Study on the Application of Time-delay Technique to Public Address System in a Tunnel

Sakae Yokoyama a, Shinichi Sakamoto b, Hideki Tachibana c, Seiya Tazawa d

a,bInstitute of Industrial Science, the University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, 153-8505, Japan
cChiba Institute of Technology, 2-17-1 Tsudanuma, Narashino-city, Chiba, 275-0016, Japan
dMetropolitan Expressway Public Corporation, 1-4-1 Kasumigaseki, Chiyoda-ku, Tokyo, 100-8930, Japan

asakae@iis.u-tokyo.ac.jp; bsakamo@iis.u-tokyo.ac.jp; ctachibana@acoust.cs.it-chiba.ac.jp; dtazawa@mex.go.jp

ABSTRACT To improve the speech intelligibility (easiness of hearing) of public address system for emergency evacuation in highway tunnels, the authors proposed an application of successive time-delay technique to the system and performed experiment in an actual tunnel. In the experiment, five horn-type directional loudspeakers were set at an interval of 150 meters in the tunnel under construction and the time-delaying networks providing the delay-time estimated from the sound speed in the field was applied. From the loudspeakers, announcements for emergency evacuation for the subjective hearing test and a swept-sine signal for the measurements of impulse response were reproduced with/without the time-delay technique. During the experiment, the effect of the time-delay technique was judged subjectively in the tunnel and the reproduced announcements and the impulse responses were recorded using 6-channel recording system for the subjective hearing test performed later in acoustic laboratory. As the psycho-acoustical experiment in the laboratory, three kinds of subjective tests were performed; (1) the effectiveness of the application of the time-delay system on speech intelligibility, (2) the influence of the error of delay-time in the system caused by the change of the atmospheric conditions in the tunnel, and (3) the effect of speech rate of the emergency evacuation announcement. From the results of these experiments, it has been confirmed that the application of the successive time-delay technique is effective to improve speech intelligibility of the emergency evacuation announcement in road tunnels.

1. INTRODUCTION

As a means to improve speech intelligibility of public address system for emergency evacuation in a tunnel, authors proposed an idea to apply the successive time-delay technique to an array of loudspeakers set in a road tunnel and preliminarily investigated the
effectiveness of this technique using electro-acoustic simulation technique [1]. The experimental results indicated that speech intelligibility can be considerably improved by applying the time-delay technique appropriately and it was desired to prove the effectiveness of the technique in a real tunnel. In July, 2004, we had an opportunity to examine the applicability of this technique experimentally in a real tunnel under construction. In the experiment, five horn-type loudspeakers were set in the tunnel at an interval of 150 m and reproduction of an announcement for emergency evacuation and measurement of impulse response were performed under both conditions of with and without time-delay. In the experimental site, we confirmed the effectiveness of the technique subjectively by directly listening to the reproduced announcements through the system with/without the technique. Furthermore, to objectively examine the improvement of audibility of emergency evacuation announcements by the time-delay technique, psycho-acoustical experiments were performed in an anechoic room using 6-channel recording/reproduction technique by which the original sound field can be reproduced with 3-dimensional information [2]. In this paper, the outline of the field experiment and the results of psycho-acoustical experiments are introduced.

2. FIELD EXPERIMENT IN A TUNNEL

2.1 Application of Time-delay Technique

The field experiment was performed just before starting traffic service of a highway tunnel. Figure 1 shows the diagram of the public address system using the successive time-delay technique set in the tunnel. Near the wall inside the tunnel, five horn-type directional loudspeakers (see. Fig.2) were set at an interval of 150 meters. In this reproduction system, the speech signal fed to a loudspeakers was delayed by $\tau_i = D_i / c$ compared to that for the adjacent loudspeaker (the left one in the figure); here, $D_i$ is the distance between the two loudspeakers and $c$ is the speed of sound. By doing so, the direct sounds generated from all loudspeakers propagate together and therefore it can be expected that the speech intelligibility would improve compared with the case where the speech signal is generated at the same time from all of the loudspeakers. In the experiment, an announcement “Fire occurred in this tunnel. Evacuate from the tunnel through the closest emergency exit.”

$\tau = 25[^{\circ}\text{C}], c = 346.5[\text{m/s}], \tau_i = D_i / c = 433[\text{ms}]$

*Figure 1: Diagram of the public address system in a tunnel with the successive time-delay function.*
(female voice, in Japanese) was reproduced. During the experiment, we listened to the reproduced announcement directly and confirmed that the multi-echo was much reduced and the speech intelligibility of the announcement was considerably improved by applying the successive time-delay.

For the psycho-acoustical experiment, the evacuation announcement reproduced from the five loudspeakers (with and without time-delay) was recorded using a 6-channel recording system consisting of six uni-directional microphones (see Fig.3). At the same time, impulse response measurement was performed under both of the conditions where each loudspeaker was driven separately and where all loudspeaker were driven simultaneously with and without time-delay. This measurement was performed using the swept-sine technique and the 6-channel microphone system and an omni-directional microphone were used for recording. These recordings were performed at the five positions between the two loudspeakers as shown in Fig.1 (d=25, 50, 75, 100, 125m).

In the experiment, the delay-time ($\tau$) between the adjacent couple of loudspeakers was set at 433 ms under the assumption of atmospheric temperature of 25 °C and no wind as a standard condition (see Fig.1). However, the air temperature and wind speed can change in the actual tunnel and it is necessary to examine the effect of the error in setting the delay-time in the system. Therefore, the experiment was performed by changing the delay-time as shown in Table 1, where $\Delta \tau=0$ is the standard condition and the other conditions ($\pm 10$, $\pm 20$, $\pm 30$ ms) are the cases where the temperature and wind speed changed from the standard condition. Under these additional conditions, the measurement was performed at only one position (d=100m; see Fig.1).

\[ \begin{array}{|c|c|c|c|c|} \hline \Delta \tau [\text{ms}] & \text{Speed of sound} [\text{m/s}] & \text{Temperature} [\degree \text{C}] & \text{Wind speed} [\text{m/s}] \\ \hline 30 & 324.0 & -12.5 & 22.5 \\ \hline 20 & 331.1 & -0.7 & 15.4 \\ \hline 10 & 338.6 & 11.8 & 7.9 \\ \hline 0 & 346.5 & 25.0 & 0.0 \\ \hline -10 & 354.6 & 38.5 & -8.1 \\ \hline -20 & 363.2 & 52.8 & -16.7 \\ \hline -30 & 372.2 & 67.8 & -25.7 \\ \hline \end{array} \]

Table 1: Conditions of delay-time and corresponding atmospheric conditions.
2.2 Experimental Results

Figure 4 shows the comparison of the omni-directional impulse responses measured at the measuring position A ($d=100$ m) and B ($d=125$ m) without time-delay (a) and with time-delay (b). In both of these results, it can be seen that in the case of (a) the direct sounds generated from the three loudspeakers located in upstream direction reach the measuring point with time deviation, while in the case of (b) the direct sounds from the three loudspeakers reach at the same time due to the effect of time-delay. For a reference, Speech Transmission Index (STI) was calculated for impulse responses and it can be seen that this index was a bit improved [3].

3. PSYCHO-AcouSgtical Experiments on “DiFFicultY of HEARING”

To examine the effectiveness of the time-delay technique, three kinds of subjective hearing tests were performed in an anechoic room: Experiment 1 is for the effectiveness of the technique, Experiment 2 is for the influence of the error of the delay-time in the system, and Experiment 3 is for the effect of speech rate.

3.1 Experimental Procedures

In this kind of subjective hearing test, it is desirable that the sound can be heard as in the real sound field with 3-dimensional impression. Therefore, the 6-channel recording/reproduction method [2] was also applied in this experiment. Figure 5 shows the diagram of the system, in which six loudspeakers are set orthogonally in an anechoic room and the six channel signals recorded in the measurement site are reproduced from respective loudspeakers. When hearing the reproduced sounds at the center position between the loudspeakers, we can get natural auditory sensation.
In Experiments 1 and 2, the recordings of the evacuation announcement made in the tunnel were used for the test sounds. In Experiment 3, the directional impulse responses measured in the tunnel through the 6-channel microphone system and dry-sources of evacuation announcement with four-step different speech-rate were convolved for the test sounds.

Figure 6 shows the subjective hearing test performed in the anechoic room. In the test, the subject was asked to judge the audibility of 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 in each experiment, the arithmetic average of the scores obtained by the scale rating was calculated.

![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.

![Subjective hearing test using 6-ch. reproduction system (in an anechoic room).](image)

Figure 6: Subjective hearing test using 6-ch. reproduction system (in an anechoic room).

![Experimental results for “Difficulty of listening”.](image)

Figure 7: Experimental results for “Difficulty of listening”.  
(Bars indicate the standard deviation.)
3.2 Experiment 1: “Comparison of the Conditions with/without Time-delay”

For the test sounds in Experiment 1, the announcements recorded at the five measuring positions in the tunnel under the conditions of with/without successive time-delay, 10 conditions in total. In this test, eleven Japanese subjects with normal hearing ability from 21 to 42 years old participated. As an example of the experimental result, Fig. 7 shows the comparison of the average score between the conditions of with/without time-delay, in which we can see that speech intelligibility (difficulty of listening) has been much improved by performing the time-delay for all of the measurement positions. Even at the position of 125 m which is the nearest to the next loudspeaker and therefore the most apt to be influenced by the sounds from the loudspeakers in downstream direction, the speech intelligibility has been improved to “moderately difficult to hear” (category 3).

3.3 Experiment 2: “Influence of Delay-time Error”

To examine the influence of the error in setting the delay-time of the system, the evacuation announcements recorded at the position of \( d = 100 \) m (see Fig.1) under various delay-time conditions shown in Table 1 were used as the test sound. The experimental conditions were twelve in total. As the test subjects, nine Japanese from 21 to 30 years old participated in this experiment and the test results for them were averaged for each of the test conditions. The test results are shown in Fig. 8, in which it is seen that the extent of the improvement of speech intelligibility is almost the same even in the cases where the delay-time was moved from the optimum value up to \( \pm 30 \) ms, which are very extreme conditions. It means that the successive time-delay technique is very robust against the error in setting of the delay-time.

3.4 Experiment 3: “Effect of Speech-rate”

The sound field in a tunnel is generally very reverberant, and it is likely that the speech intelligibility of evacuation announcement may be influenced by the speech-rate. In Experiment 3, therefore, the speech intelligibility test was performed by changing the speech-rate of the announcement in four steps under the condition of with/without time-delay. The fastest speech-rate (6.0 s) among them is a common rate for speech in radio broadcast and the

![Figure 8: Experimental results for “Difficulty of listening” when the delay-time was varied. (Bars indicate the standard deviation.)](image-url)
The slowest rate (12.0 s) is common in the announcement in stadiums with a big volume. As the test subjects, ten Japanese from 21 to 30 years old participated in this experiment and the test results were averaged for each of the test conditions. The test results are shown in Fig. 9. In the results, it is clearly seen that the speech intelligibility has been significantly improved in all of the speech-rate conditions when the time-delay technique was operated. Under the conditions of without time-delay, the speech intelligibility is gradually improved with the increase of speech-rate, whereas under the conditions of with time-delay the score is kept around 2 “a little difficult to hear” except for the fastest speech-rate condition (6 s). After the experiment, a subject commented that slow speech-rate is easy to listen but too much slow rate is not appropriate for emergency evacuation announcement, because tension under such dangerous situation can not be felt.

4. CONCLUSIONS

The successive time-delay technique for the public address system in a road tunnel was investigated in this study and the following results have been obtained.

(1) The technique is very effective to improve the speech intelligibility of emergency evacuation announcement in a tunnel by setting the delay-time appropriately by considering the distance between the adjacent loudspeakers and the velocity of sound.

(2) Regarding the setting of the delay-time, additional experiment was performed by changing the delay-time artificially. As a result, it has been found that the system is unexpectedly robust against the error in the delay-time, which might mean that it is not necessary to equip the time-delay system with a function to control the delay-time according to the change of the atmospheric condition.

(3) Regarding the speech-rate of the announcement, it has been found that the speech intelligibility improves with the increase of the speech-rate but it should be discussed with other factors such as tense situation in the case of emergency.

The sound field in a tunnel is generally very reverberant and in order to further improve the speech intelligibility, it is necessary to treat the inside of the tunnel with passive means using sound absorption materials.
5. REFERENCES

