Validation of calculation method of tunnel portal noise in ASJ RTN-Model 2018 by a field experiment

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(Received 21 August 2019, Accepted for publication 19 September 2019)

Abstract: The road traffic noise prediction model “ASJ RTN-Model 2013,” which has been developed by the Research Committee in the Acoustical Society of Japan (ASJ), includes an energy-based calculation method of tunnel portal noise. In the method, tunnel portal noise is simply modeled as the sum of direct sound from vehicle sound sources and diffused sound radiated from the tunnel portal. To calculate the diffused sound, point sources are distributed on the portal, and the point sources are assumed to be omnidirectional. ASJ RTN-Model 2018 follows the basic concept of the calculation method, and the diffused sound component has been revised so the point sources have adequate directivities. In this study, such a calculation method was validated by a field experiment using a “split bamboo type” tunnel and a test vehicle as a sound source. As a result, it was found that calculation results considerably varied depending on the treatment of the diffused sound component directivity, the positions of the point sources for the diffused sound component, and the diffraction over an oblique tunnel edge, and that the newly introduced calculation setting of the directional sources is the most accurate. The new calculation setting was found to have the advantages of high accuracy and simplicity of calculation.

Keywords: ASJ RTN-Model, Tunnel portal noise, Calculation model of sound propagation

PACS number: 43.50.Lj [doi:10.1250/ast.41.614]

1. INTRODUCTION

Vehicle noise generated in a tunnel propagates with multiple reflections on the inner surface of the tunnel and the noise is radiated to the outside space from the tunnel portal. Whereas the noise propagation in a tunnel is complicated, in ASJ RTN-Model 2013 [1], which is an energy-based practical calculation model of road traffic noise proposed by the Acoustical Society of Japan, the tunnel portal noise is simply modeled as a sum of two sound contributions. One is the direct sound from a vehicle source and the other is the diffused sound radiated from the tunnel portal as a plane source to the prediction point. In that method, the sound source of the diffused sound component is assumed to be a plane source and, practically, the contribution is calculated as an aggregation of sound propagation from omnidirectional point sources evenly distributed on the portal plane. In actuality, the diffused sound is expected to have certain directivity and this directivity becomes sharper as a vehicle source enters into a deeper position in the tunnel. To investigate the directivity, experimental studies using scale models [2,3] have been conducted, and Sakamoto proposed a practical calculation method considering the directivity characteristics of noise radiated from a tunnel portal [3]. The method was reflected in the revision of the road traffic noise prediction method, ASJ RTN-Model 2018 [4]. In this report, the validity of the proposed calculation method of noise from a tunnel portal, including the effect of directivity, was confirmed by comparison with the results of a field experiment.

2. TUNNEL UNDER INVESTIGATION AND EXPERIMENT

Figures 1(a) and 1(b) show the road tunnel under investigation with and without a noise barrier, respectively.
The cross-sectional shape of the tunnel is the “split bamboo type,” in which a semicircular tunnel is obliquely cut, as is shown in the figures. The width of the road tunnel is 12.8 m and the height of the tunnel is 6.4 m. The road surface is porous asphalt concrete, the inner surface of the tunnel is rigid concrete, and its sidewall is finished with tiles. In the experiment, as a sound source, a 10 ton truck moved along a driving lane at 60 km/h. A receiving point, \( P_S \), was set to determine the A-weighted sound power level of the test vehicle. The sound power level of the running test vehicle was determined from the maximum A-weighted sound pressure level observed at \( P_S \). To determine the radiated tunnel portal noise, 13 receiving points, \( P_1 \) to \( P_{13} \), were distributed around the tunnel portal. Among the 13 receiving points, \( P_2 \), \( P_3 \), and \( P_4 \) were at a height of 4.0 m and the other 10 points were at a height of 1.2 m. At the receiving points, unit patterns of the A-weighted sound pressure level of the running vehicle noise were measured. The obtained unit patterns were arranged to be a level relative to the A-weighted sound power level of the running test vehicle determined in advance, and the results were compared with calculation results. The experiment was performed for two cases, with and without a noise barrier 3 m high along the road outside the tunnel. In the case with the noise barrier, receiving point \( P_1 \) was positioned in front of the barrier, \( P_2 \), \( P_3 \), and \( P_4 \) were above the barrier, and \( P_5 \) to \( P_{13} \) were behind the barrier.

### 3. CALCULATION

During the revision of ASJ RTN-Model from Model 2013 to Model 2018, noise radiation directivity was taken into consideration for the diffused sound component of the tunnel portal noise, as described in the introduction. The outline of the calculation method of tunnel portal noise in
ASJ RTN-Model 2013 and the revised model in ASJ RTN-Model 2018 are described in Appendices A and B, respectively. In this investigation, the results of the calculation methods of tunnel portal noise described in ASJ RTN-Model 2013 and in ASJ RTN-Model 2018 were compared with those of the field experiment, and the validity of considering the noise radiation directivity was examined. In previous studies [2,3,5,6] on tunnel portal noise, the tunnel was assumed to have a vertical portal. The ASJ RTN-Model, which has been discussed and developed on the basis of such studies, also assumes a tunnel having a portal with a vertical section. However, the tunnel under investigation in this study has an obliquely cut cross section; therefore, several variations occur when considering the setting of a hypothetical plane source for the diffused sound component and diffraction over the tunnel portal edge. In this study, the five calculation cases illustrated in Table 1 were applied and the results for these cases were compared with each other. Outlines of the calculation methods are listed below.

| Calculation case | Direct sound | Diffused sound | Calculation method of diffused sound |
|------------------|--------------|----------------|-------------------------------------|
|                  |              | Source plane   | vertical                            |
|                  |              | Directivity    | omnidirectional                     |
|                  |              | Edge diffraction| ignored                             |
| 1                |              | Source plane   | vertical                            |
|                  |              | Directivity    | directional                         |
|                  |              | Edge diffraction| considered                         |
| 2                |              | Source plane   | vertical                            |
|                  |              | Directivity    | directional                         |
|                  |              | Edge diffraction| considered                         |
| 3                |              | Source plane   | oblique                             |
|                  |              | Directivity    | directional                         |
|                  |              | Edge diffraction| not necessary                      |

(1) Calculation case 1
The source plane for the diffused sound component is assumed to be a vertical plane positioned at the back of the tunnel portal (at a position on the topedge of the opening; see Table 1, Calculation case 1). Hypothetical point sources, the directivities of which are omnidirectional, are distributed on the vertical source plane, and diffraction over the portal edge is ignored for simplicity of the calculation.

(2) Calculation case 2
The setting of the hypothetical plane source and the directivity of the hypothetical point sources for the diffused sound component are the same as in Calculation case 1. In Calculation case 2, diffraction over the portal edge near the side of the receiving points is considered and reflection from the inner surface of the tunnel portal part on the side opposite to the receiving points is ignored.

(3) Calculation case 3
The setting of the hypothetical plane source and the
consideration of diffraction over the portal edge are the same as in Calculation case 1. In Calculation case 3, hypothetical point sources for the diffused sound component have directivity given by Eqs. (B·1) and (B·2) in Appendix B.

(4) Calculation case 4

The setting of the hypothetical plane source and the consideration of diffraction over the portal edge are the same as in Calculation case 2. In Calculation case 4, hypothetical point sources for the diffused sound component have directivity given by Eqs. (B·1) and (B·2) in Appendix B. For the diffused sound component in Calculation case 4, the consideration of edge diffraction is not necessary.

For all calculation cases, the direct sound component is calculated considering diffraction over the tunnel portal edge in propagation paths from a hypothetical source point for the direct sound component to receiving points.

4. COMPARISON BETWEEN EXPERIMENT AND CALCULATION

Figure 2 shows the experimental results and the results for Calculation cases 1 to 5 at receiving points \( P_1, P_5, P_{11}, P_{12}, \) and \( P_{13} \). At receiving points \( P_1 \) and \( P_5 \), which are positioned near the road, almost the same calculation results for all five calculation cases are obtained. At \( P_{12} \), some variation of the sound pressure level is seen among the calculation cases for \( x < 0 \), where the source vehicle existed inside the tunnel. At receiving points \( P_{11} \) and \( P_{13} \), which are positioned far from the road and whose directivity angle \( \theta \) is larger than that for \( P_{12} \), considerably large variations are seen among the calculation cases. For \( x < 0 \) at \( P_{11} \) and \( P_{13} \), calculated sound pressure levels for Calculation cases 1 and 3 were higher than the experimental results, and those for Calculation cases 2 and 4 were lower than the experimental results. The sound pressure level calculated in Calculation case 5 was an intermediate value between them and was the closest to the experimental result.

Figure 3 shows the experimental and calculation results when a noise barrier 3 m high were added at the roadside, as shown in Fig. 1(b). Note that only receiving point \( P_1 \) was positioned in front of the barrier and other receiving points \( P_5, P_{11}, P_{12}, \) and \( P_{13} \) were behind the barrier. As in Fig. 2, the calculation results were almost the same for receiving points \( P_1 \) and \( P_5 \). At \( P_{12} \), moderate variation of around 2 dB was seen among the calculation cases, and the variation became larger at receiving points \( P_{11} \) and \( P_{13} \). In this case, Calculation cases 2, 3, and 5 gave results close to the experimental result.

To examine \( L_{Aeq} \)-based prediction accuracy, the sound pressure exposure level, \( L_{PE} \), was compared between the calculations and experiment. In Figs. 2 and 3, differences in the calculated sound pressure levels among the calculation cases are seen when \( x < 0 \), where the source vehicle is inside the tunnel. Therefore, firstly, sound pressure exposure levels whose integration interval is limited to \( x < 0 \) were compared. Results of the comparison are shown in Figs. 4(a.1) and 4(a.2) for a case without a noise barrier,
Fig. 3 Calculation and experimental results for cases with barrier.

Correspondence for each receiving point.

Root mean squared error and average level difference.

Fig. 4 Correspondence of sound pressure exposure level between calculation and experiment. The integration interval is limited to the range in which the sound source is inside the tunnel.
and in Figs. 4(b.1) and 4(b.2) for a case with a noise barrier. At the receiving points where $L_{EA}$ is lower, the variation in the calculation cases is larger. At $P_{13}$, for the case without a barrier, Calculation cases 1 and 4 give the maximum and minimum $L_{EA}$, respectively, and the difference between them is over 15 dB. On the other hand, at $P_2$, the difference between the maximum and minimum values is within 1 dB. The same tendency is also seen in the case with a noise barrier. Figures 4(a.2) and 4(b.2) show the average differences of $L_{EA}$ ($L_{EA,\text{Calc.}} - L_{EA,\text{Meas.}}$, where $L_{EA,\text{Calc.}}$ and $L_{EA,\text{Meas.}}$ are the calculated and measured $L_{EA}$, respectively), $\Delta L_{EA}$, and the root mean square error, RMSE. From Fig. 4(a.2), which shows the results for a more basic case, we see that Calculation cases 1 and 3 overestimate and Calculation cases 2 and 4 underestimate $L_{EA}$; Calculation case 5 is the most accurate. In Fig. 4(b.2), $\Delta L_{EA}$ of case 1 is over 2 dB and those of cases 2 to 5 are within 1 dB. Figures 5(a.1), 5(a.2), 5(b.1), and 5(b.2) show correspondences between calculated and experimental $L_{EA}$ with integration intervals both inside and outside the tunnel. Compared with the results in Fig. 4, where integration intervals are limited to $x < 0$, variations among the calculation cases are considerably small. This is because the contribution of sound pressure exposure from the source vehicle outside the tunnel is dominant, and the sound pressure exposure when the source vehicle was outside the tunnel did not depend on the calculation case.

5. CONCLUSIONS

In this report, the validity of the revised calculation method of tunnel portal noise introduced in ASJ RTN-Model 2018, in which the directivity characteristics of noise radiated from tunnel portal are taken into consideration, was confirmed by comparison with the results of a field experiment. In the field experiment, a “split-bamboo-type” tunnel, in which a semicircular tunnel is obliquely cut, was used and sound propagation from the tunnel portal to receiving points distributed around the portal was measured using a test vehicle as a noise source. ASJ RTN-Models assume a tunnel having a portal with a vertical section. Therefore, in order to apply the model to the split-bamboo-type tunnel portal, point sources for the diffused sound component were set on a hypothetical vertical surface and the effects of directivity of the sources...
and of considering the diffraction over the oblique tunnel edge were examined. In addition, a new calculation setting in which directive point sources for the diffused sound component were distributed along the obliquely cut surface was also examined. Consequently, five calculation cases were set and the results by these five calculation cases were compared with the experimental result.

In the investigation, it was found that calculation results varied considerably as a result of differences in the treatment of the diffused sound component at receiving points far from the road, and that the newly introduced treatment of the diffused sound component at receiving points far from the road, and that the newly introduced calculation setting, diffraction over the tunnel edge is unnecessary in principle. Therefore the new calculation setting has the advantages of high accuracy and simplicity of calculation.

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APPENDIX A: CALCULATION METHOD FOR TUNNEL PORTAL NOISE IN ASJ RTN-MODEL 2013

In ASJ RTN-Model 2013 [1], tunnel portal noise is modeled as a sum of two sound contributions: direct sound from a point source positioned at a hypothetical source point and diffused sound radiated from the whole plane of the tunnel portal. The diffused sound is assumed to be omnidirectional. The specified calculation method is described below.

A.1. Propagation Model of Tunnel Portal Noise

The A-weighted sound pressure level, $L_A$ [dB], generated by a running vehicle in a tunnel and observed at a prediction point around the tunnel portal, is calculated as,

$$L_A = 10 \log_{10}(10^{L_{A,TD}/10} + 10^{L_{A,TR}/10}),$$  \hspace{1cm} (A-1)

where, $L_{A,TD}$ [dB] is the A-weighted sound pressure level of the contribution of direct sound. The direct sound is assumed to propagate from a hypothetical sound source point whose position is described in the next clause. $L_{A,TR}$ [dB] is that of the contribution of reflected and diffused sound.

$L_{A,TD}$ is calculated as

$$L_{A,TD} = L_{WA} - 8 - 20 \log_{10} r + \Delta L_{dif} + \Delta L_{grnd}.$$  \hspace{1cm} (A-2)

here, $L_{WA}$ [dB] is the A-weighted sound power level of the running vehicle source, $r$ [m] is the direct distance from the hypothetical sound source point to the receiving point, $\Delta L_{dif}$ [dB] and $\Delta L_{grnd}$ are corrections for sound diffraction over the edge of the tunnel portal and/or barrier and the ground effect between the tunnel portal and the receiving point, respectively.

To calculate $L_{A,TR}$, the plane source is set at the portal plane and divided into ten or more segments. Point sources were assumed at the centers of gravity of the respective segments, as shown in Fig. A-1. The A-weighted sound pressure level of the contribution of diffused sound, $L_{A,TR,i}$, is calculated as the sum of contributions, $L_{A,TR,i}$, from the respective point sources, as shown in Eq. (A-3). $L_{A,TR,i}$ is calculated by Eq. (A-4), considering distance attenuation from the hypothetical sound source point to the receiving point and correction terms of sound diffraction and the ground effect.

$$L_{A,TR} = 10 \log_{10} \left( \sum_{i=1}^{N} 10^{L_{A,TR,i}/10} \right),$$  \hspace{1cm} (A-3)

$$L_{A,TR,i} = L_{W,A,R} - 8 - 20 \log_{10} r_i + \Delta L_{dif,i} + \Delta L_{grnd,i},$$  \hspace{1cm} (A-4)

$$L_{W,A,R} = L_{W,A,R} - 10 \log_{10} N,$$  \hspace{1cm} (A-5)

here, $r_i$ [m] is the direct distance from a point source set on the $i$th segment to the prediction point. $\Delta L_{dif,i}$ [dB] and $\Delta L_{grnd,i}$ are corrections for sound diffraction and the ground effect, respectively. $L_{W,A,R}$ is the A-weighted sound power level of a hypothetical point source set on each segment, $L_{W,A,R}$ is the total A-weighted sound power level.
of the diffused sound component radiating from the tunnel portal, and \( N \) is the number of segments into which the plane source is divided.

### A.2. Position and Power Level of Hypothetical Sound Sources

#### (1) Direct sound component

A hypothetical sound source for the direct sound component is shown in Fig. A-1. The power level of the hypothetical source is the same as that of the real vehicle source shown in Eq. (A-2), and the distance from the tunnel portal to the hypothetical source, \( x' \) [m], is calculated using a parameter \( a \) for sound absorption inside the tunnel and the distance from the tunnel portal to the real vehicle source as

\[
x' = ax. \tag{A-6}
\]

The value of \( a \) is determined from Table A-1 in ASJ RTN-Model 2013. When the inner surface of the tunnel consists of multiple portions with different sound absorbing properties, \( a \) is calculated as a weighted average as follows.

\[
a = \frac{\sum (a_i x_i)}{\sum x_i}, \tag{A-7}
\]

here, \( a_i \) is the parameter for the \( i \)th portion and \( x_i \) [m] is the length of portion \( i \).

#### (2) Diffused sound component

The A-weighted sound power level of the plane source set at the tunnel portal, \( L_{WA,R} \), is calculated by subtracting the A-weighted sound power of direct sound emitted from the tunnel portal, \( P_{AD} \), from the total A-weighted sound power emitted from the tunnel portal, \( P_{AT} \).

\[
L_{WA,R} = 10 \log_{10} \left( \frac{P_{AT} - P_{AD}}{10^{-12}} \right) \tag{A-8}
\]

When the cross section of the tunnel is a semicircle with radius \( h \) [m], \( P_{AD} \) and \( P_{AT} \) are calculated as

\[
P_{AD} = \frac{P_{A}}{2} \left\{ 1 - \frac{ax}{\sqrt{h^2 + (ax)^2}} \right\}, \tag{A-9}
\]

\[
P_{AT} = \frac{P_{A}}{2} \left\{ 1 - \sqrt{\frac{\pi}{4}} \right\}, \tag{A-10}
\]

\[
\text{here, } P_{A} \text{ [W]} \text{ is the A-weighted sound power of the real vehicle source.}
\]

### APPENDIX B: REVISION OF CALCULATION MODEL OF TUNNEL PORTAL NOISE

In ASJ RTN-Model 2018 [4], which is the latest version of ASJ RTN-Model, sound propagation of the diffused sound component is modified. Equation (A-4) is changed to the following Eq. (B-1) by taking into consideration the directivity of sound radiation from the tunnel portal.

\[
L_{A,TR,i} = L_{WA,R} - 8 - 20 \log_{10} r_i \quad + \Delta L_{\text{dif},i} + \Delta L_{\text{grnd},i} + n \cdot 10 \log_{10} \cos \theta_i, \tag{B-1}
\]

here, \( r_i \) [m], \( \Delta L_{\text{dif}} \) [dB], and \( \Delta L_{\text{grnd}} \) are the same as described in Appendix A. \( \theta_i \) is the angle formed by the road direction and the vector connecting the point source to the prediction point, as shown in Fig. B-1. \( n \) is a parameter determining the directivity of the diffused sound and its value is dependent on the position of the vehicle source, as shown in the following equation.

\[
n = n_s (1 - e^{-n_b x}), \tag{B-2}
\]

here, \( n_s \) and \( n_b \) are constants for the directivity and their values are given in Table B-1. These values were determined using an experimental result obtained with a scale model [3].