Study on the speech intelligibility of public address system in a tunnel

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ABSTRACT
The Metropolitan Highway Shinjuku Line under construction in Tokyo has a tunnel of 11 km length. For the public address system for emergency evacuation announcement in this tunnel, it has been decided to apply the successive time-delay technique to improve speech intelligibility. The effectiveness of this technique has been confirmed by the field experiments performed in a real tunnel and the laboratory experiments performed in an anechoic room equipped with a 6 channel recording/reproduction system as presented in the past inter-noise congresses. Following these basic investigations, the authors have performed further psycho-acoustical studies in the laboratory to examine the effect of the speech-rate of the emergency evacuation announcement, the transmission frequency range for the P.A. system and the influence of reverberation in the tunnel. In this paper, the results of these subjective experiments are presented.

1 INTRODUCTION
As a mean to improve speech intelligibility of public address system for emergency evacuation in a tunnel, the authors have proposed to apply the successive time-delay technique to an array of loudspeakers in a road tunnel and investigated the effectiveness of this technique by performing field experiment in a real tunnel under construction [1-3], and it has been confirmed that speech intelligibility can be significantly improved by this technique. Based on this finding, we have been continuing further investigations on such problems as (1) suitable speech-rate of evacuation announcements in the reverberant tunnel, (2) the transmission frequency range of the P.A. system and (3) the influence of reverberation on speech intelligibility. In this paper, the successive time-delay technique for the emergency evacuation announcement system is reviewed and the results of the psycho-acoustical experiments on the problems mentioned above are presented.

2 FIELD EXPERIMENT IN A TUNNEL
2.1 Application of Successive Time-delay Technique
Field experiment was performed in a highway tunnel just before its completion in July, 2004. Figure 1 shows the diagram of the temporary P.A. system equipped with the successive time-delay system set in the tunnel for the experiment. Near the wall inside the tunnel, five

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horn-type directional loudspeakers (see Fig.2) were set at an interval of 150 meters. In this P.A. system, the speech signal fed to respective loudspeakers was delayed by \( \tau_i = \frac{D_i}{c} \) compared to that for the adjacent upper loudspeaker (the left one in the figure), where \( D_i \) is the distance between the two adjacent loudspeakers and \( c \) is the speed of sound.

### 2.2 Measurement of Impulse Response in the Tunnel

In the tunnel, the impulse responses from the five loudspeakers to the five receiving points \( d = 25 \text{ m, 50 m, 75 m, 100 m, 125 m} \) shown in Fig.1 were measured under the two conditions with/without time-delay. In these measurements, the Swept-sine technique was applied. As the receiving system, a 6-channel microphone system including an omnidirectional microphone was used (see Fig.3) [4,5].

Figure 4 shows the impulse responses measured through the omni-directional microphone at the receiving point of \( d = 100 \text{ m} \) under the two conditions of (a) without time-delay and (b) with time-delay. In comparison between these two impulse responses, it is clearly seen that the direct sounds from respective loudspeakers were converged by the effect of the time-delay processing.

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Figure 1: Diagram of the public address system in a tunnel with successive time-delay function.

Figure 2: Directional Loudspeaker (TOA, TC-730M)

Figure 3: 6-channel microphone system (SONY, C48)
3 PSYCHO-ACOUSTICAL EXPERIMENTS ON “DIFFICULTY OF HEARING”

As reported in our papers [1,2], the effectiveness of the successive time-delay system was confirmed by psycho-acoustical experiments. Based on this result, it has been decided that the system will be practically applied in the newly constructed highway tunnel in Tokyo. Therefore, we have further performed psycho-acoustical experiments regarding the following points: (1) the speech-rate of the evacuation announcement, (2) the frequency range of the P.A. system and (3) the influence of reverberation in the tunnel.

3.1 3-dimensional Sound Field simulation

For this kind of psycho-acoustical experiment, it is desirable that the test sound can be heard as in the real sound field with 3-dimensional spatial impression. Therefore, the 6-channel recording/reproduction system [4,5] was applied. Figure 5 shows the diagram of the system, in which six loudspeakers are set orthogonally in an anechoic room and the six channel signals for each hearing test are reproduced from respective loudspeakers. When hearing the reproduced sounds at the center position, natural auditory sensation can be realized with 3-dimensional spatial impression.

3.2 Test Sounds

For respective hearing tests, the 6-channel test sounds were prepared as mentioned below. To simulate the reverberant sound field in a road tunnel, the 6-channel directional impulse responses (6ch.IR) measured at the receiving point of \( d = 100 \) m in the tunnel through the 6-channel microphone system under the conditions of with/without time-delay were used. They

![Diagram of 6-channel recording/reproduction system](image)

(a) 6-channel recording system  (b) 6-channel reproduction system (in an anechoic room)

Figure 5: Diagram of 6-channel recording/reproduction system.
were convolved with dry-sources of emergency evacuation announcement. The announcement was made by a Japanese female announcer in an anechoic room and its content was “Fire occurred in this tunnel. Evacuate from the tunnel through the closest emergency exit. (in Japanese)”.

(1) **Speech-rate of the announcement**

To examine the suitable speech-rate for the emergency evacuation announcement in the reverberant tunnel, the 6ch.IR with/without time-delay and the dry-sources with five-step different speech-rate (7 s, 9 s, 12 s, 15 s and 20 s) were convolved. The fastest speech-rate among them (7 s) is a common rate for the speech in radio broadcast and the slowest one (20 s) is common in the announcement in stadiums with a big volume.

(2) **Transmission frequency range of the P.A. system**

The transmission frequency range of the P.A. system equipped in the tunnel is planned to be from 300 Hz to 3.4k Hz. To examine the effect of this frequency range limitation on speech intelligibility, the frequency range of the dry-source (speech-rate; 9 s) was limited to nine steps of frequency range by changing the lower cut-off frequency and the higher cut-off frequency.

(3) **Reverberation time in the tunnel**

The reverberation time inside the tunnel is very long (about 20 s in 500 Hz) and it is desirable to suppress the reverberation in order to improve the speech intelligibility. To examine this point, the reverberation time of the 6ch.IR was artificially changed in six steps; from 20 s (real case) to 15 s, 10 s, 6 s, 4 s and 2 s. For the test sounds, these modified 6ch.IR with/without time-delay and the dry-source (speech-rate; 9 s) were convolved.

### 3.3 Experimental Procedures

In the three kinds of hearing tests, the subject was asked to judge the extent of difficulty in hearing the evacuation announcement in 6-step categories: “the contents can not be understood at all” (6), “extremely difficult to hear” (5), “very difficult to hear” (4), “moderately difficult to hear” (3), “a little difficult to hear” (2) and “not difficult to hear at all” (1). In each experiment, each test sound was reproduced twice in random order. For each test sound, the arithmetic average of the scores obtained by the scale rating was calculated.

![Figure 6: Experimental results for the effect of speech-rate of the announcement](image_url)
3.4 Experiment 1: “Effect of Speech-rate”
As the test subjects, fifteen Japanese from 21 to 32 years old participated in this experiment. Figure 6 shows the test results, in which it is clearly seen that the speech intelligibility has been significantly improved in all speech-rate conditions when the time-delay technique was applied. Except for the fastest speech-rate condition, the score was kept around “a little difficult to hear” (2).

3.5 Experiment 2: “Suitable frequency range”
As the test subjects, thirteen Japanese from 21 to 32 years old participated in this experiment. Figure 7 shows the experimental results for the effect of frequency range limitation for the P.A. system on speech intelligibility. In the result, it is clearly seen that the speech intelligibility has been significantly improved by the time-delay technique in all of the frequency range conditions. Under the conditions that the lower cut-off frequency was set at 320 Hz, it is seen that speech intelligibility was gradually improved with the increase of higher cut-off frequency, especially under the condition of with time-delay. Under the conditions that the higher cut-off frequency was set to 4k Hz, except for the condition that the lower limit frequency was set at 250 Hz, the score was kept around “a little difficult to hear” (2). From the experimental results, it has been found that the designed frequency range for the P.A. system in the tunnel (300 Hz to 3.4k Hz) is suitable.

3.6 Experiment 3: “Influence of Reverberation in the tunnel”
As the test subjects, fourteen Japanese from 21 to 32 years old participated in this experiment. The test results are shown in Fig.8. In the results, it is seen that the speech intelligibility has been significantly improved by the time-delay technique under all of the reverberation time conditions. Under both conditions of with/without time-delay, it can be clearly seen that the speech intelligibility can be improved by shortening the reverberation time.
4 SUMMARY

For the design of P.A. system for emergency evacuation announcement in a reverberant tunnel, subjective experiment on speech intelligibility was performed and the following results have been obtained.

(1) The successive time-delay technique is very effective to improve the speech intelligibility of evacuation announcement in a tunnel.

(2) Regarding the suitable speech-rate of the announcement, the tendency has been seen that the speech intelligibility improves with the increase of the speech-rate. However, there might be a speech-rate suitable for such a tense situation as fire emergency.

(3) Regarding the transmission frequency range of the P.A. system, it has been confirmed that the frequency range from 300 Hz to 3.4k Hz is proper.

(4) To further improve the speech intelligibility, it is desirable to suppress the reverberation in the tunnel by sound absorption treatment.

5 REFERENCES


