Sound propagation and speech hearing in a curved reverberant tunnel

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Transmission of correct speech in underground is essential to keep people safe in case of emergency. On the other hand, sound propagation characteristics is influenced by acoustical conditions of the sound field. From the viewpoints, sound propagation experiments, hearing tests of speech by subjects and measurements of RASTI are conducted in a reverberant curved tunnel. From measurements of pink noise propagation, relative attenuations less than 315 Hz are much small, and those at higher frequencies rapidly increase with distance. The attenuations may be influenced by not only absorption characteristics but also the curved feature of the tunnel. While hearing scores of speech decrease with distance, differences between the scores are observed and may depend on the kinds of speech. From analyzing the hearing results, mistakes are occurred by influences of both reverberant condition near the sound source and degradation of signal-to-noise ratio of speech signal due to many times of reflection at further points. Positive correlation is observed between RASTI and scores of the articulation syllables. Relationships between RASTI and scores of the other speech are indicated through the results of articulation tests. Possibility on prediction of speech transmission by the objective physical measurements is suggested.

Keywords: Reverberation, Sound propagation, Articulation, Intelligibility, RASTI, Curved tunnel

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1. INTRODUCTION

In Japan and other countries, underground spaces are developing year after year for the purpose of public transportations, industrial facilities and others. When such spaces are used for people's activities, some countermeasures in case of an emergency such as a fire or an earthquake always have to be considered. To properly transmit sound or speech information is important and essential for rapid evacuation and keeping people's lives safe.

Authors have studied sound propagation and speech transmission characteristics under some environmental conditions in an underground tunnel. In previous studies, we mainly discussed the propagation characteristics of sound and speech in a straight tunnel, and reported anomaly that sound attenuates much more in case of propagating downwind on the contrary with the case on surfaces. Hearing scores of speech were lower in the same conditions than those measured upwind. The experimental results agree qualitatively with the numerical calculations by the sound ray tracing method.

Several studies on evacuation using a guide by sound or speech were presented. From the evaluations by subjects in these studies, Haas effect was helpful to let people to safety zone in a straight corridor or a corridor with a bend. In addition, interval of sound sources and optimal sound pressure levels of signal or speech were also investigated. On the other hand, it was pointed out that effects of the emergency guide by sound or speech were remarkably influenced by acoustical conditions of
the sound field. Namely, it is suggested that studies on sound propagation in evacuation spaces with many kinds of acoustical characteristics may also be essential.

From the above points of view, measurements of sound propagation and hearing tests for several speech stimuli were carried out in a reverberant curved tunnel. The purposes of the study are to experimentally investigate influences on propagation attenuation characteristics of sound waves by the reverberant condition and the curved shape of the tunnel. Acoustical factors which influence on confusions or hearing mistakes of speech are also examined. In addition, an objective prediction method on a degree of speech transmission by physical measurements, Rapid Speech Transmission Index (RASTI), is applied and possibility on application is discussed from correlations between hearing scores of speech stimuli and RASTI measured along the tunnel.

2. EXPERIMENTS

2.1 Experimental Tunnel

The experiments were carried out in a tunnel for underground mine fire tests located at the Coal Mine Safety Research Center, Kyushu of the National Institute for Resources and Environment. Figure 1 schematically shows a whole feature and a cross section of the tunnel. The tunnel is curved as a circular arc with a radius of around 200 m and the length is 400 m. The shape of cross section is almost circle of 2.65 m in diameter except for the flat floor, and the area is around 5.4 m². The inner wall is covered by smooth concrete. The part of 200 m length was used in all the experiments as indicated in Fig. 1.

Reverberation times were measured at several points and several times, and these averages and the standard deviations are shown in Fig. 2. The reverberation time is around 7.5 s at 100 Hz and rapidly decreases up to 500 Hz. On the other hand, the reverberation times are between 1.2 and 1.5 s at the other higher frequencies.

Background noise level measured by a precision sound level meter was around 34 dB. Temperature and relative humidity in the tunnel are 16 degrees centigrade and 90 percent, respectively.

2.2 Subjects

Four Japanese males participated in the hearing experiments used several speech stimuli. Ages of the subjects are between 22 and 48 years old. Before the hearing experiments, hearing threshold levels of each subject were measured by an audiometer (RION AA-96). Figure 3 shows average hearing threshold levels and standard deviations. From this result, we concluded that these subjects had normal hearing abilities without any auditory diseases, though the deviation at 8 kHz is larger than the other measured frequencies.
2.3 Speech Stimuli

Three kinds of speech stimuli were used for the hearing experiments by the subjects. The first speech is consisted of 100 Japanese nonsense syllables defined by the Acoustical Society of Japan for articulation test. These syllables were pronounced by a male professional announcer and recorded on the tape in an anechoic room. The announcer was instructed to pronounce each syllable at the same sound pressure level clearly. The second is a record from a radio broadcast of weather forecast report in Japanese. The broadcast was read by a female professional announcer. The third is also a record from the radio broadcast in the same channel concerning with stock market report which was read by a male professional announcer in Japanese. Long-term spectrums in one third octave bands for the weather forecast report and stock market report were derived from linear averaging for two minutes. There were no differences in the sound pressure levels and frequency components except for around 10 dB at 80 Hz. Table 1 indicates the other specifications of each speech stimulus used in the experiments.

2.4 Apparatus

To know propagation attenuation characteristics of sound with distance, pink noise from a noise generator (RION SF-05) was transmitted through a loud speaker with a power amplifier (YAMAHA MS202). The loud speaker was fixed on a tripod at the height of 1.2 m from the floor and set up in the center of the cross section. Propagated pink noise along the tunnel were measured at several points by an omnidirectional microphone (Brüel & Kjaer type 4133) with a wind screen and recorded by a data recorder (NAGRA IV-SJ). The microphone was also fixed on a tripod in the same way as the loud speaker.

Three kinds of speech stimuli were played back by another data recorder (NAGRA IV-SJ) through the same loud speaker and recorded in the same manners as the measurements of propagated pink noise. RASTI were measured by speech transmission meter (Brüel & Kjaer type 3361) along the tunnel. RASTI signal of a reference level was transmitted by the Brüel & Kjaer type 4225 and received by the Brüel & Kjaer type 4419. Measurement period of 32 s was selected to minimize the random errors. The transmitter and receiver were also set up in the same way as the pink noise propagation experiments.

2.5 Procedures

Hearing experiments were conducted from the furthest measuring point toward the sound source to prevent influences on the subject's learning of the presentation order in each speech stimulus. Answer sheets of each speech stimulus were given to the subjects before each measurement. The subjects were requested to hear and write all of them for the articulation syllables. They were also requested to hear and fill several blank spaces by key words such as name of places, weather, wind direction etc. for

### Table 1 Specifications of each speech stimulus.

<table>
<thead>
<tr>
<th></th>
<th>Nonsense syllables</th>
<th>Weather forecast report</th>
<th>Stock market report</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of words</td>
<td>100</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Speech rate (words/s)</td>
<td>2.0</td>
<td>5.2</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Number of words means the numbers which subjects were requested to hear and write them on the answer sheets. And each speech rate indicates a mean rate which was calculated from dividing number of the stimulus by duration of each speech material.
the weather forecast report and stock name, final price etc. for the stock market report. In the hearing experiments, the subjects were instructed to write down the speech stimuli only on the basis of them they heard.

Sound pressure level at one meter front of the loud speaker was kept at 100 dB during the pink noise propagation experiments. The sound pressure level of a reference signal at 1 kHz recorded in the test tape with the articulation syllables was also kept at 100 dB in one meter front of the loud speaker during the hearing experiments.

3. RESULTS

3.1 Propagation Attenuation of Pink Noise

Recorded pink noise were analyzed by a real time frequency analyzer (Bruel & Kjaer type 2133) in one third octave bands. The vertical axis in Fig. 4 indicates relative attenuations due to propagation distance of pink noise, and these attenuations were calculated from the sound pressure levels measured at one meter front of the sound source.

Maximum attenuations up to 315 Hz are around 25 dB or less, even when propagation distance increases up to 200 m. The attenuations in this frequency range may be influenced mainly by reverberant characteristics of the tunnel as indicated in Fig. 2. Especially, it is suggested that small attenuations at around 315 Hz are related to standing waves which are formed by the size of the cross section of the tunnel. On the other hand, relative attenuations rapidly increase with propagation distance in another frequency range. This tendency is remarkable toward the higher frequencies, and frequency components more than 2 kHz attenuate up to the same level as background noise at 150 and 200 m.

Figure 5 compares to attenuations with distance of several one third octave bands which are selected adequately from dividing into two groups with frequencies up to 315 Hz and others. While the gradients of attenuations of lower frequency group are around −6 dB per doubling distance at more than 50 m, those more than 2 kHz is −6 dB or more in the same region.

3.2 Hearing Tests by Subjects

Average hearing scores and standard deviations for each speech stimulus are plotted in Fig. 6. Hearing scores decrease with distance from the source in general. While the scores of the weather forecast report are the highest of all the measurements and drop remarkably at 200 m, tendencies of hearing scores of the other two speech stimuli are similar. However, the scores of the stock market report are slightly higher than those of the articula-
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Fig. 6 Correct hearing scores of three kinds of speech stimuli.

Confusion matrices of the articulation syllables were made at each measuring point. At the nearest point from the sound source, confusions between syllables with phonemes /m/ and /n/, /g/ and /r/ are slightly observed. While these confusions are also measured, confusions between syllables with phonemes /k/ and /p/ increase at 50 m. Number of confusions rapidly increase at the measuring points more than 100 m, and there are examples of confusions between syllables with phonemes /g, b/ and /r/, /g/ and /b, z/ as well as /k/ and /t, h, p/ at 100 m. We can remarkably find confusions between syllables with phonemes /m, n/ and /y/, /g, d, b, r/ and /z/ as well as /s, h, k/ and /t/ at 150 m. In addition, we observe some mistakes of combination between correct consonant parts and incorrect vowels. While the tendency of confusions up to 150 m is indicated more clearly, we can find many answers with blank space, mistakes from consonant to contracted sound and mistakes in part of vowel at the furthest measurement.

In the test of the stock market report, we can indicate examples of hearing mistakes from /DAISUE/ to /DAISUI/, /TOBISHIMA/ to /TOISHIMA/ or /TORISHIMA/ as well as /DAIKOU/ to /DAIKOU/ near the sound source. The mistakes from /SATA/ to /HATA/ are also observed at 100 m in addition to the previous mistakes. Though we can not find typical mistakes in case of the weather forecast report, mistakes of digits are smaller than those of words such as name of place and so on.

3.3 Distribution of RASTI along the Tunnel

Figure 7 shows distribution of RASTI measured along the tunnel. While small fluctuations of RASTI values are observed up to 25 m, the RASTI at measurements more than 50 m gradually decrease with propagation distance. Whole tendency of the distribution of RASTI indicates slight exponential decrement with distance. From qualitative interpretation of the values of RASTI, it is predicted that communication with speech will be carried out well up to 50 m. Communication is difficult at the measuring points more than 100 m under the conditions of the tunnel.

4. DISCUSSION

4.1 Influence of Reverberation and Curve of the Tunnel on Sound Propagation

To quantitatively understand sound propagation characteristics in the experimental tunnel by numerical analysis is very difficult because of the curved
shape with the irregular cross section, reverberant conditions and others. Then, from qualitative point of view, sound propagations within a plane of a circular arc as shown in Fig. 8 are considered. This is because the influences of curved shape of the tunnel on sound propagation may be most remarkable. For the qualitative consideration, the study carried out by A. Berry and G. Daigle is useful.

In their research, both of small scale experiments and theoretical calculations were carried out to investigate sound propagation outdoors within a shadow zone. Analogy is applied to the sound propagation between in the shadow zone on a flat surface and on a curved surface. Measurements on sound attenuations were made on the surfaces of a rigid boundary and the surface with a finite impedance. The experimental condition is similar to the case that the outer side of the tunnel wall is assumed to be complete absorptioan in our qualitative consideration.

From their experiments, sound on the rigid boundary in case that receivers are located in the shadow region attenuates mainly at higher frequencies. When the receivers come in sight from the source, sound attenuations in the frequency range decrease rapidly. As the receivers are in sight, we observe an interference dip in high frequency due to acoustical characteristics of the surface.

For the configurations of experimental tunnel, average absorption coefficients of octave band frequencies are calculated by the equation proposed by Bolt Beranek and Newman Inc. for underground mine roadways. As the method is applied to calculate absorption coefficients in the experimental tunnel, the coefficients increase up to 0.09 or less toward higher frequency and those at frequencies more than 1.6 kHz were almost constant.

Basically sound propagates with many times of reflection on the wall in a tunnel. Sound field may be influenced by direct and reflect waves in case that the receivers are in sight of the sound source. The reflect waves and partly creeping waves may control the field in case that the receivers get out of sight. In addition, the sound waves which are reflected only on the outer side of wall may also affect on sound attenuations in any cases of the receivers. From the combination of both characteristics of absorption and sound propagation, attenuations at higher frequencies may relatively increase at the further measuring points. More attenuations at higher frequencies may be observed in case that the receivers locate in the shadow region. This qualitative consideration agrees well with the facts that the receivers are in sight of the sound source up to 50 m and the higher frequency components rapidly attenuate at the measurements behind 50 m in our experiments.

Much attenuations, especially in higher frequency components, at the further measuring points may be partly caused by air absorption from atmospheric conditions measured in the experimental tunnel.

4.2 Confusions of Speech Stimuli
4.2.1 Articulation syllables

Haruta reported experimental results on articulation test used nonsense syllables by some subjects under several kinds of conditions such as reverberation time and signal-to-noise ratio. The tendencies of observed confusions were presented with regard to some acoustical conditions. Here, we discuss factors which have an effect on the occurrence of confusions by comparing with the results of Haruta and our experiments. Furthermore, transmission degrees of speech stimuli are estimated qualitatively from the experimental results on relative attenuations of the sound.

As considered sound propagation characteristics described in previous section, it may be reasonable that considerations are divided into two groups by the measurements up to 50 m and others. We observed confusions between syllables with phonemes /g/ and /r/, /m/ and /n/ as well as /k/ and /p/ up to 50 m. When we refer to a confusion matrix measured under a similar reverberant condition to our current study, it is found that confusions
between syllables with phonemes /g/ and /r/, /m/ and /n/ easily occur. However, confusions between syllables with phonemes /k/ and /p/ are rarely observed. While the transmission degree of speech signals at 25 m is kept well, the confusions may be occurred by both influences of reverberation and slight deterioration of the speech signals due to propagation up to 50 m. The estimation is supported by both the results measured under lower signal-to-noise ratios at 2 and 4 kHz in a octave band described in the Ref. 12 and more attenuations in higher frequencies shown in Fig. 4. Confusions between syllables with phonemes /g/ and /b, z/, /b/ and /r/ as well as /k/ and /h/ can be pointed out as the differences between the measurement up to 50 m and at 100 m. These confusions may be occurred by influences from not only reverberation but also further degradation of the speech due to long propagation. Increase of confusions between syllables with phonemes /m, n/ and /y/, /g, d, b, r/ and /z/ as well as /k, s, h/ and /t/ suggests the situation of much more decrease of the transmission degree of speech at 150 m. In addition, mistakes in part of vowel are observed in several cases at this measurement. From rapid increase of no answers by subjects and mistakes between consonants and contracted sounds as well as mistakes in part of vowel, it is considered that speech signals degrade below some limitations which subjects can decide what speech transmitted.

After these considerations, factors related to reverberation influenced on the occurrences of confusions at the measurements near the sound source where decline of speech signals may be small. On the other hand, it is considered that influence of deterioration of speech on hearing mistakes becomes relatively larger than that of reverberation at the further measuring points.

4.2.2 Key words in the radio broadcast

Analysis of hearing mistakes of key words in the radio broadcast is effective to understand more realistic situation in communication. It is pointed out that the hearing scores of key words in a sentence are generally higher than those of nonsense syllables by the effect of familiarity to the speech information.13) Speech rate, sex of talker, and so on may also give some effects on the differences in the scores.

As indicated in Table 1, speech rate of the stock market report is the fastest in all the speech materials. Relationships between speech rate and reverberation time are reported by Watanabe and Inomoto.14) In their study, it is pointed out that the articulation of speech except for vowels may be easily interfered by faster speech rate under a reverberant condition. Mistakes observed such as /SUE/ to /SEI/, /TOBI/ to /TOI/ etc. are basically occurred in middle part of each key word, and it is predicted that prior syllable prevent to hear next syllables correctly by reverberation. Consequently, it may mean decline of the articulation in the posterior syllables.

Miller et al.13) considered that the digits can be heard easier than the other speech stimuli because of the phonemic limitation of the alternatives. The digits selected in the sentence of the weather forecast report and the stock market report as key words may be interpreted much easier, though syllables composed each digit were more than their case.

4.3 Correlations between RASTI and Hearing Scores

Figure 9 shows relationship between RASTI and the hearing scores of the articulation syllables. Hearing scores indicated in the vertical axis are converted to logarithm in the same manner as calculating an articulation index.15) Relationship between RASTI and hearing scores shows high positive correlation. Similar relationship between

![Fig. 9 Correlation between RASTI and hearing scores of the articulation syllables.](image-url)
syllable articulation and RASTI is also reported by Fujimiya et al.16) from the experiments in the tunnel for the roadway. It is generally pointed out that hearing condition of the articulation score less than 70 percent is poor in Japanese. From the figure, range of hearing score less than 70 percent corresponds to values less than 0.45 which indicate “Poor” or “Bad” in the qualitative interpretation of RASTI.8)

On the other hand, relationships between hearing scores of the articulation syllables and those of the other speech stimuli are indicated in Fig. 10. A score of the articulation syllables corresponds to a value of hearing score of each speech stimulus. Combining the results of Figs. 8 and 9, hearing scores of the key words in the radio broadcast may be roughly predicted by RASTI through the results of articulation tests.

It should be taken notice that relationships between speech articulation in Japanese and objective prediction methods of speech transmission such as STI and RASTI have some problems in difference of values between measurement setups and applicable ranges in terms of measuring spaces. Though other research works may remain to apply objective physical values to prediction of a degree of speech transmission,17,18) RASTI may be one of effective methods to estimate the hearing situations of some speech in the tunnel spaces.

5. CONCLUSIONS

Influences of reverberant condition on sound propagation characteristics typically appeared in small attenuations at frequencies less than 315 Hz which are dependent on the size of cross section of an experimental tunnel. It is assumed that rapid attenuations at the higher frequencies are caused by the curved shape of the tunnel because of the fact that the receivers are not in sight from the sound source and qualitative consideration using the experimental results obtained from sound propagation on the curved surface with a rigid boundary.

While hearing scores of speech stimuli by subjects decrease with distance from the sound source, differences in scores among each speech are observed as compared at the same measuring points. From analysis of confusion matrices of articulation syllables, it is suggested that confusions appeared near the source are mainly affected by the reverberant condition and those at further measuring points are influenced by not only reverberation but also degradation of speech signals. Such tendency is remarkably observed with increase of propagation distance.

Some problems concerning fluctuations of values in each measuring setup and its applicable range of measurement space etc. in terms of the relationships between speech articulation in Japanese and some prediction methods of speech transmission by physical measurements are pointed out. High positive correlation is observed between measured RASTI and hearing scores of articulation syllables in the experiments. In addition, hearing scores of the other speech stimuli also indicate simple relationships with those of the articulation syllables. From the experimental results, it is suggested that prediction of the degree of speech transmission may be possible by some physical measuring methods such as RASTI in a tunnel.

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