evaluate the annoyance in the passenger compartment based on sound quality metrics is described here.

2. Measurements of sound pressure and its psychoacoustic characteristics

2.1. Measurements in passenger compartments

The interior sounds were measured for the two kinds of high-speed trains currently operating in Korea: KTX and KTX-Sancheon. The sound samples were taken in the middle and window seats of the passenger compartments for entire tracks from Seoul to Busan. A system from Head Acoustics (model HMS-III) was used for data acquisition. The running speed of the train was measured using GPS system (Asen gps-741). During data acquisition, the information about the operating condition such as the velocity, rail types (concrete or ballast), existence of tunnel, or pass-by the other train was recorded as accurately as possible. The data was taken using more than 20 trains (operating between Seoul and Busan) to increase the number of operating conditions required for the analysis. The psychoacoustic metrics of the recorded samples were calculated using commercial sound quality analysis software (Artemis by Head Acoustics).

2.2. Effects of operating conditions on the interior noise and its ratings

Fig. 1 shows a comparison of the sound pressure level of the stationary sounds taken in the passenger compartments on the open land and inside a tunnel for the concrete and ballast tracks, respectively. The sound pressure levels were greatest at 30–70 Hz and decreases monotonically with increasing frequency. When the train runs inside a tunnel and on the concrete track, the sound pressure level increased across the entire frequency range compared to those measured in the open land and on the ballast track, respectively. The tonal component near 270 Hz showed distinct amplification when the train runs inside a tunnel. The difference between noises measured for concrete and ballast tracks was not large in the open land, but became much more significant when the train ran inside the tunnel.

For the train running through a relatively short tunnel, the sound pressure increased suddenly, and the spectral characteristics remained constant inside the tunnel, as shown in Fig. 2(a) and (b) for the ballast and concrete tracks, respectively. Note that the increase in sound pressure level was still greater for the tunneled concrete track when compared to those in the relatively large tunnel, as shown in Fig. 2(a). When passing another train on the open land, Fig. 2(c) shows that the sound pressure level in the range of 800–5000 Hz increased only at the start and end of the intersection. This abrupt variation is the fundamental difference compared to those encountered from a short tunnel shown in Fig. 2(a) and (b). However, when the two trains passed inside the tunnel, the variation in the sound pressure level was insignificant, as shown in Fig. 2(d). Nonetheless, passengers easily noticed the difference in sound when the trains were passing each other. This suggests that the sound pressure level alone may not predict the passenger's

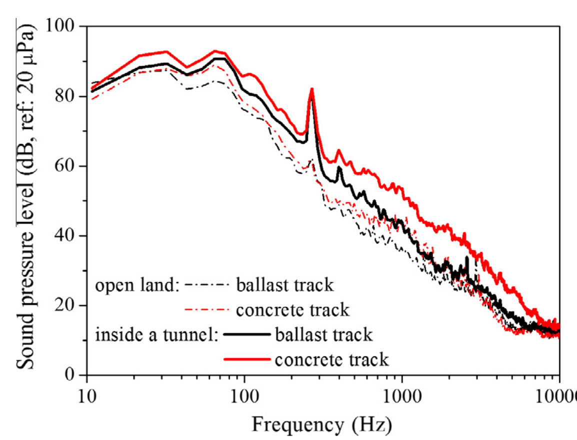

Fig. 1. Spectrum of interior sound measured when the train runs on open land and inside tunnels with 300 km/h running speed. The interior sound pressure level measured on a ballast was smaller than those on a concrete track. The difference in the sound pressure level at frequencies higher than 500 Hz was larger for the train inside a tunnel. In addition, the tonal noise near 270 Hz contributed from inter-coach spacing significantly increased inside a tunnel.