Road traffic noise prediction model “ASJ RTN-Model 2018”:
Report of the Research Committee on Road Traffic Noise

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PREFACE

Background

In 1974, the Acoustical Society of Japan first organized a research committee to develop a road traffic noise prediction model. This committee has been continuously undertaking research activities since then with the aim of developing an adequate prediction method for road traffic noise on the basis of state-of-the-art knowledge in response to the demands of trends [1]. As a result of its activities, a prediction model called ASJ Model 1975 was published in 1975, which provided a method of calculating the 50 percentile A-weighted sound pressure level ($L_{A50}$) [2,3]. This model was widely accepted and applied to assessments of noise around roads for many years. After that, research activities were continued to improve the accuracy of prediction and expand the scope of its application [4–6]. In parallel with these activities, from 1988, the committee worked on the development of a new prediction method based on the equivalent continuous A-weighted sound pressure level ($L_{Aeq}$). The outcomes of the research were summarized, and the calculation model (ASJ Model 1993) was published in 1994 [7]. This model proposed general procedures for the calculation of $L_{Aeq}$ at roads with a uniform cross-sectional structure.

Afterwards, there was a substantial change in the environmental administration concerning noise. In June 1997, the “Environmental Impact Assessment Law” was promulgated, whose enactment was based on the “Environmental Basic Law” (the law revising the “Basic Law for Environmental Pollution Control,” which was issued in November 1993), and it was enforced in June 1999, two years after its promulgation. In addition, the “Environmental Quality Standards for Noise” (enacted in 1971) was revised in September 1998 and enforced in April of the following year. In the standards, $L_{Aeq}$ was adopted in place of $L_{A50}$ as the noise index for road traffic assessment. At the same time, the standard values for general residential areas and areas facing roads were renewed.

Corresponding to these changes, the above-mentioned ASJ Model 1993 was later developed further on the basis of a surveillance study, and ASJ Model 1998 was reported in April 1999 as a new model based on $L_{Aeq}$ assessment [8]. The model had an expanded scope of application to cover almost all types of roads and structures, including general roads and special road sections, such as interchanges, road tunnels, semi-underground roads, and overhead/double-deck viaducts. In addition, the structure-borne noise of viaduct roads was newly included in this model. Shortly after its report, further research activity was started with the aims of expanding its field of application, introducing wave-based computational methods for sound propagation, and improving the prediction accuracy. As a result, ASJ RTN-Model 2003 [9], ASJ RTN-Model 2008 [10], and ASJ RTN-Model 2013 [11] were completed and published in April 2004, April 2009, and April 2014, respectively.

ASJ Model 1998 and newer models were comprehensively adopted in the “Technical Method for Environmental Impact Assessment of Roads” and have been widely used for road traffic noise prediction (the assessment of future environments) in Japan [12,13]. The ASJ RTN-Model is also used to design environmental preservation measures (noise abatement measures) and to estimate the current state of noise during environmental monitoring (regular observation). Thus, on the basis of the fact that the prediction model is used for not only the prediction of future environments but also the estimations of present environments and the design of noise mitigation measures, the research committee has been working on finding solutions to the problems remaining unsolved in ASJ RTN-Model 2013 [14]. After five years of research and investigation, the new model, “ASJ RTN-Model 2018,” has been completed and is published in this Journal.
Table 1.1 Organization and members of the research committee on road traffic noise.

| Name                  | Affiliation                                      |
|-----------------------|--------------------------------------------------|
| **Chair** Shinichi Sakamoto | Institute of Industrial Science, The University of Tokyo |
| **Secretaries** Ken Anai | Faculty of Engineering, Fukuoka University         |
|                       Yasuaki Okada                  | Faculty of Science and Technology, Meijo University |
|                       Akinori Fukushima            | NEWS Environmental Design Inc.                   |
|                       Toshio Matsumoto              | Kobayasi Institute of Physical Research           |
|                       Youseke Yasuda                | Faculty of Engineering, Kanagawa University       |
|                       Katsuya Yamauchi             | Faculty of Design, Kyushu University              |
|                       Takatoshi Yokota              | Kobayasi Institute of Physical Research           |
| **Members** Ryuji Inoue*1 | National Institute for Land and Infrastructure Management |
|                      Akiryoushi Ito                  | Japan Automobile Research Institute               |
|                       Hiroyuki Imaizumi            | National Institute of Advanced Industrial Science and Technology |
|                       Terutoshi Tajika             | Environmental Technical Laboratory, Ltd.         |
|                       Kunio Nakasaki*1  | Nippon Expressway Research Institute Co., Ltd.   |
|                       Osamu Funahashi*2 | Nippon Expressway Research Institute Co., Ltd.   |
|                       Toshiaki Mabuchi*2 | National Institute for Land and Infrastructure Management |
| **Technical adviser** Hideo Ohno | Hino Motors, Ltd.                              |
| **Advisers** Teuro Iwase | Professor Emeritus at Niigata University          |
|                      Yasuo Oshino                  | Former Senior Chief at Japan Automobile Research Institute |
|                      Kazutoshi Fujimoto            | Professor Emeritus at Kyushu University           |
|                      Kohei Yamamoto               | Kobayasi Institute of Physical Research          |

*1Until fiscal 2017. *2From fiscal 2018

Table 1.1 shows the organization and the members of the committee. In this report, the results of research and investigation are summarized.

Summary of the revisions in the current version

The contents of ASJ RTN-Model 2018 are shown in Table 1.2. The current model is based on ASJ RTN-Model 2013 to which the following revisions were made.

(1) Sound source characteristics

- The classification of road vehicles from an acoustical viewpoint was reviewed and changed from the conventional four-category classification to a three-category classification.
- The values of the A-weighted sound power level of road vehicles were updated, and their calculation methods were given for respective types of road pavement.
- In the types of road pavement, a gap-graded asphalt mixture (referred to as “KOUKINOU II”) was newly included.
- The representative sound power spectra of vehicle noise, which are shown in Appendix A1, are revised using the latest data.
- The latest knowledge on the A-weighted sound power levels of hybrid vehicles (HVs) and electric vehicles (EVs) is shown in Appendix A2.
- Sound power levels on dense asphalt in an accelerating traffic flow section are shown in Appendix A3. Sound power levels on general roads paved with porous asphalt are shown in Appendix A4.

(2) Calculation of sound propagation

- The corrections due to sound attenuation by diffraction and reflection were reviewed, and part of calculation formulae and values of coefficients were updated.
- For correction for diffraction, sound diffraction over a knife wedge (assuming a barrier) and that over a right-angled wedge (assuming an embankment or a building) were discriminated, and formulae for respective fundamental correction terms were given.
- According to the update of sound power spectra of vehicles and the addition of KOUKINOU II to road pavement types, values of the coefficients for calculation formulae for correction terms for diffraction were updated.
- The calculation methods for a thick barrier and a barrier with an overhung were changed.
The calculation method for the ground effect over a porous asphalt pavement was newly added.
For the scattered reflection method included in the calculation method of sound reflection, the method of setting the calculation conditions was described.
On the basis of the numerical investigation of the meteorological effect on the sound propagation of road traffic noise, the upper limit of attenuation effect due to diffraction and the ground effect was determined.
The calculation method of frequency-dependent propagation was updated to the generalized energy-based method. The method is shown in Appendix A5.
For a calculation method based on the wave-based numerical analyses, the contents are updated. The details are shown in Appendix A6.

(3) Special road sections
The calculation method of noise around a road tunnel was changed to a method taking into consideration directivity characteristics of sound radiation from the tunnel mouth.
For noise around flat/overhead roads and double-deck viaducts, the calculation method of scattered reflection was simplified.
The calculation method of noise prediction at signalized intersections was updated. The details are shown in Appendix A7.

(4) Noise behind a single building and in built-up areas
For road traffic noise in built-up areas, the calculation method based on a point source model given in the previous model was simplified from an engineering viewpoint and the content was updated.
The detailed calculation method based on a point source model was simplified from an engineering viewpoint and the content was updated.

Table 1.2 Contents of ASJ RTN-Model 2018.

| Chapter | Section |
|---------|---------|
| 1. Outline of the prediction method (general procedure) | 1.1 Scope<br>1.2 Terms and definitions<br>1.3 General calculation procedure and basic equations |
| 2. Sound source characteristics | 2.1 Classification of road vehicles<br>2.2 Sound power levels of road vehicles<br>2.3 Correction of sound power level for various factors |
| 3. Method of calculating sound propagation | 3.1 Basic equations<br>3.2 Correction for diffraction $\Delta L_{\text{dif}}$<br>3.3 Correction for ground effect $\Delta L_{\text{grnd}}$<br>3.4 Correction for atmospheric absorption $\Delta L_{\text{air}}$<br>3.5 Calculation of sound reflection<br>3.6 Meteorological effect |
| 4. Noise at special road sections | 4.1 Interchanges<br>4.2 Junctions<br>4.3 Signalized intersections<br>4.4 Road tunnels<br>4.5 Depressed and semi-underground roads<br>4.6 Flat roads with an overhead viaduct, double-deck viaducts |
| 5. Structure-borne noise of viaducts | 5.1 Scope<br>5.2 Noise calculation procedure |
| 6. Noise behind single building and in built-up areas | 6.1 Noise behind single building<br>6.2 Noise behind building complex |
| Appendices | Appendix A1 Sound power spectra of vehicle noise<br>Appendix A2 Sound power levels of hybrid and electric vehicles<br>Appendix A3 Sound power levels of road vehicles on dense asphalt pavement in acceleration<br>Appendix A4 Sound power levels of road vehicles on porous asphalt general roads<br>Appendix A5 Calculation of frequency-dependent propagation<br>Appendix A6 Wave-based numerical analysis<br>Appendix A7 Signalized intersections<br>Appendix A8 Advanced calculation method for noise behind building complex |
| References | Reference R1 Noise reduction effect of double-layer porous asphalt pavement<br>Reference R2 Sound propagation around barriers with overhangs and edge-modified barriers<br>Reference R3 Expressions for $L_{\text{Aeq}}$ under simple road conditions<br>Reference R4 Study of prediction accuracy |
source model is described in Appendix A8.

(5) Others
- Regarding the prediction accuracy of ASJ RTN-Model 2018, the examinations based on latest knowledge are shown in Reference R4.

ACKNOWLEDGEMENTS

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MAIN BODY

1. OUTLINE OF THE PREDICTION METHOD (GENERAL PROCEDURE)

In this chapter, the scope of ASJ RTN-Model 2018, the definition or interpretation of technical terms used in this model, the concept of the calculation method, and the general procedure of calculation are described.

1.1. Scope

The conditions applicable to ASJ RTN-Model 2018 are as follows. For conditions related to the structure-borne noise of viaducts, refer to Chapter 5.

(1) Types of road
- General roads (flat, bank, cut, and viaduct) and special road sections (interchanges, junctions, signalized intersections, road tunnels, depressed/semi-underground roads, flat roads with overhead viaducts, and double-deck viaducts).

(2) Traffic volume
- No limitation.

(3) Running speed of vehicles
- 40 to 140 km/h for sections of a steady traffic flow on expressways and general roads, 0 to 60 km/h for sections of non-steady traffic flow on general roads, 0 to 80 km/h for acceleration/deceleration sections on expressways such as interchanges, 0 to 60 km/h for acceleration/deceleration sections on general roads, such as in the vicinity of signalized intersections.

(4) Prediction range
- Up to a horizontal distance of 200 m from the road under consideration and up to a height of 12 m above the ground.

Note: The validity of the model has been examined for this prediction range; however, the model is applicable without any limitation on the calculation range.

(5) Meteorological conditions
- No wind or strong temperature profile is assumed as the standard condition.

1.2. Terms and Definitions

The meanings of the main terms related to the road traffic noise used in ASJ RTN-Model 2018 are as follows.

(1) A-weighted sound pressure level ($L_A$)

$L_A$ is ten times the logarithm to base 10 of the ratio of the square of the A-weighted sound pressure $p_{Ae}(t)$ to the square of a reference value $p_0$, defined as

$$L_A(t) = 10 \log \left( \frac{p_{Ae}^2(t)}{p_0^2} \right),$$

where $L_A(t)$ and $p_{Ae}(t)$ are the A-weighted sound pressure level [dB] and the root-mean-square A-weighted sound pressure $p_A(t)$ [Pa], respectively. The reference value $p_0$ is 20 μPa.

In the case of road traffic noise measurement, $L_A(t)$ is obtained with the standard frequency weighting (A-weighting) and the standard time weighting (F-weighting), which are specified in IEC 61672-1:2013. It is expressed as

$$L_{A,F}(t) = 10 \log \frac{1}{\tau_F} \int_{-\infty}^{t} p_A^2(\xi) \exp \left( -\frac{\xi}{\tau_F} \right) d\xi,$$

where $\tau_F$ is the time constant of the standard time weighting, the value is 125 ms for F-weighting. $\xi$ is the variable expressing time [s].

(2) A-weighted equivalent continuous sound pressure level ($L_{Aeq,T}$)

$L_{Aeq,T}$ [dB] is the time-averaged A-weighted sound pressure of fluctuating noise during a stated time interval of duration $T$ [s] (starting at $t_1$ and ending $t_2$), defined as

$$L_{Aeq,T} = 10 \log \left( \frac{1}{T} \int_{t_1}^{t_2} p_{Ae}^2(t) dt \right).$$

$L_{Aeq,T}$ is also termed the time-averaged sound pressure level. In the following, the symbol $T$ can be omitted and represented by the symbol $L_{Aeq}$ if the time interval does not need to be stated.

(3) Sound exposure level ($L_{EA,T}$)

$L_{EA,T}$ [dB] represents the total sound energy of fluctuating noise over the measurement period $T$ [s] (starting at $t_1$ and ending $t_2$). It is ten times the logarithm to base 10 of the ratio of the integral of the square of the
A-weighted sound pressure over a duration $T$ to the square of the reference value $P_0$, defined as

$$L_{EA,T} = 10 \lg \frac{1}{T_0} \int_{t_1}^{t_2} \frac{p_A^2(t)dt}{P_0^2},$$

where $T_0$ is a reference time of 1 s.

**Note:** For measurements of sound exposure over a specified time interval, the duration of integration should be reported and the notation should be $L_{EA,T}$.

(4) **Single-event sound exposure level ($L_{EA}$)**

This represents the sound exposure level for a single noise event, for example, when one vehicle passes in front of a receiver. The value [dB] is defined as ten times the logarithm to base 10 of the ratio of the A-weighted sound pressure, which is integrated over the entire time of the event and normalized by the reference time, i.e.,

$$L_{EA} = 10 \lg \frac{1}{T_0} \int_{t_1}^{t_2} \frac{p_A^2(t)dt}{P_0^2}.$$  

**Note:** If the whole duration of the single noise event is included within the duration $T$ (from $t_1$ to $t_2$), the sound exposure level $L_{EA}$ does not depend on the duration $T$.

(5) **A-weighted sound power level of running vehicle ($L_{WA}$)**

$L_{WA}$ is ten times the logarithm to base 10 of the ratio of the A-weighted sound power $P_A$ [W] (the sound energy emitted in 1 s) radiated from a single running vehicle to the sound power reference level $P_0$,

$$L_{WA} = 10 \lg \frac{P_A}{P_0},$$

where $L_{WA}$ is the A-weighted sound power level [dB], and $P_0 = 10^{-12}$ [W]. The sound power level is determined on the assumption that the vehicle is a point source.

The A-weighted sound power level calculated for each 1/N-octave band using Eq. (1.6), to show the frequency characteristics, is referred to as the 1/N-octave band sound power level.

(6) **Unit pattern**

The time history of the A-weighted sound pressure level observed at a prediction point (observation point) when a single vehicle travels along a road is referred to as the unit pattern. This is generally expressed as a function of time but also can be treated as a function of distance along the traffic lane for practical calculation.

(7) **Major source of vehicle noise**

The noise from a running vehicle includes engine noise, exhaust system noise, suction system noise, tire/road noise, driving system noise, and cooling system noise. In the prediction model, all components of noise are assumed to be emitted from a single point source.

(8) **Vehicle classification**

Two types of vehicle classification are applicable, that is, a three-category classification (light vehicles, medium-sized vehicles, and large-sized vehicles) and a two-category classification (light vehicles and heavy vehicles). In addition, motorcycles and buses are classified as other categories.

**Note:** The sound power levels of hybrid and electric vehicles (HV and EV, respectively) are almost the same as that of gasoline engine vehicles (GEV) at a running speed of 40 km/h or more. Thus, HVs and EVs are included in the same classification as GEVs (refer to Appendix A2).

(9) **Running conditions of vehicles**

The states are classified into two types: a state with an almost constant speed flow (steady running condition) and a state with varying speed (non-steady running condition or transient running condition). The latter includes the non-steady running condition at general roads, and acceleration, deceleration, and halting at interchanges, junctions, and signalized intersections.

(10) **Types of pavement**

This prediction model is applicable to road surfaces with the following three types of surface:

1) **Dense asphalt pavement**: pavement made of dense asphalt concrete.

2) **Porous asphalt pavement**: drainage asphalt concrete pavement with a porous structure, which is sometimes referred to as KOUKINOU I, high-performance pavement, or low-noise pavement. In this prediction model, pavement with a maximum chipping size of 13 mm and a designed void content of 20% is considered to be the standard type.

3) **KOUKINOU II**: porous asphalt formed in layers with the top layer having a maximum chipping size of 13 mm and the bottom layer of stone mastic asphalt (SMA). Its drainage performance is slightly inferior to that of porous asphalt; however, it has better durability.

**Note 1:** A double-layer porous asphalt pavement, which has a self-cleaning effect on pore clogging and acoustic absorption properties for enhanced noise reduction, has been developed. The details of this type of pavement are shown in Reference R1. The double-layer porous asphalt pavement adopted by Tokyo Metropolitan Government is made of porous asphalt formed in layers with the top layer having a maximum chipping size of 5 mm, a target void content of 18–25%, and a thickness of 20 mm, and the bottom layer having a maximum chipping size of 13 mm, a target void content of 16–22%, and a thickness of 50 mm.

**Note 2:** Other types of pavement, such as heat-reflective pavement, are also being developed. However, these have not been considered in this model owing to their limited use.
(11) Noise barriers

There are two types of noise barrier, a reflective barrier, which consists of reflective materials on both sides, and an absorptive barrier, whose surface on the source side is treated with an absorptive material. The absorptive noise barrier made of metal is widely used as a countermeasure for road traffic noise.

Note: A representative absorptive noise barrier, which is sometimes called the “standard metallic absorptive-type barrier” in Japan, consists of a 95-mm-thick metal box filled with a fibrous porous material (thickness of 50 mm and density of 32 kg/m$^3$). The box is constructed of aluminum plates with slits on the road side and a 1.6-mm-thick iron plate on the back to optimize its sound insulation performance.

(12) Structure-borne noise of viaducts

The structures of a viaduct, such as the slabs and girders, vibrate when vehicles are running on it. Running vehicles generate mechanical vibrations in these structures. The vibrations produce noise at audible frequencies, which is referred to as the structure-borne noise of viaducts. However, the impulsive sound generated at expansion joints is not included in this model.

(13) Effective (air) flow resistivity ($\sigma_e$)

This is the equivalent flow resistivity (unit: kPa s/m$^2$) deduced by the theoretical curve fitting of frequency characteristics of the excess attenuation observed above a finite-impedance boundary such as the ground surface.

1.3. General Calculation Procedure and Basic Equations

The principles and basic equations used in the present prediction model and the flow of the calculation are as follows.

1.3.1. Principles and basic equations used in the prediction model

In the calculation of road traffic noise using $L_{Aeq,T}$, the basic procedure is to obtain the time history of $L_A$ observed at a prediction point (the unit pattern) for a single vehicle that is considered to be an omnidirectional point source passing along the road under consideration, and to calculate the sound pressure exposure level $L_{EA}$ for the single vehicle. By taking account of the traffic conditions (traffic volume, vehicle type composition, etc.) in the above results, the time-averaged value of the noise at a prediction point in terms of energy is calculated. The concrete procedure is as follows.

First, the objective road (lane) is divided into several sections (see Fig. 1.1). Here, the running speed $v_i$ [m/s] and the A-weighted sound power level $L_{WA,i}$ of the running vehicle at the $i$th divided section should be regarded as constant. One of the sections is selected, and a representative point (source point) is set at the center point of the section, and the A-weighted sound power level $L_{WA,i}$ is set.

Next, the A-weighted sound pressure level $L_{A,i}$ at the prediction point is calculated according to calculation method of sound propagation. The sound exposure level for the $i$th section $L_{EA,T,i}$ during the interval $T_i$, in which the vehicle exists in the $i$th section, is calculated as follows (see Fig. 1.2)

$$L_{EA,T,i} = L_{A,i} + 10 \log \frac{T_i}{T_0},$$

where $T_0 = 1$ s (the reference time).

The above calculation is performed for every section. Then, the single-event sound exposure level $L_{EA}$ [dB] at the prediction point when a vehicle travels along the entire road (lane) is calculated as

$$L_{EA} = 10 \log \sum_i \frac{L_{EA,T,i}}{T_i}.$$  (1.8)

The sound power level is dependent on the vehicle type. Therefore, $L_{EA}$ is calculated for each vehicle type, and the equivalent continuous A-weighted sound pressure level $L_{Aeq,T}$ is calculated by taking into consideration the traffic volume for the vehicle type,

$$L_{Aeq,T} = 10 \log \frac{\sum_j N_{T,j} 10 \frac{L_{EA,j}}{W}}{T},$$  (1.9)

where $T$ [s] is the total time interval, $L_{EA,j}$ [dB] is the single-event sound exposure level for vehicle type $j$ calculated by Eq. (1.8), and $N_{T,j}$ is the traffic volume
1.3.2. General calculation procedure

A flow showing the general procedure for calculating road traffic noise based on this model is shown in Fig. 1.3. The outline of the calculation procedure is as follows.

1. Setting road structures, roadside conditions, and prediction point

The first step of the procedure includes setting the road structure, the position of the source, the prediction point, the positions of the sound obstacles, the ground surface conditions along the propagation path, and so on.

2. Setting positions of lanes

The calculation position for each lane is located at the center of the lane. However, it is possible to combine two or more lanes into a single hypothetical lane. For instance, a hypothetical lane can be located along the centerline between two lanes of traffic traveling in opposite directions.

3. Setting discrete source positions

Discrete source positions are set on the lanes at 0m height. The positions are generally located within a range of ±20l (l: shortest distance from the calculation lane to the prediction point) from the point of intersection of lines representing the lane and the perpendicular from the prediction point on the lane. They are located with an interval of l or less. On the other hand, in the cases where the vehicle running speed varies with acceleration-deceleration as seen in special road sections or where the propagation property rapidly changes with the arrangement of the sound source, the prediction point, and other acoustical factors, it may be necessary to shorten the intervals of the discrete sources to capture the maximum level of the unit pattern correctly. Moreover, to obtain an accurate value of the single-event sound exposure level of the unit pattern, the point sources should be set in the range where the sound pressure level goes down to −10 dB or less than the maximum level.
Note: Since the maximum level is not always observed by a source that is located at a position where the distance between the lane and the prediction point is the shortest, it is necessary to set the calculation conditions around the prediction point by preliminary calculations.

(4) Setting the power level of the source

$L_{WA}$ is set considering the running condition of the vehicle (steady flow, non-steady flow, acceleration, deceleration, and idling while at rest), running speed, and corrections (power-level change due to the type of pavement, road gradient, directivity, and other factors).

(5) Calculation of the unit pattern

The unit pattern $L_{A,j}$ at the prediction point is calculated when a single vehicle runs alone along the objective road. The unit pattern is calculated separately by lane and by vehicle type.

(6) Calculation of the energy integration of the unit pattern and $L_{Aeq}$

The single-event sound exposure level $L_{EA}$ for the respective vehicle type is calculated using Eq. (1.8). By taking into consideration the traffic volume $N_T$ [number of vehicles] during time interval $T$ [s], the equivalent continuous A-weighted sound pressure level $L_{Aeq,T}$ is obtained using Eq. (1.9). When the road has multiple lanes, $L_{Aeq,T}$ for the entire road is calculated using the energy summation of the obtained results for respective driving lanes.

In the case of noise prediction around a viaduct road, the structure-borne noise of the viaduct should be taken into consideration in addition to vehicle noise. If a viaduct has a structure separated by a gap between lanes, the noise is calculated by considering that each set of lanes exists independently. Sound attenuation caused by buildings and the variation of sound due to the effect of wind can also be calculated when required.

2. SOUND SOURCE CHARACTERISTICS

In ASJ RTN-Model 2018, the calculation method for the sound power level of each type of road vehicle is specified. The sound power level of road vehicles depends on the pavement type and road gradient, as well as the vehicle type and running speed. Moreover, because there is directivity in the noise radiation of road vehicles, this factor may have to be considered. The basic equation for the sound power level in the model is given as a function of the running speed separately for sections under several vehicle running conditions and pavement types, and the effects of other factors are considered in the correction terms.

The representative sound power spectra of vehicle noise for each type of pavement are shown in Appendix A1.

2.1. Classification of Road Vehicles

Road vehicles are basically classified into three or two categories, as shown in Table 2.1 [15]. The three-category classification places importance on noise radiation characteristics, whereas the two-category classification takes practicality into account. When the noise generated from motorcycles is considered separately, the motorcycle category shown in Table 2.2 can be added [16]. In the prediction of road traffic noise, not only the sound power level of each road vehicle but also the percentage of each type of vehicle comprising the traffic volume is an important factor. Thus, the percentage of heavy vehicles (large-sized and medium-sized vehicles) in the two-category classification is widely used and is sometimes referred to as a factor affecting road traffic noise.

Note 1: In the previous model (ASJ RTM-Model 2013), light vehicles were classified into two types: passenger cars and small-

| Two-category | Three-category | Characteristics |
|--------------|----------------|-----------------|
| Light vehicles | Passenger cars used exclusively for carrying passengers with capacity of 10 or fewer | Small-sized vehicles with engine displacement exceeding 0.050 liter and with overall length of 4.7 m or less |
| Medium-sized vehicles | Vehicles with overall length exceeding 4.7 m excluding large-sized vehicles (most vehicles in this category have 2 axles) | Medium-sized buses with capacities from 11 to 29 passengers |
| Heavy vehicles | Large-sized vehicles | Vehicles with gross vehicle weight of over 8t or maximum authorized payload of over 5t (most vehicles in this category have 3 or more axles) |
|             |                   | Large-sized buses with capacity of 30 or more passengers |
|             |                   | Large-sized special motor vehicles |

Note: The three-category classification nearly corresponds to that in road vehicle noise regulations in Japan, which is based on vehicle weight and engine output.
sized vehicles. However, these vehicle types are specified in the same category, because the ratio of the number of registered small-sized vehicles to that of passenger cars has been very small [15].

Note 2: Hybrid vehicles (HVs) and electric vehicles (EVs) are included in the category of light vehicles. Latest knowledge regarding the sound power levels of these vehicles is introduced in Appendix A2.

2.2. Sound Power Levels of Road Vehicles

The sound power levels of road vehicles generally vary with vehicle speed, engine rotational speed, and engine load. However, in this model, the sound power level is given simply as a function of vehicle speed, similarly to that in the previous model, for practicality and convenience. The change in the generated noise due to the road gradient and sound radiation directivity is considered in the correction terms.

2.2.1. Calculation method for sound power level for each type of pavement and section

The A-weighted sound power level of a road vehicle is given for each type of pavement, namely, dense asphalt, porous asphalt, and KOUKINOU II pavement (see Subsections 2.2.2–2.2.4). A schematic of the A-weighted sound power level in the steady and non-steady traffic flow sections, which are defined in the following parts, is shown in Fig. 2.1.

1) Steady traffic flow section

This is a section of an expressway or a general road sufficiently distant from signalized intersections where vehicles can be driven in the top-gear position or its equivalent. The vehicle speed \( V \) is in the range from 40 to 140 km/h.

2) Non-steady traffic flow section

This is a section of general road including signalized intersections where vehicles frequently accelerate and decelerate. \( V \) is in the range from 10 to 60 km/h.

Note: The average sound power level under the running conditions including acceleration, deceleration, and stopping can be obtained by applying the equation used for the non-steady traffic flow section described here.

The A-weighted sound power levels can be individually calculated for the sections under running conditions including acceleration and deceleration, as seen in the section near an expressway tollgate or a junction to a general road. Figure 2.2 shows a schematic of the A-weighted sound power level for the acceleration and deceleration running conditions.

1) Sound power level near an expressway tollgate

1) Acceleration running condition

The acceleration running condition is defined as the transitional state from stopping at a tollgate to steady running in the main lane. The speed range is from 1 to 80 km/h. When the vehicle starts moving and accelerates from the tollgate, a constant power level is applied until it reaches 1 km/h (the value obtained when \( V = 10 \) km/h is substituted into the equation for the deceleration running condition, see Fig. 2.2(a)). Acceleration at speeds exceeding 80 km/h is treated as the steady running condition.

2) Deceleration running condition

The deceleration running condition is defined as the transitional state from steady running in the main lane to stopping at the tollgate. The speed range is from 10 to 140 km/h. The sound power level at 10 km/h is applied at speeds of less than 10 km/h.

2) Sound power level near a junction

A junction is defined as a road section where the running condition of vehicles changes from acceleration to steady-state running or vice versa, for example, a road section where vehicles exit an expressway along a ramp to a non-expressway road.

1) Acceleration running condition

The speed range is from 1 to 60 km/h. Acceleration at speeds exceeding 60 km/h is treated as the steady running condition (see Fig. 2.2(b)).

2) Deceleration running condition

The speed range is 10 km/h or more. The sound power level at 10 km/h is applied at speeds of less than 10 km/h.

2.2.2. Sound power levels of road vehicles on dense asphalt pavement

The A-weighted sound power level \( L_{WA} \) [dB] of a road vehicle running on a dense asphalt pavement is given by

\[
L_{WA} = a + b \log V + C
\]

Table 2.2 Vehicle category (motorcycles).

| Category               | Characteristics                  |
|------------------------|----------------------------------|
| Motorcycles            | Motorcycles and mopeds           |

Fig. 2.1 A-weighted sound power level in steady and non-steady traffic flow sections.
where $V$ is the vehicle speed [km/h], $a$ and $b$ are regression coefficients, and $C$ is the correction term from a reference value.

$L_{WA}$ varies with the road conditions, such as the road surface or gradient. Because there are various sound sources in a road vehicle and the noise generated from these sources is affected by the body shape, the vehicle noise has directivity. To consider the change in noise radiation caused by these factors, the correction term $C$ is given by

$$C = \Delta L_{\text{grad}} + \Delta L_{\text{dir}} + \Delta L_{\text{etc}},$$

(2.2)

where $\Delta L_{\text{grad}}$ is the correction for road gradient [dB], $\Delta L_{\text{dir}}$ is the correction for sound radiation directivity [dB], and $\Delta L_{\text{etc}}$ is the correction for other factors [dB] (see Section 2.3).

(1) Sound power levels in steady and non-steady traffic flow sections

The values of coefficients $a$ and $b$ in Eq. (2.1) are given in Table 2.3, which are provided separately for the steady- and non-steady traffic flow sections. The coefficient $b$, which represents the speed dependence of the noise generated, is 30 for the steady traffic flow section and 10 for the non-steady traffic flow section.

(2) Sound power levels in acceleration and deceleration sections

In the sections near an expressway tollgate or a junction, vehicle noise depends on its running condition. The A-weighted sound power levels during acceleration and deceleration are individually calculated. For the acceleration running condition, the values of coefficients $a$ and $b$ in Eq. (2.1) are given in Appendix A3. For the deceleration running condition, the values of steady traffic flow, which are given in Table 2.3, are applied. The speed dependent coefficient $b$ is 30 for the deceleration section and 10 for the acceleration section.

2.2.3. Sound power levels of road vehicles on porous asphalt pavement

The noise reduction effect due to a porous asphalt pavement depends on the vehicle types, and the number of years since the pavement was constructed. The correction value is based on measurement data. The A-weighted

\[ L_{WA} = a + b \log V + C, \]  

(2.1)

Table 2.3 Coefficients $a$ and $b$ for dense asphalt pavement (steady and non-steady traffic flow sections).

| Classification       | Steady traffic flow section (40 $\leq V \leq$ 140 km/h) | Non-steady traffic flow section (10 $\leq V \leq$ 60 km/h) |
|----------------------|----------------------------------------------------------|----------------------------------------------------------|
|                      | $a$            | $b$            | $a$            | $b$            |
| Three-category       |                |                |                |                |
| Light vehicles       | 45.8           | 30             | 82.3           | 10             |
| Medium-sized vehicles| 51.4           | 30             | 87.1           | 10             |
| Large-sized vehicles | 54.4           | 30             | 90.0           |                |
| Two-category         |                |                |                |                |
| Light vehicles       | 45.8           | 30             | 82.3           | 10             |
| Heavy vehicles       | 53.2           | 30             | 88.8           | 10             |
| Motorcycles          | 49.6           | 30             | 85.2           | 10             |

Note: For $L_{WA}$ in deceleration running condition on expressways (10 km/h $\leq V$), the coefficients $a$ and $b$ are given by those of the steady traffic flow section.
sound power level $L_{WA}$ [dB] of a road vehicle running on the porous asphalt pavement is given as

$$L_{WA} = a + b \log V + c \log(1 + y) + C,$$  \hspace{1cm} (2.3)

$$C = \Delta L_{grad} + \Delta L_{dir} + \Delta L_{traf} + \Delta L_{etc},$$  \hspace{1cm} (2.4)

where $a$, $b$, and $c$ are regression coefficients and $y$ indicates the number of years since the pavement was constructed. The terms making up the correction term $C$, $\Delta L_{traf}$ is a term taking into account the changes in the noise reduction effect depending on the daily traffic volume (see Note 3 below). Concerning the other correction factors ($\Delta L_{grad}$, $\Delta L_{dir}$, and $\Delta L_{etc}$), see Section 2.3.

**Note 1:** The coefficients of $L_{WA}$ on a porous asphalt pavement were determined using the measurement data for the steady running condition on expressways where the elapsed time since the construction of the pavement was within 11 years and the traffic volume was 15,000 or less vehicles per day [17]. Therefore, the calculation equations are applicable under those conditions.

**Note 2:** According to results of recent measurements, it is clear that the frequency characteristics of vehicle noise differ among the measurement sites but do not differ in terms of the elapsed years after the construction [17].

**Note 3:** The noise reduction effect due to a porous asphalt pavement depends on not only the elapsed years but also the daily traffic volume. However, the relationships between the traffic volume and the noise reduction effect of the porous pavement have not yet been analyzed quantitatively. Therefore, the correction value $\Delta L_{traf}$ is assumed to be 0 dB.

**Note 4:** The noise reduction effect of a double-layer porous asphalt pavement is introduced in Reference R1.

(1) **Sound power levels in steady traffic flow section**

The values of coefficients $a$, $b$, and $c$ in Eq. (2.3) for the steady traffic flow section on an expressway are given in Table 2.4. The speed range is from 60 to 140 km/h. The speed dependent coefficient $b$ on a porous asphalt pavement is 25. In the case of motorcycles, $b$ and $c$ are always 30 and 0, respectively.

With regard to the sound power levels on a general road with porous asphalt pavement, the coefficients $a$, $b$, and $c$ are given in Appendix A4 using Eqs. (2.3) and (2.4).

(2) **Sound power levels in acceleration and deceleration sections**

The A-weighted sound power levels in the sections near an expressway tollgate or a junction are given for each type of vehicle using Eqs. (2.3) and (2.4), the coefficients $a$, $b$, and $c$ for an acceleration running condition are given in Table 2.5, whereas those for a deceleration running condition are given in Table 2.4. In the case of motorcycles, $c$ is always 0.

2.2.4. **Sound power levels of road vehicles on KOUKINOU II pavement**

The A-weighted sound power level $L_{WA}$ [dB] of a road vehicle running on a KOUKINOU II pavement is given by Eqs. (2.3) and (2.4), as similarly to the porous asphalt pavement [17].
Note 1: The coefficients of $L_{WA}$ on a KOUKINOU II pavement were determined using the measurement data for the steady running condition on expressways where the elapsed time since the completion of the construction of the pavement was within 6 years and the traffic volume was 15,000 or less vehicles per day [17]. Therefore, the equations are applicable under those conditions.

Note 2: The noise reduction effect due to a KOUKINOU II pavement depends on not only the elapsed years but also the daily traffic volume. However, the relationships between the traffic volume and the noise reduction effect of the pavement have not yet been analyzed quantitatively. Therefore, the correction value $C_1$ is assumed to be 0 dB.

2.3. Correction of Sound Power Level for Various Factors

In this section, the equations used to calculate the correction for road gradient, sound radiation directivity, and other factors are described.

### 2.3.1. Correction for road gradient

To consider the change in the power level due to the road gradient, $\Delta L_{\text{grad}}$ is calculated as

$$\Delta L_{\text{grad}} = 0.14i_{\text{grad}} + 0.05i_{\text{grad}}^2 \quad 0 \leq i_{\text{grad}} \leq i_{\text{grad,max}}, \quad (2.5)$$

where $i_{\text{grad}}$ is the gradient of the road [%] and $i_{\text{grad,max}}$ is the maximum applicable gradient; their values at various vehicle speeds are shown in Table 2.7. This correction is applied only to heavy vehicles ascending inclined roads of sufficient length.

Note: This correction term is derived from the running load on inclined sections obtained from the equation of motion of a vehicle [18,19].

### 2.3.2. Correction for sound radiation directivity

A vehicle is considered to be a compound sound source comprising multiple sound sources such as the engine, tires, and mufflers. Because the noise generated from these sources is affected by the body shape, vehicle noise has directivity [20,21]. This directivity is taken into account in the following ways.

The correction related to the directivity of vehicles $\Delta L_{\text{dir}}$ is given by

$$\Delta L_{\text{dir}} = \begin{cases} (a + b \cdot \cos \varphi + c \cdot \cos 2\varphi) \cos \theta & \varphi < 75^\circ \\ 0 & \varphi \geq 75^\circ \end{cases}, \quad (2.6)$$

where the coordinate system is shown in Fig. 2.3 and the

| Classification | Acceleration running condition |
|----------------|--------------------------------|
|                | Near an expressway tollgate (1 \leq V \leq 60 km/h) | Near a junction (1 \leq V \leq 60 km/h) |
|                | $a$ $b$ $c$ | $a$ $b$ $c$ | $a$ $b$ $c$ |
| Light vehicles | 79.1 6.4 88.0 | 76.6 6.4 83.2 | 84.9 10 3.6 |
| Medium-sized vehicles | 85.7 10 3.6 | 94.6 5 3.6 | 86.1 3.6 3.6 |
| Large-sized vehicles | 88.6 3.6 97.5 | 83.2 10 3.6 | 84.9 10 3.6 |

Note: For $L_{WA}$ of large-sized buses, the coefficients $a$, $b$, and $c$ are given by those of large-sized vehicles.

### Table 2.5 Coefficients $a$, $b$, and $c$ for porous asphalt pavement (acceleration sections near an expressway tollgate and a junction).

| Classification | Acceleration running condition |
|----------------|--------------------------------|
|                | Near an expressway tollgate (1 \leq V \leq 60 km/h) |
| Light vehicles | 79.1 6.4 88.0 |
| Medium-sized vehicles | 85.7 10 3.6 |
| Large-sized vehicles | 88.6 3.6 |
| Motorcycles   | 87.7 10 — |

Note: For $L_{WA}$ of large-sized buses, the coefficients $a$, $b$, and $c$ are given by those of large-sized vehicles.
coefficients \(a\), \(b\), and \(c\) are given in Table 2.8. This equation is applicable at speeds of 40 km/h or more. In the case of \(\theta \geq 80^\circ\), \(\theta\) is treated as \(\theta = 80^\circ\). \(\theta\) has the following relationship with \(\Theta\) (the projection angle of \(\theta\) on the horizontal plane):

\[
\theta = \tan^{-1}(\sin\varphi \tan \Theta) \quad \varphi \neq 0.
\]  

This correction is applied to the calculation of sound reflection from the underside of a viaduct and noise propagation to the higher floors of buildings in the vicinity of roads.

Note: Although it is also possible to apply this correction to positions where a high noise barrier is installed, an additional consideration is required in the case of a reflective noise barrier, since the sound field becomes complicated owing to the multiple reflections generated between the noise barrier surface and the vehicle body.

2.3.3. Correction for other factors

Regarding the correction for other factors \(\Delta L_{\text{etc}}\), it is necessary to consider the change in noise from running vehicles owing to illegal remodeling (vehicles equipped with illegal tires and mufflers), different types of tire, and pavement surface temperature. However, the relationships between these factors and noise generation have not yet been analyzed quantitatively. Therefore, the correction value \(\Delta L_{\text{etc}}\) is assumed to be 0 dB.

3. METHOD OF CALCULATING SOUND PROPAGATION

An engineering method of calculating outdoor noise propagation considering the decay with distance due to geometrical spreading (inverse-square law), the diffraction
effect, ground absorption, and attenuation due to atmospheric absorption is described in this chapter. The method of calculating the fluctuation in the A-weighted sound pressure level due to meteorological factors such as wind, and of calculating the reflection and transmission of sound are also described. Overall values (i.e., the summation of all frequency components) of the A-weighted sound pressure level are directly calculated by the method described in this chapter.

The methods of calculating the propagation for each frequency component are described in Appendix A5. For complicated boundary shapes or absorption characteristics, the wave-based numerical analyses described in Appendix A6 or scale-model experiments [22] can be applied.

3.1. Basic Equations

The A-weighted sound pressure level $L_{W,A,j}$ [dB] for noise propagation from the $i$th source position to the prediction point is calculated considering attenuation due to various factors in the sound propagation from an omnidirectional point source in a hemi-free field as

$$L_{W,A,j} = L_{W,A,i} - 8 - 20 \log r_i + \Delta L_{cor,i}, \quad (3.1)$$

where $L_{W,A,i}$ is the A-weighted sound power level of a single running vehicle at the $i$th source position [dB] and $r_i$ is the direct distance from the $i$th source position to the prediction point [m]. $\Delta L_{cor,i}$ denotes the correction related to various attenuation factors in the sound propagation from the $i$th source position to the prediction point [dB], and is given by

$$\Delta L_{cor,i} = \Delta L_{dif,i} + \Delta L_{grnd,i} + \Delta L_{air,i}, \quad (3.2)$$

where $\Delta L_{dif,i}$ is the correction for diffraction [dB], $\Delta L_{grnd,i}$ is the correction for the ground effect [dB], and $\Delta L_{air,i}$ is the correction for atmospheric absorption [dB]. The suffix $i$ for the source position is hereafter omitted for simplicity of notation.

3.2. Correction for Diffraction $\Delta L_{dif}$

The correction for diffraction $\Delta L_{dif}$ due to acoustical obstacles such as noise barriers is calculated using $\Delta L_{dif,k}$ and $\Delta L_{dif,r}$, which are functions of the diffraction path difference $\delta$. Correction terms due to various types of diffraction are listed in Table 3.1.

3.2.1. Fundamental correction terms for diffraction, $\Delta L_{dif,k}$ and $\Delta L_{dif,r}$

The fundamental correction terms for diffraction, $\Delta L_{dif,k}$ and $\Delta L_{dif,r}$ [dB], are calculated using Eqs. (3.3) and (3.4), respectively, as functions of the path difference $\delta$ [m] for diffraction considering a point source $S$, a diffraction point $O$, and a prediction point $P$ (see Fig. 3.1). $\Delta L_{dif,k}$ is applied for diffraction around a knife wedge, such as a simple thin barrier [23,24]. $\Delta L_{dif,r}$ is applied for diffraction around a wedge with an opening angle of approximately 90°, such as a building and an embankment [25,26].

(1) Knife wedge $\Delta L_{dif,k}$ (for a simple barrier)

$$\Delta L_{dif,k} = \begin{cases} 
-20 - 10 \log(c_{spec}\delta), & c_{spec}\delta \geq 1 \\
-5 - 17.0 \cdot \sinh^{-1}(c_{spec}\delta)^{0.415}, & 0 \leq c_{spec}\delta < 1 \\
\min(0, -5 + 17.0 \cdot \sinh^{-1}(c_{spec}\delta)^{0.415}), & c_{spec}\delta < 0 
\end{cases} \quad (3.3)$$

(2) Wedge with an opening angle $\Delta L_{dif,r}$ (for a building and an embankment)

$$\Delta L_{dif,r} = \begin{cases} 
-17.5 - 10 \log(c_{spec}\delta), & c_{spec}\delta \geq 1 \\
-2.5 - 17.0 \cdot \sinh^{-1}(c_{spec}\delta)^{0.415}, & 0 \leq c_{spec}\delta < 1 \\
\min(0, -25 + 17.0 \cdot \sinh^{-1}(c_{spec}\delta)^{0.415}), & c_{spec}\delta < 0 
\end{cases} \quad (3.4)$$

Here, $\delta$ is defined as a negative value when $S$ is visible from $P$. The function $\min(a, b)$ gives the smaller value of $a$ and $b$. The coefficient $c_{spec}$ is defined as shown in Table 3.2. $\Delta L_{dif,k}$ and $\Delta L_{dif,r}$ as functions of $\delta$ are illustrated in Fig. 3.2.

Note 1: Equations (3.3) and (3.4) are determined by curve-fitting to approximate the correction values obtained from the equations for sound diffraction at a single frequency (see Appendix A5) and the frequency characteristics of the noise from a running vehicle (see Appendix A1).

Note 2: The data used for the above-mentioned curve-fitting are limited to those for a path difference $\delta$ up to approximately 20 m and for $\Delta L_{dif,k}$ and $\Delta L_{dif,r}$ down to about −30 dB. If the path difference is more than 20 m, the attenuation value is not as high as that obtained from the above equations because the power in the low-frequency range is dominant.

Note 3: If the path difference $\delta$ exceeds 20 m, the correction for diffraction for the overall value is calculated through the method for frequency-dependent propagation presented in Appendix A5. If the transmission through the barrier is considered, the correction for transmission should be taken into account through the procedure presented in Subsection 3.2.8.

Note 4: The directivity of the vehicle noise can be considered in the calculation for diffraction by applying the directivity correction of the power level (see Subsection 2.3.2) to the direction from point source $S$ to diffraction point $O$.

3.2.2. Correction for single diffraction

(1) Simple barrier $\Delta L_{dif,SB}$

The correction term $\Delta L_{dif,SB}$ for diffraction around a single diffraction point, such as the top of a simple plane barrier, is calculated as
Table 3.1 Symbols of correction terms for various types of diffraction.

| Purpose                                    | Symbols       | Summary                                                                 | Equation |
|--------------------------------------------|---------------|-------------------------------------------------------------------------|----------|
| Fundamental term                           | $\Delta L_{dk}$ | Fundamental terms for various types of diffraction: $\Delta L_{dk}$ is applied for diffraction around a knife wedge, such as a simple thin barrier; $\Delta L_{di}$ is applied for diffraction around a wedge with an opening angle, such as a building and an embankment. | Eq. (3.3) Eq. (3.4) |
| Single diffraction by simple barrier       | $\Delta L_{diff, sb}$ | Single diffraction around a simple barrier                              | Eq. (3.5) |
|                                             | $C_{diff, abs}$ | Absorption effect of the standard metallic absorptive-type barrier     | Eq. (3.6) |
| Single diffraction by embankment           | $\Delta L_{diff, emb}$ | Single diffraction at an edge of a bank road, a cut road, and a building | Eq. (3.7) |
| Double diffraction by double barriers      | $\Delta L_{diff, db}$ | Double diffraction around double barriers with a spacing of 5 m or more | Eq. (3.8) |
| Double diffraction by thick barrier        | $\Delta L_{diff, th}$ | Double diffraction around two diffraction wedges with an opening angle of about 90°, such as an embankment or a building | Eq. (3.9) |
| Barrier with overhang                      | $\Delta L_{diff, ob}$ | Diffraction around a barrier with an overhang on the edge              | Eq. (3.10) |
|                                             | $C_{diff, ob}$ | Overhang effect (additional correction term by a barrier with an overhang) | Eq. (3.11) |
| Edge-modified barrier                      | $\Delta L_{diff, emb}$ | Diffraction around a barrier with acoustic device on the top edge to reduce diffracted sound | Eq. (3.12) |
|                                             | $\Delta L_{diff, sb}$ | Diffraction around a hypothetical simple barrier                        | Eq. (3.3) |
|                                             | $C_{diff, emb}$ | Additional correction term by a modified edge                          | Reference R2 |
| Low-height barrier                         | $\Delta L_{diff, low}$ | Single diffraction around a low-height barrier with a height of 1 m or less in flat terrain; calculated as the insertion loss to a barrier with a height of 0 m | Eq. (3.13) |
| Transmission through barrier               | $\Delta L_{diff, trans}$ | Summation of diffraction over a barrier and transmission through barrier | Eq. (3.14) |
|                                             | $\Delta L_{diff, slit}$ | Diffraction around a slit opening                                       | Eq. (3.15) |

Fig. 3.1 Direct path $R = SP$, diffraction path $L = SO + OP$ and path difference $\delta$.

$$\Delta L_{diff, sb} = \begin{cases} 
\Delta L_{dk} & \text{for standard metallic absorptive-type barrier} \\
\Delta L_{di} + C_{diff, abs} & \text{for standard metallic absorptive-type barrier}
\end{cases}, \quad (3.5)$$

where $C_{diff, abs}$ is the correction term for the absorption effect of the standard metallic absorptive-type barrier and is calculated as [27]

$$C_{diff, abs} = \begin{cases} 
-0.5 \log(1 + 20\delta) & \delta > 0 \\
0 & \delta \leq 0
\end{cases}. \quad (3.6)$$

Note 1: Transmitted sound is considered if it cannot be ignored. The calculation procedure is presented in Subsection 3.2.8.

Note 2: The correction term $C_{diff, abs}$ can be considered for the absorptive barrier, the absorption coefficient of which is larger than that of the standard metallic absorptive-type barrier.
The correction term $\Delta L_{\text{dif},r}$ for diffraction around a wedge with an opening angle, such as the edge of a bank road, a cut road, and a building, is given by

$$\Delta L_{\text{dif},r} = \Delta L_{d,r}.$$  (3.7)

**Note:** Small obstacles such as curbstones, guardrails, and guard ropes around the road are ignored.

### (2) Embankment $\Delta L_{\text{dif},rw}$

The correction term $\Delta L_{\text{dif},rw}$ for diffraction around a wedge with an opening angle, such as the edge of a bank road, a cut road, and a building, is given by

$$\Delta L_{\text{dif},rw} = \Delta L_{\text{dif},r}.$$ (3.7)

**Note:** Small obstacles such as curbstones, guardrails, and guard ropes around the road are ignored.

### (3) Barrier with a finite length

There are two methods for obtaining the correction term due to diffraction around a barrier with a finite length: one is a “one-path” method considering only diffraction over the top edge of the barrier, and the other is a method involving the summation of diffractions over the top edge and around the side edges [28]. The latter method is used to calculate the unit pattern, whereas the values of $L_{\text{AE}}$ or $L_{\text{Aeq}}$ calculated by integrating the unit pattern are almost the same regardless of the method. Here, the one-path method is described.

If line segment SP from point source S to prediction point P crosses a finite barrier, as shown in Fig. 3.3, $\Delta L_{\text{dif},sb}$ is calculated using Eq. (3.7). If not, the propagation from S to P is calculated for the terrain without a barrier.

Note 1: To obtain more accurate unit patterns or to investigate the dependence of the A-weighted sound pressure level on the source position, a method involving the summation of diffractions over the top edge and around the side edges can be used [28].

Note 2: When vehicles run on a viaduct with a finite barrier and line segment SP does not cross the barrier, the railings along the road are considered as barriers.

### 3.2.3. Correction for double diffraction $\Delta L_{\text{dif},db}$

(1) Parallel double barriers

The correction term $\Delta L_{\text{dif},db}$ for diffraction around a pair of barriers with a spacing of 5 m or more, shown in Figs. 3.4 and 3.5(a), is calculated as [29]

$$\Delta L_{\text{dif},db} = \begin{cases} \Delta L_{\text{SXP}} + \Delta L_{\text{YPX}} & \delta_{\text{SXP}} \geq \delta_{\text{SYP}} \\ \Delta L_{\text{SYP}} + \Delta L_{\text{XYP}} & \delta_{\text{SXP}} < \delta_{\text{SYP}} \end{cases},$$ (3.8)

where X and Y are diffraction points, and $\Delta L_{\text{ABC}}$ is $\Delta L_{\text{dk}}$ for diffraction path ABC with path difference $\delta_{\text{ABC}}$.

**Note 1:** The power of the lower frequency range is more dominant behind double barriers than behind a single barrier. In the former case, the attenuation value may not be as high as the correction for the overall value calculated using Eq. (3.8) with the fundamental correction term calculated using Eq. (3.3). If the attenuation for diffraction due to the double barriers exceeds approximately 30 dB ($\Delta L_{\text{dif},db} < -30 \text{ dB}$), $\Delta L_{\text{dif},db}$ should be calculated from the insertion loss obtained by using the equations for sound diffraction at a knife wedge at a single frequency (see Appendix A5.2.1) and the frequency characteristics of the noise from a running vehicle (see Appendix A1). See Appendix A5.2.4.
Note 2: See Ref. [30] for a calculation method of the correction for the diffraction around triple barriers. The power of the lower frequency range may be more dominant behind triple barriers than behind double barriers.

(2) Irregular double diffraction

There are some irregular cases of double diffraction as shown in Figs. 3.5(b) and 3.5(c). Figure 3.5(b) shows the case of double diffraction at a tunnel portal and a barrier outside, and Fig. 3.5(c) shows the case in which barriers are installed at the roadsides of both a main road and a side road that joins the main road. In such cases, the correction term for the double diffraction \( \Delta L_{\text{dif,db}} \) is calculated using Eq. (3.8) after the determination of diffraction points X and Y [31].

3.2.4. Thick barrier \( \Delta L_{\text{dif,tb}} \)

The correction term \( \Delta L_{\text{dif,tb}} \) for double diffraction around an acoustical obstacle, such as an embankment and a building, is calculated, considering two diffraction points as shown in Fig. 3.6, as [25,32]

\[
\Delta L_{\text{dif,tb}} = \begin{cases} 
\Delta L_{\text{SXP}} + \Delta L_{\text{XYP}, \delta} & \delta_{\text{SXP}} \geq \delta_{\text{SYP}} \\
\Delta L_{\text{SYP}} + \Delta L_{\text{SXY}, \delta} & \delta_{\text{SXP}} < \delta_{\text{SYP}}
\end{cases},
\]

(3.9)

where X and Y are the diffraction points, and \( \Delta L_{\text{AB}, \delta} \) is \( \Delta L_{\text{dif}} \) for diffraction path ABC with path difference \( \delta_{\text{AB}} \).

Note: The power of the lower frequency range is more dominant behind a thick barrier than behind a single barrier. In the former case, the attenuation value may not be as high as the correction for the overall value calculated using Eq. (3.9) with the fundamental correction term calculated using Eq. (3.4). If the attenuation for diffraction due to the thick barrier exceeds approximately 30 dB (\( \Delta L_{\text{dif,tb}} < -30 \text{ dB} \)), \( \Delta L_{\text{dif,tb}} \) should be calculated from the insertion loss obtained using the equations for sound diffraction at a wedge with an opening angle at a single frequency (see Appendix A5.2.2) and the frequency characteristics of the noise from a running vehicle (see Appendix A1). See Appendix A5.2.4.

3.2.5. Barrier with an overhang \( \Delta L_{\text{dif,ob}} \)

The correction term \( \Delta L_{\text{dif,ob}} \) for diffraction around a barrier with an overhang, i.e., a barrier with its top end folded, is obtained by adding a correction term to the correction term for diffraction around a hypothetical thick barrier whose edges correspond to the diffraction points X and Y of the barrier with an overhang as shown in Fig. 3.7 [33]:

\[
\Delta L_{\text{dif,ob}} = \Delta L_{\text{dif,tb}} + C_{\text{dif,ob}},
\]

(3.10)

\[
C_{\text{dif,ob}} = A \left\{ \left( \frac{B}{B - \Delta L_{\text{dif,tb}}} \right)^{C} - 1 \right\},
\]

(3.11)

where \( \Delta L_{\text{dif,tb}} \) is the correction term for diffraction around a thick barrier [dB], and \( C_{\text{dif,ob}} \) is the correction term for the difference in insertion loss between the barrier with an overhang and the thick barrier. The coefficients \( A, B, \) and \( C \) are presented in Table 3.3 with the profiles of the barrier.

Note 1: The values in Eq. (3.11) and Table 3.3 were obtained by function approximation of the difference in the insertion loss of road traffic noise level between reflective barriers with overhangs and thick barriers. The values of the insertion loss were obtained through wave-based numerical analysis.
Cases of overhang width less than 50 cm have not been investigated. In such cases, calculate for a hypothetical simple barrier, i.e., the effect of the overhang of several types of sound-absorbing barriers. The correction term \( C_{\text{dif,emb}} \) for diffraction around an edge-modified barrier is obtained by adding the correction term for slit diffraction, and \( R_{\text{LRTN}} \) [dB] is the sound reduction index of the barrier considering the

\[ \Delta L_{\text{dif,emb}} = \Delta L_{\text{dif,hb}} + C_{\text{dif,emb}}, \]  
\( \text{(3.12)} \)

where \( \Delta L_{\text{dif,hb}} \) is the correction term for diffraction around a hypothetical simple barrier, i.e., \( \Delta L_{\text{dif}} \) [dB] obtained by Eq. (3.3) with the path difference \( \delta \) for diffraction point \( O \) in Fig. 3.8, and \( C_{\text{dif,emb}} \) is the correction term for the acoustic device on the top of the barrier. \( C_{\text{dif,emb}} \) depends on the size and sound reduction mechanism of the device; it is difficult to establish a generalized scheme to calculate this term. The procedure to obtain this term for some edge-modified barriers is presented in Reference R2.

### 3.2.7. Low-height barrier \( \Delta L_{\text{dif,low}} \)

The correction term \( \Delta L_{\text{dif,low}} \) for diffraction around a barrier with a height of 1 m or less in flat terrain is given as the insertion loss of the barrier:

\[ \Delta L_{\text{dif,low}} = \Delta L_{\text{dif,k,1}} - \Delta L_{\text{dif,k,0}}, \]  
\( \text{(3.13)} \)

where \( \Delta L_{\text{dif,k,1}} \) and \( \Delta L_{\text{dif,k,0}} \) are \( \Delta L_{\text{dif}} \) for \( O_1 \) (the top edge of the barrier) and \( O_0 \) (the intersection of the barrier and the ground) shown in Fig. 3.9, respectively.

### 3.2.8. Transmission through barrier \( \Delta L_{\text{dif,trans}} \)

If the transmission through a barrier is considered in the geometry shown in Fig. 3.10, the correction term \( \Delta L_{\text{dif,trans}} \) for the summation of diffraction around a barrier and the transmission is calculated as

\[ \Delta L_{\text{dif,trans}} = 10 \log(10^{\Delta L_{\text{dif,k,1}}/10} + 10^{\Delta L_{\text{dif,slit}}/10}) - R_{\text{LRTN}}/[\text{dB}], \]  
\( \text{(3.14)} \)

where \( \Delta L_{\text{dif,k,1}} \) is \( \Delta L_{\text{dif}} \) for the top edge \( O_1 \), \( \Delta L_{\text{dif,slit}} \) [dB] is the correction term for slit diffraction, and \( R_{\text{LRTN}} \) [dB] is the sound reduction index of the barrier considering the
A-weighted spectra of vehicle running noise. Examples of $R_{A,RTN}$ for typical barrier panels in Japan are given in Table 3.4.

$$\Delta L_{\text{dif,slit}}$$ denotes the energy of sound propagating through the slit opening $O_0-O_1$, corresponding to the barrier with sound reduction index $R_{A,RTN} = 0$ [dB] as shown in Fig. 3.11; this is given as the difference between the sound energies diffracted around two hypothetical barrier tops $O_0$ and $O_1$ as shown in Fig. 3.12,

$$\Delta L_{\text{dif,slit}} = \begin{cases} 10 \lg (10^{\Delta L_{\text{dif,k,0}}/10} - 10^{\Delta L_{\text{dif,k,1}}/10}) & \text{if } SO_1 + O_1P \geq SO_0 + O_0P \cr 10 \lg (10^{\Delta L_{\text{dif,k,0}}/10} - 10^{\Delta L_{\text{dif,k,1}}/10}) & \text{if } SO_1 + O_1P < SO_0 + O_0P \end{cases},$$

$$\Delta L_{\text{dif,k,n}} = \Delta L_{\text{dif,k}}$$ for the diffraction point $O_n$.

Note: It is preferable to apply $R_{A,RTN}$ values measured for actual barrier panels instead of the example values in Table 3.4. Barriers built on-site do not always accomplish the expected effect, which was previously measured in laboratories, because of gaps between the panels and posts.

3.3. Correction for Ground Effect $\Delta L_{\text{grnd}}$

(1) Basic equations

Sound propagated from road traffic to a receiver on the roadside is attenuated owing to the effects of ground surfaces, that is, road surfaces, road slopes, and roadside ground surfaces. The correction term $\Delta L_{\text{grnd}}$ for excess attenuation is calculated as the summation of attenuations due to all surfaces, independently of the type of road surface pavement, as [35]

$$\Delta L_{\text{grnd}} = \sum_{i=1}^{n} \Delta L_{\text{grnd},i},$$

$$\Delta L_{\text{grnd},i} = \begin{cases} -K_i \lg \frac{r_i}{r_c,i} & r_i \geq r_c,i \cr 0 & r_i < r_c,i \end{cases},$$

where $\Delta L_{\text{grnd},i}$ is the correction for attenuation [dB] due to the $i$th ground surface, $K_i$ is the coefficient for the excess attenuation due to the $i$th ground surface, and $r_i$ is the propagation distance [m] over the $i$th ground surface. The attenuation due to the $i$th ground surface is considered only in the range $r_i \geq r_c,i$.

The coefficient $K_i$ and critical distance $r_c,i$ depend on the type of ground surface. Equations for $K_i$ and $r_c,i$ for three typical types of ground surface are described in the following. $\Delta L_{\text{grnd},i} = 0$ [dB] for surfaces paved with asphalt concrete.

Note 1: Ground and meteorological effects are not independent but closely related to each other [36,37]. Therefore, when the propagation distance is long and the calculation value for attenuation due to the ground effect exceeds 30 dB ($\Delta L_{\text{grnd},i} < -30$ dB), $\Delta L_{\text{grnd},i} = -30$ dB, because such a large attenuation as the calculation value does not occur owing to wind and atmospheric turbulence, especially under headwind conditions [38].

Note 2: Equation (3.16) is defined on the basis of excess attenuation calculated for various situations considering sound propagation over homogeneous boundary surfaces with a finite impedance and the average sound power spectrum of noise from vehicles on a dense asphalt pavement [39].

Note 3: It has been confirmed through experiments using loudspeakers on an expressway that excess attenuation over a porous asphalt pavement is equivalent to that over compacted ground [40].
Note 4: Careful attention is required when using the method presented in Section 3.3. If the ground surface is divided finely, the propagation distance on each ground surface does not reach the critical distance \( r_{c,i} \), and excess attenuation does not occur. A simple calculation method [41] that approximates the cumulative excess attenuation for the subdivision of the ground surface has been proposed.

Note 5: Diffraction and ground effects are not independent but closely related to each other. When a barrier is installed at a roadside, the diffraction effect increases whereas the ground effect decreases because the height of the propagation path increases. The ground effect in such a case is calculated as the sum of the correction terms due to the two ground surfaces on both sides of the barrier. If the reflection from the ground cannot be ignored at the prediction point behind the barrier due to the pavement surface and others, the reflected sound from the ground is added assuming specular reflection (see Appendix A5).

(2) Coefficient for excess attenuation due to ground \( K_i \)

The coefficient \( K_i \) in Eq. (3.17) is calculated for each ground surface as a function of the average height of the propagation path \( H_{a,i} \) [m] [42].

1) Loose soil

\[
K_i = \begin{cases} 
3.93\sqrt{H_{a,i} + 0.081} + 15.1 & 0.6 \leq H_{a,i} < 1.5 \\
20.0 & H_{a,i} \geq 1.5 
\end{cases}
\]

(3.18)

2) Grassland

\[
K_i = \begin{cases} 
6.98\sqrt{H_{a,i} - 0.537} + 9.85 & 0.6 \leq H_{a,i} < 1.5 \\
2.48\sqrt{H_{a,i} - 1.42} + 16.0 & 1.5 \leq H_{a,i} < 4.0 \\
20.0 & H_{a,i} \geq 4.0 
\end{cases}
\]

(3.19)

3) Compacted ground and porous asphalt pavement

\[
K_i = \begin{cases} 
4.97H_{a,i} - 0.472H_{a,i}^2 + 5.0 & 0.6 \leq H_{a,i} < 3.0 \\
1.53\sqrt{H_{a,i} - 2.94} + 15.3 & H_{a,i} \geq 3.0 
\end{cases}
\]

(3.20)

The average height of the propagation path \( H_{a,i} \) is defined as the average of the two heights \( H_{i-1} \) and \( H_i \) at both ends of the considered ground surface along the shortest propagation path, as shown in Fig. 3.13. When \( H_{a,i} \) is less than 0.6 m, \( H_{a,i} = 0.6 \).

\[
H_{a,i} = \begin{cases} 
\frac{1}{2} (H_{i-1} + H_i) & H_{i-1} + H_i \geq 1.2 \\
0.6 & H_{i-1} + H_i < 1.2 
\end{cases}
\]

(3.21)

(3) Critical distance for excess attenuation due to the ground \( r_{c,i} \)

The critical distance \( r_{c,i} \) for excess attenuation due to the ground is calculated as

\[
r_{c,i} = g(Z) \cdot (H_{a,i})^{f(Z)},
\]

where \( Z_i \) is given by

\[
Z_i = \frac{|H_{i-1} - H_i|}{(H_{i-1} + H_i)}
\]

(3.22)

using the two heights \( H_{i-1} \) and \( H_i \) at both ends of the considered ground surface. \( f(Z) \) is a function of \( Z \) as follows:

Fig. 3.13  Heights of propagation paths for various terrains.
1) Loose soil

\[
f(Z_i) = \begin{cases} 
2.09 & 0.0 \leq Z_i < 0.4 \\
2.09 - 0.124(Z_i - 0.4) & 0.4 \leq Z_i < 0.8 \\
+0.711(Z_i - 0.4)^2 & \\
-2.47(Z_i - 0.4)^3 & \\
2.00 - 1.72(Z_i - 0.8) & \\
+21.6(Z_i - 0.8)^2 & 0.8 \leq Z_i \leq 1.0 \\
-189(Z_i - 0.8)^3 & 
\end{cases}
\]

(3.24)

2) Grassland

\[
f(Z_i) = \begin{cases} 
2.3 & 0.0 \leq Z_i < 0.4 \\
2.3 - 0.387(Z_i - 0.4) & 0.4 \leq Z_i < 1.0 \\
+0.920(Z_i - 0.4)^2 & \\
-5.47(Z_i - 0.4)^3 & 
\end{cases}
\]

(3.25)

3) Compacted ground and porous asphalt pavement

\[
f(Z_i) = \begin{cases} 
2.3 & 0.0 \leq Z_i < 0.2 \\
2.3 + 0.170(Z_i - 0.2) & 0.2 \leq Z_i \leq 1.0 \\
-1.38(Z_i - 0.2)^2 & \\
-0.648(Z_i - 0.2)^3 & 
\end{cases}
\]

(3.26)

\[g(Z_i) = \text{Eq. (3.22)} = a + bZ_i + cZ_i^2 + dZ_i^3,\]

(3.27)

where the values of coefficients \(a, b, c,\) and \(d\) in this equation for each type of ground are listed in Table 3.5. Note that \(r_{ij}\) for \(H_{ij} < 1.1\) over a compacted ground surface or porous asphalt pavement is calculated as

\[r_{ij} = g(Z_i) \cdot (1.1)^{f(Z_i)} \cdot 10^{(H_{ij} - 1.1) h(Z_i)},\]

(3.28)

where

\[h(Z_i) = 0.517 - 0.0592Z_i - 1.30Z_i^2 + 1.19Z_i^3.\]

(3.29)

3.4. Correction for Atmospheric Absorption \(\Delta L_{\text{air}}\)

The correction term \(\Delta L_{\text{air}}\) for attenuation due to atmospheric acoustical absorption is calculated considering the standard state of the atmosphere (temperature: 20°C, relative humidity: 60%, static pressure: 101.325 kPa) as

\[\Delta L_{\text{air}} = -6.84\left(\frac{r}{1000}\right) + 2.01\left(\frac{r}{1000}\right)^2 - 0.345\left(\frac{r}{1000}\right)^3,\]

(3.30)

where \(r\) is the distance from the source to the prediction point [m].

Note: Equation (3.30) is derived from the method of calculating atmospheric acoustical absorption defined in ISO 9613-1:1993 by applying a spectrum model for noise from vehicles running in the steady state on dense asphalt concrete [43]. If it is necessary to predict different atmospheric states from the standard state, \(\Delta L_{\text{air}}\) can be calculated from the attenuation values obtained by using equations for atmospheric absorption at a single frequency (see Appendix A5.3.1) and the frequency characteristics of the noise from a running vehicle (see Appendix A1). See Appendix A5.3.2.

3.5. Calculation of Sound Reflection

Sound reflection is significant and not negligible in the prediction of sound propagation around depressed/semi-underground roads and roads under viaducts. Specular reflection is considered if the reflecting surface is flat and of sufficient size. For uneven surfaces, scattered reflection is considered.

3.5.1. Specular reflection

(1) Basic equation

A semi-infinite flat reflecting surface is considered as shown in Fig. 3.14(a); the source \(S\) and prediction point \(P\) are located away from the end \(O\) of the reflecting surface. The reflection in this situation is equivalently considered as the contribution from a mirror-image source \(S'\) diffracted around a hypothetical absorbing barrier, which is set complementarily to the original reflecting surface, as shown in Fig. 3.14(b). The specular reflection is calculated as

\[L_{\text{A, refl}} = L_{\text{WA}} - 8 - 20 \log r + \Delta L_{\text{refl}} + \Delta L_{\text{abs}},\]

(3.31)

where \(L_{\text{A, refl}}\) is the A-weighted sound pressure level of the reflected sound [dB], \(r\) is the direct path length from \(S'\) to \(P\) [m], \(\Delta L_{\text{refl}}\) is the correction for the finiteness of the size of the reflecting surface [dB] (referred to as the “correction for reflection” hereafter), and \(\Delta L_{\text{abs}}\) is the correction for the absorbing characteristics of the reflecting surface [dB] (see Subsection 3.5.3).

(2) Correction for reflection \(\Delta L_{\text{refl}}\)

The calculation of \(\Delta L_{\text{refl}},\) using a fundamental correction term for reflection \(\Delta L_r,\) is described below.

1) Fundamental correction term for reflection \(\Delta L_r\)

\(\Delta L_r\) is calculated as a function of the path difference \(\delta\) [m] between the diffraction path \(S'P\) and the direct path \(SP:\)

\[\Delta L_r = \begin{cases} 
-20 - 10 \log (c_{\text{spec}} \delta) & c_{\text{spec}} \delta \geq 1 \\
-3 - 19.3 \cdot \sinh^{-1}((c_{\text{spec}} \delta)^{0.33}) & 0 \leq c_{\text{spec}} \delta < 1 
\end{cases}\]

(3.32)
The values in Table 3.2 are applied to the coefficient $c_{\text{spec}}$. $L_r$ is shown as a function of $\delta$ in Fig. 3.15.

Note: Energy complementarity is assumed in Eq. (3.32) [44].

2) Correction term for reflection from a semi-infinite plane $\Delta L_{\text{refl,semi}}$

The correction term $\Delta L_{\text{refl,semi}}$ for reflection from a semi-infinite plane in Fig. 3.14(a) is calculated considering the hypothetical barrier as shown in Fig. 3.14(b). For $S'$ invisible from $P$ in Fig. 3.14(b),

$$\Delta L_{\text{refl,semi}} = \Delta L_r; \quad (3.33)$$

otherwise, for $S'$ visible from $P$ in Fig. 3.14(b),

$$\Delta L_{\text{refl,semi}} = 10 \lg(1 - 10^{\Delta L_r/10}). \quad (3.34)$$

3) Correction term for reflection from a finite-width plane $\Delta L_{\text{refl,slit}}$ (slit method)

As shown in Fig. 3.16(a), consider a source $S$, prediction point $P$, and flat reflective plane $O_1$–$O_2$ with a finite width and an infinite length (i.e., a strip). The reflected sound from the strip is equivalently considered as the contribution from a mirror-image source $S'$ to prediction point $P$ through slit opening $O_1$–$O_2$ with the same width as the strip (see Fig. 3.16(b)).
The energy of sound passing through the slit opening is calculated as the difference between the energies of sounds diffracted around the two hypothetical barriers shown in Fig. 3.16(c). The correction term $\Delta L_{\text{refl}, \text{slit}}$ is calculated as

$$\Delta L_{\text{refl}, \text{slit}} = 10 \log \left| 10^{\Delta L_{\text{refl},1}/10} - 10^{\Delta L_{\text{refl},2}/10} \right|, \quad (3.35)$$

where $\Delta L_{\text{refl},1}$ is defined as $\Delta L_{\text{refl}, \text{semi}}$ for $O_1$ using Eq. (3.33) and $\Delta L_{\text{refl},2}$ is defined as $\Delta L_{\text{refl}, \text{semi}}$ for $O_2$ using Eq. (3.34).

4) Reflection from a rectangular plane $\Delta L_{\text{refl, rect}}$

Reflection from a rectangular plane such as an exterior wall around a building is calculated as the contribution from a mirror-image source $S'$ to prediction point $P$ through an opening in an infinite screen that is equivalent to the rectangular plane.

As shown in Fig. 3.17, consider a hypothetical infinite screen with a rectangular opening $\Gamma_0$; the surface of the screen is divided into eight segments, $\Gamma_1$ to $\Gamma_8$, with four lines that include the four sides of the opening. $D_{ijk}$ is defined as the summation of the sound contributions from regions $\Gamma_i$, $\Gamma_j$, and $\Gamma_k$. The correction term for the reflection $\Delta L_{\text{refl, rect}}$ [dB] is calculated as a decibel conversion of the ratio of energy passing through the rectangular opening $(\text{region } \Gamma_0)$ to the energy passing through all regions [44]:

$$\Delta L_{\text{refl, rect}} = 10 \log D_0 = 10 \log (1 - D_{1-8}), \quad (3.36)$$

where $D_0$ is the relative contribution through region $\Gamma_0$, and $D_{1-8}$ is the relative contribution through regions $\Gamma_1$ to $\Gamma_8$, i.e., $D_0 + D_{1-8} = 1$. $D_{1-8}$ is calculated as

$$D_{1-8} = D_{123} + D_{678} + D_4 + D_5,$$

$$D_4 = (1 - D_{123} - D_{678}) \times D_{146},$$

$$D_5 = (1 - D_{123} - D_{678}) \times D_{358},$$

$$D_{ijk} = 10 \Delta L_{\text{refl, ijk}}/10,$$  

where $\Delta L_{\text{refl, ijk}}$ is $\Delta L_{\text{refl}}$ for the situation with regions $i$, $j$, and $k$ open and the other regions closed and is calculated using Eqs. (3.33) and (3.34).

3.5.2. Scattered reflection

A method of calculating scattered reflection from an uneven surface, such as the underside of a viaduct with a girder structure, is presented here assuming Lambert’s cosine law [45,46]. As shown in Fig. 3.18, point source $S$, prediction point $P$, and reflecting surface $B$ are located in a hemi-free field above the ground. Vector $n$ denotes the normal of the small element $\Delta \sigma$ of the reflecting surface $B$. The A-weighted sound pressure level at $P$, $L_{A, \text{refl}}$ [dB], of the sound reflected from the whole reflecting surface is calculated as

$$L_{A, \text{refl}} = L_{W_A} - 16$$

$$+ 10 \log \int_B \frac{\cos \theta \cos \psi}{r^2 R^2} \, d\sigma + \Delta L_{\text{abs}}, \quad (3.41)$$

where $\theta$ and $\Psi$ are the incidence and reflection angles at the reflecting surface $B$, $r$ and $R$ are the distances from the center of the small element $\Delta \sigma$ to the point source $S$ and prediction point $P$ [m], respectively, and $\Delta L_{\text{abs}}$ is the correction term for sound absorption of the reflecting surface $B$ [dB].

To numerically execute the integration in Eq. (3.41), the reflecting surface $B$ is divided into $N$ elements $B_i$ $(B_i \in B$, $i = 1$ to $N)$, and $L_{A, \text{refl}}$ is calculated using the following equation:

$$L_{A, \text{refl}} = L_{W_A} - 16$$

$$+ 10 \log \sum_{i=1}^N \frac{S_i \cos \theta_i \cos \psi_i}{r_i^2 R_i^2} + \Delta L_{\text{abs}}, \quad (3.42)$$

where $S_i$ is the area of $B_i$ [m$^2$], and $r_i$, $R_i$, $\theta_i$, and $\psi_i$ are $r$, $R$, $\theta$, and $\Psi$ for the center of $B_i$, respectively.

Note 1: When the reflection angle $\Psi$ approaches $90^\circ$, the energy of the reflected sound approaches zero in Eq. (3.41) owing to $\cos \Psi \approx 0$, leading to a significant error; careful attention is required.

Note 2: Equations (3.41) and (3.42) are those for a free field. When the sound source is on a road surface (in a hemi-free field), the constant “$-16$” in the equations is replaced with “$-13$.”

Note 3: There is a method of calculating reflection from a rectangular scattering surface using the angle of view [47].

---

**Fig. 3.17** Calculation of reflection from a rectangular plane (region $\Gamma_0$).

**Fig. 3.18** Scattered reflection method.
3.5.3. Correction for sound absorption $\Delta L_{\text{abs}}$

The correction term for sound absorption $\Delta L_{\text{abs}}$ is calculated as

$$\Delta L_{\text{abs}} = 10 \log (1 - \alpha_{\text{ARTN}}), \quad (3.43)$$

where $\alpha_{\text{ARTN}}$ is the absorption coefficient considering the spectrum of typical road traffic noise. A measured value of $\alpha_{\text{ARTN}}$ is preferred; the typical values of the average absorption coefficient against oblique incidence [48] in Table 3.6 are applicable if the measured values of $\alpha_{\text{ARTN}}$ are not provided.

3.6. Meteorological Effect

The methods of calculating sound propagation presented above are those in a homogeneous atmosphere with no wind. In reality, however, meteorological factors such as wind, temperature gradient, and atmospheric turbulence affect sound propagation. According to numerical analyses, the effect of barriers changes owing to the effect of wind, and it may not be as effective as when there is no wind [38]. The change in $L_{\text{Aeq}}$ due to the effect of wind, $\Delta L_{\text{m,line}}$, [dB], for a straight road is estimated independently of the road structure, the presence of noise barriers, and the ground surface condition as

$$\Delta L_{\text{m,line}} = \begin{cases} 0.88 \log \left( \frac{l}{15} \right) \cdot U_{\text{vec}} & l > 15 \\ 0 & l \leq 15 \end{cases}, \quad (3.44)$$

where $l$ is the horizontal distance from the center of the road to the prediction point [m] and $U_{\text{vec}} = U \cos \theta$ is the vector component of the average wind speed $U$ [m/s] for angle $\theta$ between the wind direction and the line perpendicular to the road through the prediction point. $U_{\text{vec}}$ is positive in the downwind direction and negative in the upwind direction.

Examples of $\Delta L_{\text{m,line}}$ obtained from Eq. (3.44), rounded to the nearest 0.5 dB, are given in Table 3.7.

| Materials                                      | $\alpha_{\text{ARTN}}$ |
|-----------------------------------------------|------------------------|
| Absorptive panels covering bottom surfaces     | 0.90                   |
| of viaducts                                   |                        |
| Absorptive panels covering side surfaces      | 0.85                   |
| of depressed roads                            |                        |
| Absorptive panels (standard metallic absorptive type) | 0.75                  |
| Absorptive materials on exterior walls of     | 0.75                   |
| buildings                                      |                        |
| Absorptive materials covering bridge columns  | 0.70                   |
| Absorptive panels covering side surfaces of   | 0.70                   |
| roadside grass planters                       |                        |
| Concrete, dense asphalt                       | 0.00–0.02              |

Table 3.6 Typical values of absorption coefficient.

| Vector wind speed $U_{\text{vec}}$ [m/s] | Distance from road center $l$ [m] | $\Delta L_{\text{m,line}}$ [dB] |
|------------------------------------------|----------------------------------|---------------------------------|
| 50                                       | 50                               | $\pm1$                          |
| 100                                      | 50                               | $\pm0.5$                        |
| 200                                      | 50                               | $\pm1.0$                        |
| $\pm3$                                   | $\pm0.5$                         | $\pm1.5$                        |
| $\pm5$                                   | $\pm2.0$                         | $\pm3.0$                        |
| $\pm2.5$                                 | $\pm3.5$                         | $\pm5.0$                        |

Note: Equation (3.44) is tentatively given on the basis of on-site measurements of road traffic noise after consideration of empirical equations derived from experiments on the effect of wind in propagation around a point source [49].

4. NOISE AT SPECIAL ROAD SECTIONS

At special road sections, including interchanges, junctions, signalized intersections, tunnels, depressed roads, semi-underground roads, flat roads with overhead viaducts and double-deck viaducts, the road structure and traffic flow are very complicated. For the calculation of road traffic noise, special treatment is required. The following methods are applied to individual road sections.

4.1. Interchanges

Interchange sections consist of a main road and a ramp with varying horizontal and vertical alignments. At the branch section, where the main road and ramp are connected, vehicles decelerate to leave or accelerate to join the main traffic flow. At the tollgate in the interchange, vehicles decelerate, stop (or move slowly), and accelerate. Generally, the geometrical configuration of the interchange and the traffic flow are complicated (see Fig. 4.1). The noise calculation method at interchange sections was developed as a result of research based on the above characteristics and is described in the following.

4.1.1. Calculation procedure

Since the speed of vehicles at an interchange, including the tollgate, depends on their position on the road, the method of calculating a unit pattern is slightly more complicated than that for general roads. First, the sound power level corresponding to the running condition at each discrete source position is calculated by the method described in Chapter 2. Then, the sound propagation from each source to a prediction point is calculated by the method described in Chapter 3. As a result of the calculation, a unit pattern as a function of time is obtained by taking the relationship between the vehicle running position and the elapsed running time into consideration. As an example, a schematic illustration of the position of a vehicle, the running condition and speed, the emitted sound power level, and the unit pattern in the vicinity of a tollgate is shown in Fig. 4.2 for a vehicle moving from a main road
to a branch road through a ramp and tollgate with variable running speed. To obtain the unit pattern as a function of time, it is necessary to provide a time history as shown in this figure. The unit pattern is calculated by setting the position of the vehicle, its initial speed, acceleration, final speed, and standstill time. The method for the calculation of $L_{Aeq}$ from the obtained unit pattern is the same as that for general roads.

### 4.1.2. Acceleration of vehicles

When a vehicle accelerates or decelerates at an interchange, the values of acceleration shown in Table 4.1 are applied [6,50]. For the acceleration of motorcycles, the values for passenger cars are applied.

### 4.1.3. Service time at tollgate

The service time at a tollgate is defined as the standstill time for vehicles, which is required for issuing tickets at the entrance and collecting fare at the exit. The values indicated in Table 4.2 are applied [51].

**Note:** If an Electronic Toll Collection (called ETC in Japan) system is installed at the tollgate, the acceleration and passing speed through the tollgate, which are set on the basis of *in-situ* measurement results, are used [52].

### 4.2. Junctions

Here, a junction is defined as a road section where vehicles are joining or leaving a traffic flow while accelerating or decelerating. An example is shown in Fig. 4.1, where the ramp of an expressway is connected with a general road. The noise calculation method is the same as that used when vehicles join or leave a main road through a ramp in an interchange.
The sound power levels under accelerating or decelerating running conditions are calculated by the method described in Item (2) of Subsection 2.2.3. When a vehicle accelerates or decelerates, fixed values of acceleration of 0.4 m/s² when accelerating and −1.3 m/s² when decelerating are applied regardless of the vehicle type.

**Note:** The above value of acceleration when accelerating was obtained by an investigation involving in-situ measurements. As the value of acceleration when decelerating, the value obtained by in-situ measurements in the vicinity of signalized intersections (see Appendix A7) is expediently used.

### 4.3. Signalized Intersections

Along an urban road, there are many signalized intersections, and an individual vehicle must repeatedly start from rest at a green (go) signal, accelerate to a constant speed, then decelerate until it stops at a red (stop) signal. The traffic flow of such a road is clearly under a non-steady running condition. The noise at a signalized intersection with two straight roads crossing each other, as shown in Fig. 4.3, is calculated by a simple method, in which $L_{eq}$ for each road is calculated on the basis of a non-steady traffic flow, and the results are summed in energy [53].

**Note:** In the vicinity of an actual signalized intersection, the running condition of an individual vehicle changes as the signal phase changes. Corresponding to the change in the running behavior, the sound power level of the vehicle varies considerably. Therefore, if one studies the effect of the signal phase on the noise level in detail, it may be important to consider the running behaviors of individual vehicles in the noise calculation. In this case, one can apply the practical method [54] that calculates the noise in the vicinity of the signalized intersection from the unit pattern of an individual vehicle, or the simplified method [54], which is a simplification of the practical method. These calculation methods are outlined in Appendix A7.

### 4.4. Road Tunnels

In this calculation model, vehicle noise radiated from a tunnel portal (portal sound) is modeled by the summation of two sound contributions, i.e., direct sound from a vehicle in a tunnel and indirect sounds that represent multiple-reflected and diffused sounds inside the tunnel. The former is assumed to be radiated from an equivalent point source in a tunnel through the portal, and the latter is assumed to be radiated from an equivalent plane source that has a size corresponding to that of the portal surface [55].

**Note:** This calculation model is basically applicable to portals with a semicircular or rectangular shape; however, its applicability to portals with other shapes is being studied [56]. This model can also be applied to a tunnel whose inside is composed of sections with different absorption coefficients.

#### 4.4.1. Calculation procedure

When a single vehicle is running in a tunnel, as shown in Fig. 4.4, the A-weighted sound pressure level $L_A$ [dB] observed in the area surrounding the portal is calculated as

$$L_A = 10 \log (10^{L_{A, TD}/10} + 10^{L_{A, TR}/10}),$$

(4.1)

where $L_{A, TD}$ is the A-weighted sound pressure level of the direct sound from an equivalent point source [dB] and $L_{A, TR}$ is that of other reflected and diffused sounds (equivalent plane source) [dB].

$L_{A, TD}$ is calculated using the basic equation for propagation calculation given in Section 3.1 as

$$L_{A, TD} = L_{WA} - 8 - 20 \log r + \Delta L_{dif} + \Delta L_{grnd},$$

(4.2)

where $L_{WA}$ is the A-weighted sound power level of the running vehicle [dB], $r$ is the direct distance from the equivalent point source to the prediction point [m], $\Delta L_{dif}$ is the correction for sound diffraction at the portal edge [dB], and $\Delta L_{grnd}$ is the correction for the ground effect [dB].

$L_{A, TR}$ is obtained by dividing the equivalent plane source into approximately 10 elements having the same area, substituting a point source for each element, and then summing the energies of the A-weighted sound pressure levels $L_{A, TR,i}$ from each point source:

$$L_{A, TR} = 10 \log \left( \sum_{i=1}^{N} 10^{(l_{A, TR,i}/10)} \right),$$

(4.3)
The sound power level of the equivalent plane source is calculated using Eq. (4.5) with the real distance x [m] along the lane from the tunnel portal to the real point source [57]. The values in Table 4.3 are used for $n_a$ and $n_b$. $N$ is the number of elements into which the plane source is divided, $L_{W_A,R}$ is the A-weighted sound power level of the plane source [dB], and $L'_{W_A,R}$ is the A-weighted sound power level when the divided elements of the plane source are considered as point sources [dB].

### 4.4.4. Location and sound power level of equivalent point source

The sound power level of the equivalent point source is specified as that of the actual sound source (running vehicle), and its position $x'$ (distance from the portal) [m] is calculated by applying the parameter related to absorption in the tunnel, $a$, and the actual distance from the portal to the vehicle $x$ [m] as

$$x' = ax.$$  \tag{4.7}

If the tunnel is composed of several sections with different absorption coefficients, $a$ is calculated as

$$a = \frac{\sum_{i=1}^{n} a_i x_i}{\sum_{i=1}^{n} x_i},$$  \tag{4.8}

where $a_i$ is the parameter related to absorption in the $i$th section and $x_i$ is the length of the $i$th section [m].

The sound power level of the equivalent plane source $L_{W_A,R}$ [dB] set at the portal plane position is calculated by subtracting the A-weighted sound power $P_{A,D}$ [W] of the sound radiated as direct sound from the A-weighted sound power $P_{A,T}$ [W] of all sound radiated from the portal. It is calculated as

$$L_{W_A,R} = 10\log\left(\frac{P_{A,T} - P_{A,D}}{10^{-12}}\right).$$  \tag{4.9}

If the tunnel has a semicircular portal with radius $h$ [m], $P_{A,T}$ and $P_{A,D}$ are calculated as

$$P_{A,T} = \frac{P_A}{2} \left\{ 1 - \frac{ax}{\sqrt{h^2 + (ax)^2}} \right\},$$  \tag{4.10}

$$P_{A,D} = \frac{P_A}{2} \left\{ 1 - \frac{x}{\sqrt{x^2 + h^2}} \right\}.$$  \tag{4.11}

Where $P_A$ is the A-weighted sound power of the actual source [W].

If the tunnel has a rectangular portal with width $2w$ [m] and height $h$ [m], $P_{A,T}$ and $P_{A,D}$ are calculated as

$$P_{A,T} = \frac{P_A}{\tan^{-1} \left( \frac{wh}{\sqrt{ax^2 + (w^2 + h^2) \cdot (ax)^2}} \right)},$$  \tag{4.12}

$$P_{A,D} = \frac{P_A}{\tan^{-1} \left( \frac{wh}{\sqrt{x^4 + (w^2 + h^2) \cdot x^2}} \right)}.$$  \tag{4.13}

### 4.4.3. Parameter related to absorption inside a tunnel

For the parameter related to sound absorption inside a tunnel $a$, the values shown in Table 4.4 are applied depending on the type of pavement on the road surface.

| Wall surface condition | Dense asphalt | Drainage asphalt |
|------------------------|---------------|-----------------|
| Without absorption measure | 0.04          | 0.1             |
| Absorption measure on sidewalls | —             | 0.4             |
| Absorption measure on entire wall | 0.6           | —               |

*Note:* The relationship between $a$ and the mean absorption coefficient of the inner wall of a tunnel $\alpha_{A,RTN}$ (refer to Subsection 3.5.3) has been investigated, and the value of $a$ can be estimated by applying the mean absorption coefficient $\alpha_{A,RTN}$ [55,56].

### 4.5. Depressed and Semi-Underground Roads

A depressed road is defined as a road whose surface is lower than the surrounding ground and has artificial sidewall structures (retained walls). If a depressed road has a horizontal overhang structure on the ceiling, it is referred to as a semi-underground road in this model. On a depressed road, multiple sound reflections may occur between sidewalls. In contrast, on a semi-underground road, multiple sound reflections tend to occur in the space surrounded by the road surface, the sidewalls, and the ceiling. To calculate sound propagation from a depressed/semi-underground road with these characteristics, several methods can be used. Among these methods, a calculation method using a slit method (image source method) and a
simple method assuming a directional point source model are provided here. If a more precise prediction is required, wave-based numerical analysis (see Appendix A6) or a scale-model experiment [22] is available.

Note: Correction for the noise mitigation effect of absorptive louvers [58], which are installed on the aperture of a semi-underground road, is applicable only for the simple calculation method using a directional point source model.

4.5.1. Slit method (image source method)

(1) Scope

The slit method is applied to depressed roads and semi-underground roads where the width of the aperture above the road is at least approximately 75% of the road width.

(2) Basic equations

As shown in Fig. 4.5, the actual source is denoted as \( S_0 \), and mirror-image sources, which are the origins of sound sources reflected by the sidewalls, are denoted as \( S_1 \) to \( S_n \). The A-weighted sound pressure level \( L_A \) [dB] at prediction point \( P \) is calculated as

\[
L_A = 10 \log_{10} \left[ 10^{L_{A,0}/10} + \sum_{i=1}^{N} (1 - \alpha_{A,RTN})^i \cdot 10^{L_{A,i}/10} \right].
\]

(4.14)

where \( L_{A,0} \) is the contribution to the A-weighted sound pressure level of the actual source [dB], which is calculated using Eq. (3.1). \( L_{A,i} \) is the contribution to the A-weighted sound pressure level of the \( i \)th mirror-image source [dB], \( n \) is the number of mirror-image sources (number of reflections), and \( \alpha_{A,RTN} \) is the absorption coefficient of the sidewalk surface (see Subsection 3.5.3).

The contribution from a mirror-image source \( L_{A,i} \) is calculated as

\[
L_{A,i} = L_{WA} - 8 - 20 \log r_i + \Delta L_{cor,i} + \Delta L_{refl,slit,i}.
\]

(4.15)

where \( L_{WA} \) is the A-weighted sound power level of a running vehicle [dB], \( r_i \) is the distance from the \( i \)th mirror-image source to the prediction point [m]. \( \Delta L_{cor,i} \) is the correction for sound attenuation during the propagation from the \( i \)th mirror-image source to the prediction point [dB], and \( \Delta L_{refl,slit,i} \) is the correction for the reflection at a slit part against the \( i \)th mirror image source [dB] (refer to Section 3.5).

Note: In the calculation of the slit method, since the convergence will be slow even if the number of reflections is increased, one can end at an appropriate number of reflections, but at least two reflections must be used.

4.5.2. Simple calculation method using a directional point source model

(1) Scope

This calculation method is applied to the case where both left and right sides of the cross section of a semi-underground road are symmetric, and the traffic flows (composition of vehicle classification and traffic volume) on the lanes with traffic moving in opposite directions are almost equivalent.

(2) Basic equations

The A-weighted sound pressure level \( L_A \) observed at prediction point \( P \) is calculated by considering propagation in a hemi-free field and an equivalent directional point source located at the center of an aperture (see Fig. 4.6) as

\[
L_A = L_{WA} + 10 \log \left( a + (1 - a) \cos^m \theta \phi \right) - 8 - 20 \log r,
\]

(4.16)

\[
m(\theta) = n_{max} \sin^\beta \theta,
\]

(4.17)

where \( a, n_{max} \), and \( \beta \) are parameters for the directivity of each equivalent point source and \( r \) is the distance from the equivalent point source \( S' \) to prediction point \( P \) [m]. \( L_{WA} \) is the apparent sound power level of the equivalent directional point source \( S' \) determined from the direction of \( \phi = 0 \) [deg] in the coordinate system shown in Fig. 4.6, given by

\[
L_{WA} = L_{WA} + \Delta L_{dim,su} + \Delta L_{dir,su} + \Delta L_{dir,slit} + L_{fouler}.
\]

(4.18)

where \( L_{WA} \) is the A-weighted sound power level of a running vehicle [dB], \( \Delta L_{dim,su} \) is the correction for the dimensions of a semi-underground road structure [dB], \( \Delta L_{dir,su} \) is the correction for the directivity of an equivalent source, \( \Delta L_{abs,su} \) is the correction for the absorption in a

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**Fig. 4.5** Actual source and mirror-image source groups of a depressed road.

**Fig. 4.6** Coordinate system for calculation of semi-underground roads.
semi-underground road [dB], and $\Delta L_{\text{louver}}$ is the correction for the noise mitigation effect of absorptive louvers when the louvers are installed on the aperture of a semi-underground road [dB].

$\Delta L_{\text{dim, su}}$ is calculated using the absorption coefficient of the road surface $\alpha_{\text{A,RTN}}$ considering the spectrum of typical road traffic noise, the width of the road $L$ [m], the width of the aperture $W$ [m], and the height $H$ [m] (see Fig. 4.6) as [59]

$$
\Delta L_{\text{dim, su}} = 10 \log \left\{ \frac{2}{\pi} \tan^{-1} \left( \frac{W}{2H} + \frac{\pi WH}{3L^2} \right) + \frac{(L - W)(1 - \alpha_{\text{A,RTN}})W}{[L\alpha_{\text{A,RTN}} + (1 - \alpha_{\text{A,RTN}})W]L} \right\}. \tag{4.19}
$$

The values given in Table 4.5 for $a$, $n_{\text{max}}$, $\beta$, and $\Delta L_{\text{dir, su}}$ for each dimension are applied, which are derived from the results of scale-model experiments and numerical analysis based on wave theory [60,61]. The value for $\alpha_{\text{A,RTN}}$ is 0 for a dense asphalt pavement. In the case of a porous asphalt pavement, values determined on the basis of in-situ measurement results are used as $\alpha_{\text{A,RTN}}$ [62]. The value for $\Delta L_{\text{louver}}$ is 0 dB when the wall surface of the inner structure has a reflective finish and $-1$ dB when it has an absorptive finish. An example of a directivity pattern calculated using the values in Table 4.5 is shown in Fig. 4.7. The value for $\Delta L_{\text{louver}}$ is 0 dB when no absorptive louvers are installed. When louvers are installed, the value determined based on the results of in-situ measurement and scale model experiment is used [63].

### (3) Correction for diffraction by noise barriers

If a noise barrier is installed in the vicinity of an aperture of a semi-underground road, the A-weighted sound pressure level $L_A$ [dB] at prediction point $P$ is calculated as

$$
L_A = L_{\text{A,RTN}} + \Delta L_{\text{dir, su}} + \Delta L_{\text{louver}},
$$

where $L_{\text{A,RTN}}$ is the A-weighted sound pressure level at the reference point, $\Delta L_{\text{dir, su}}$ is the correction for directivity, and $\Delta L_{\text{louver}}$ is the correction for the noise mitigation effect of absorptive louvers when the louvers are installed on the aperture of a semi-underground road.

### Table 4.5 Parameters for directivity of equivalent point source.

| Road width | Overhang length | Aperture width (as percentage) | Inner structure of semi-underground road has a reflective finish | Inner structure of semi-underground road has an absorptive finish |
|------------|-----------------|--------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
|            |                 |                                | $a$ $n_{\text{max}}$ $\beta$ $\Delta L_{\text{dir, su}}$ [dB] | $a$ $n_{\text{max}}$ $\beta$ $\Delta L_{\text{dir, su}}$ [dB] |
| 20 m       | 1 m             | 5 m (25%)                      | 0.15 1.4 1.7 1.61 | 0.05 2.0 1.2 2.68 |
|            |                 | 7.5 m (37.5%)                  | 0.15 1.2 1.7 1.45 | 0.05 2.0 1.2 2.68 |
|            |                 | 10 m (50%)                     | 0.15 1.0 2.0 1.20 | 0.05 2.1 1.2 2.77 |
|            | 4 m             | 5 m (25%)                      | 0.13 1.5 2.0 1.62 | 0.03 1.9 1.1 2.77 |
|            |                 | 7.5 m (37.5%)                  | 0.13 1.5 2.0 1.40 | 0.03 2.1 0.9 3.15 |
|            |                 | 10 m (50%)                     | 0.13 1.2 2.0 1.20 | 0.05 2.1 1.2 2.77 |
| 30 m       | 1 m             | 5 m to 7.5 m (16.7% to 25%)    | 0.15 1.6 2.2 1.58 | — — — — |
|            |                 | 10 m (33%)                     | 0.15 1.2 2.0 1.36 | — — — — |
|            |                 | 15 m (50%)                     | 0.15 1.0 2.0 1.20 | — — — — |
|            | 4 m             | 5 m to 7.5 m (16.7% to 25%)    | 0.12 1.6 2.2 1.65 | — — — — |
|            |                 | 10 m (33%)                     | 0.12 1.2 2.0 1.42 | 0.03 1.9 1.0 2.99 |
|            |                 | 15 m (50%)                     | 0.12 1.0 2.0 1.25 | 0.03 2.0 1.0 3.09 |

Fig. 4.7 Example of radiation directivity of noise (road width: 20 m, overhang width: 4 m, aperture width: 7.5 m, reflective finish inside).
where $L'_A$ is the A-weighted sound pressure level calculated at hypothetical prediction point $P'$ [dB]; $P'$ is located in the direction from $S'$ to the top edge of a noise barrier $O$ (diffraction point) and $S'P = S'P'$ (see Fig. 4.8). $\Delta L_{\text{dif, sb}}$ is the correction for diffraction calculated with the path difference $\delta$ [m], determined from the path from $S'$ to $P$ through $O$ [dB].

**Note:** If a semi-underground road with an identical cross section is straight for a sufficient length, discrete equivalent point sources in line can be treated as a line source. From this concept, a method for providing directivity as a function of only $\varphi$ is being studied [64].

**4.6. Flat Roads with an Overhead Viaduct, Double-Deck Viaducts**

**4.6.1. Types of underside of viaduct and calculation methods**

The underside of a viaduct may have a smooth and flat shape, or an uneven shape, as shown in Fig. 4.9. Depending on the shape of the underside, either the slit method or the scattered reflection method is applied, as described next. For ordinal noise calculation, the former method is generally applied, while the latter is applied if the unevenness is not negligible [46,65]. These methods are applicable to the cases in which a noise barrier is not installed on a flat road with an overhead viaduct, or a noise barrier is installed only on a single side of a flat road. The concept of the calculation for double-deck viaducts is the same as that for flat roads with overhead viaducts. When especially high barriers are installed on both sides of a flat road with an overhead viaduct, neither the slit method nor the scattered reflection method can be applied because the sound field is complicated in the space surrounded by the road surface, the noise barriers, and the underside of the viaduct. In this case, wave-based numerical analysis is applied (see Appendix A6).

**Note 1:** In addition to the void slab structure shown in Fig. 4.9, structures with flat sound-absorbing boards installed on the underside can be regarded as “flat type.”

**Note 2:** When the overhead viaduct is wide, for example, owing to a tollgate, the effect of high-order reflected sound cannot be ignored. The boundary energy integral equation method has been proposed as an energy-based noise prediction method for such cases [66].

**Note 3:** The geometrical ray-tracing method is one of the qualitative prediction methods and effective for investigating the range of the reflected sound from the underside of a viaduct.

**4.6.2. Slit method (image source method)**

As shown in Fig. 4.10, consider a case when a noise barrier is installed on a single side of a flat road. For an ordinary viaduct road with four to six lanes, consider the four major sound paths of (a) a direct sound ($S$ to $P$), (b) a reflection from the underside of a viaduct road ($S'$ to $P$), and (c) reflections from the underside and ground ($S'$ to $P'$ and $S''$ to $P$). The A-weighted sound pressure level $L_A$ [dB] at prediction point $P$ is calculated using the following
Among them, the noise barrier for the calculation of the edge of the slit is neglected in the calculation of correction for sound attenuation due to the absorptive material, the beams of piers may not be absorptive. Even if the underside of a viaduct is treated with an absorptive material, the beams of piers may not be absorptive. Therefore, it is desirable to use a mean sound absorption coefficient and correction \( [\text{dB}] \) for sound attenuation due to the absorptive material. The reflection path from the underside and ground \((S' \text{ to } P' \text{ from the underside of a viaduct } S' \text{ to } P)\), respectively. Sources may be combined into a representative hypothetical lane. For the case where the underside of a viaduct is absorptive, the correction for absorption is applied (see Subsection 3.5.3).

Since the range of the effect of a reflected sound from the underside of a viaduct strongly depends on the position of the sound source, the sound source is set at the center of an actual lane in the calculation (here, two or more lanes should not be combined into one hypothetical lane). For the case when no noise barrier is installed on a flat road, only the path \( S' \text{ to } P' \) is selected to calculate the reflection from the underside and ground. In the actual calculation, the term for \( L_{A,3} \) of Eq. (4.21) is ignored, and \( L_{A,1} \) and \( L_{A,2} \) in Eq. (4.22) are calculated by setting \( \Delta L_{\text{dif,sh},1} = 0 \) and \( \Delta L_{\text{dif,sh},2} = 0 \).

Note: Even if the underside of a viaduct is treated with an absorptive material, the beams of piers may not be absorptive. Therefore, it is desirable to use a mean sound absorption coefficient weighted by the ratio of the areas of the absorptive and non-absorptive surfaces.

### 4.6.3. Scattered reflection method [47]

#### (1) Equations

As shown in Fig. 4.11, a scattered reflection surface \( B \) with a width of the viaduct is assumed beneath girder \( j \) on the underside of the viaduct above source and prediction points. Similarly to the slit method, we consider the four major paths of (a) a direct sound \((S \text{ to } P)\), (b) the reflection from the underside of a viaduct \((S \text{ to } P \text{ through } B)\), and (c) the reflections from the underside and ground \((S \text{ to } P' \text{ through } B \text{ and } B')\). The A-weighted sound pressure level \( L_A \) \([\text{dB}]\) at prediction point \( P \) is calculated using Eq. (4.21). Different from the slit method, however, the reflected surface \( B \) is divided into elements \( B_j \) \((j = 1 \text{ to } N)\), and \( L_{A,1}, L_{A,2}, \) and \( L_{A,3} \) in Eq. (4.21) are calculated as

\[
L_{A,j} = L_{WA} - 13 + 10 \lg \left( \sum_{j=1}^{N} S_j \cos \theta_j \cdot \cos \psi_j \cdot D_j \rho_j \right)
\]

\[
D_j = 10^{\Delta L_{\text{dif,sh},i}/10}
\]

where \( S_j \) is the area \([\text{m}^2]\) of element \( B_j \) of the scattered reflection surface \( B \), \( \theta_j \) and \( \psi_j \) are the incidence and reflection angles at the center of \( B_j \), respectively, \( r_j \) is the distance \([\text{m}]\) from source point \( S \) to the center of \( B_j \), and \( R_j \) is the distance \([\text{m}]\) from the center of \( B_j \) to prediction point \( P \) (see Fig. 4.12). \( D_j \) and \( \Delta L_{\text{dif,sh},j} \) are the diffraction coefficient and correction \([\text{dB}]\) for sound attenuation due to the noise barrier, respectively, when a point source is set at the center of \( B_j \). \( \rho_j \) is the reflection and absorption coefficients of \( B_j \), respectively. The reflection angle \( \psi_j \) is the angle between the normal vector \( n \) and the propagation direction as shown in Fig. 4.12.

If a noise barrier is not installed on the roadside of a flat road, only the path from \( S \) to \( P' \) through \( B \) is specified as the reflection path from the underside and ground. In the actual calculation, the term for \( L_{A,3} \) of Eq. (4.21) can be ignored, and \( L_{A,2} \) is calculated using Eq. (4.23) with \( D_j = 1 \). Sources may be combined into a representative hypothetical lane (see Item 1.3.2 (2)).

#### (2) Calculation settings

When a flat road and an overhead viaduct road are parallel and the cross sections of the roads are regarded as being uniform, the scattered reflection surface \( B \) is divided with quadrilateral elements, the width of which is one-quarter or less of the height \( H \) \([\text{m}]\) of the surface \( B \). The ranges of the discrete point sources and of the reflection surface for the calculation are shown in Table 4.6 and Fig. 4.13.
This method cannot be used if the flat road and the overhead viaduct road are crossed. When calculating $L_{Aeq}$ in such cases, first, calculate the unit pattern of the reflected sound from the underside of the viaduct through three-dimensional calculation (summation of $L_{A,1}$ to $L_{A,3}$ in Eq. (4.21)). Next, for the range from the maximum value of the unit pattern to approximately $-15\,\text{dB}$, add the direct sound $L_{A,0}$ using Eq. (4.21); for the other range, omit $L_{A,1}$ to $L_{A,3}$, i.e., use only the direct sound $L_{A,0}$. Lastly, calculate $L_{Aeq}$ from $L_{AE}$ obtained from the total unit pattern.

Note: The direct sound $L_{A,0}$ is calculated according to Item 1.3.2 (3).

5. STRUCTURE-BORNE NOISE OF VIADUCTS

When vehicles run on a viaduct road, noise is generated by the vibration of the structure, which is referred to as structure-borne noise of the viaduct. The degree of noise depends on the type of viaduct and the speed and weight of vehicles. The noise calculation method is described in the following [67,68].

5.1. Scope
(1) Type of viaduct
General steel viaducts and concrete viaducts, as shown in Table 5.1.

(2) Type of vehicle
Only heavy vehicles are considered.

Note: Since the structure-borne noise of viaducts for light vehicles is relatively minor, it is omitted in this model.

(3) Running speed of vehicles
Applicable for vehicles running at 40 km/h or more.

5.2. Noise Calculation Procedure
5.2.1. Setting of hypothetical sound source
The structure-borne noise of a viaduct is radiated from...
the entire slab and girder structure. However, for convenience of calculation, an omnidirectional point source is assumed as an equivalent moving sound source that is synchronized with the running vehicle. The moving point source is set on the surface of the underside of the viaduct (on the bottom edge of the main girders for a girder structure, or on the bottom surface of a slab for a void slab structure) at a hypothetical lane that is located directly beneath the center of each set of lanes traveling in both directions. In the calculation of $L_{Aeq}$, discrete point sources are set on the hypothetical lane (see Fig. 5.1).

5.2.2. A-weighted sound power level of hypothetical point source

The A-weighted sound power level of a hypothetical point source $L_{W,A,str}$ [dB] is calculated as

$$L_{W,A,str} = a + 30 \lg V,$$

where $V$ is the running speed [km/h] and $a$ is the value allocated to each type of viaduct as given in Table 5.2. Regarding the type of viaduct, a five-category classification is recommended. A three-category classification can be used if the type of viaduct cannot be fixed precisely.

| Type       | Steel viaduct          | Concrete viaduct          |
|------------|------------------------|---------------------------|
| Slab       | Steel                  | Concrete                  |
| Girder      | Steel box girder       | I-girder                  |
| structure   | Steel I-girder         | Box girder                |
| Illustration| [Diagram]              | Void slab girder          |

Note: The parts colored in black are slabs. All illustrations in this table show concrete slabs.

5.2.3. Calculation of unit pattern

The A-weighted sound pressure level of noise propagated from each source point on the hypothetical lane to the prediction point $L_{A,str}$ [dB] is calculated as

$$L_{A,str} = L_{W,A,str} - 8 - 20 \lg r + \Delta L_{dif},$$  \hspace{1cm} (5.2)

where $r$ is the distance from the source point to the prediction point [m] and $\Delta L_{dif}$ is the correction to the structure-borne noise of the viaduct due to the sound diffraction effect due to shielding by the slab or girder structure [dB]. $\Delta L_{dif, sb}$ is used as $\Delta L_{dif}$ for diffraction around the I-girders and steel I-girders, and $\Delta L_{dif, rw}$ is used for diffraction around the steel box girders, box girders, and void slab girders, shown in Table 5.1 (see Subsection 3.2.2).

Note 1: The value of $a$ for each type of viaduct was determined by power-averaging a number of values $a_i$ each of which was calculated using Eq. (5.1) with measured data for each individual viaduct. This procedure is the same as that for determining the constant values used in the equations for sound power level for running vehicles.

Note 2: For other types of viaduct, studies based on in-situ investigations (Reference R5.2) are necessary [69].

| Type of viaduct | $a$      | $\Delta L_{dif}$ |
|-----------------|----------|------------------|
| Steel slab      | 40.7     |                  |
| Concrete slab   | 35.5     | 38.9             |
| Steel I-girder  | 40.4     | 34.8             |
| Concrete I-girder| 31.8    |                  |
| Other than I-girder | 35.9  |                  |

Note 1: It is not necessary to consider the contribution of the sound reflection from the ground surface in the above calculation procedure, because its effect is already taken into account when determining the constant $a$ in the equation for $L_{W,A,str}$.

Note 2: The correction for the sound diffraction effect due to the structure-borne noise of the viaduct $\Delta L_{dif}$ is formulated using a
calculation chart for diffraction [23,24] and the measured spectrum of the structure-borne noise.

The unit pattern of the structure-borne noise is obtained by applying the above-mentioned calculation to all source points. The method of calculating $L_{Aeq}$ from the unit pattern is similar to that for calculating vehicle running noise on general roads.

6. NOISE BEHIND SINGLE BUILDING AND IN BUILT-UP AREAS

Behind a single building or building complex along the sides of roads, the road traffic noise is attenuated by their screening effect. To predict the degree of attenuation, methods of calculating noise around a single building and behind a dense building complex are given below using the following prediction model.

6.1. Noise behind Single Building

As a method of calculating noise around a single building along the sides of roads, the following prediction model is considered. In this method, only the diffraction by the top of a single building is considered (referred to as the one-path method), and diffraction by the sides of the building is ignored.

Buildings are thick obstacles with limited lengths. Around a single building, it is necessary to consider the noise attenuation due to the screening effect of the building. Thus, $L_{Aeq}$ behind a single building is calculated by applying the methods of calculating the correction for diffraction caused by a finite-length barrier (Subsection 3.2.2(3)) and diffracted sounds (Subsection 3.2.4), and finally summing the direct sounds and diffracted sounds (see Fig. 6.1(a)). In this model, the building is represented by a rectangular parallelepiped, and it is assumed that there is no sound absorption on the walls of the building.

The unit pattern is calculated as

$$L_{A0,i} = L_{WA,i} - 8 - 20 \log r_{0,i} + \Delta L_{bldg,i},$$  \hspace{1cm} (6.1)

where $L_{A0,i}$ is the A-weighted sound pressure level [dB] of the direct sound component (or diffracted sound component) from $S_i$, $\Delta L_{bldg,i}$ is the correction for the diffraction by the building [dB], $r_{0,i}$ is the distance [m] between the sound source $S_i$ and the receiver $P$.

In the calculation of the unit pattern, as shown in Fig. 6.1(b), when line segment SP crosses the building, the building is treated as an infinite-length barrier with depth $D$ [m], and then $\Delta L_{bldg}$ is calculated similarly to $\Delta L_{dif,lb}$ using Eq. (3.9). When the line segment does not cross the building, it is concluded that there is no building and then $\Delta L_{bldg}$ is equal to zero.

Note 1: $L_{A0,i}$ calculated by the one-path method mentioned above widely changes when the line segment SP is positioned near the end of the building. Therefore, the method cannot be applied in the case of calculating a precise unit pattern. The detailed calculation method considering the diffraction by the top and sides of the building is provided in the literature [70,71].

Note 2: The calculated $L_{Aeq}$ using the one-path method and that using the method considering the diffraction by the top and sides of the building are approximately equal except only in very special cases [71].

6.2. Noise behind Building Complex

In this prediction model, a practical calculation method is provided for predicting noise behind a dense building complex. It is assumed for the methods described here that the detached houses are of standard size in Japan; therefore, the calculation methods are not applicable to built-up areas with buildings of different sizes and different conditions of building locations.

It is recommended to employ the advanced calculation method, which is described in Appendix A8, in certain situations, for example, when the unit patterns must be calculated more correctly for planning countermeasures against noise or when the detailed diffraction and reflection by the sides of the buildings must be considered.

6.2.1. Practical calculation method using a point source model [72]

When detached houses are located in an area facing a plane road, noise behind the detached houses attenuates owing to the screening effect of the houses. In this case, the
A-weighted sound pressure level \( L_{A,i} \) at a prediction point from the \( i \)th source position is calculated as

\[
L_{A,i} = L_{W,A,i} - 8 - 20 \log r_i + \Delta L_{B,i},
\]

where \( L_{W,A,i} \) is the A-weighted sound power level of a single running vehicle at the \( i \)th source position [dB] and \( r_i \) is the direct distance from the \( i \)th source position to the prediction point [m]. \( \Delta L_{B,i} \) denotes the correction related to the attenuation due to the detached houses along the propagation path from the \( i \)th source position to the prediction point [dB]. It is given by the following equation. The suffix \( i \) for the source position is hereafter omitted for simplicity of notation.

\[
\Delta L_{B} = p \cdot \Delta L_{BB} + q
\]

\[
p = 0.017(H - h_p - 8.8) + 1
\]

\[
q = -0.063(H - h_p - 8.8)
\]

Here, \( H \) is the height of the detached houses [m] and \( h_p \) is the height of the prediction point [m]. \( \Delta L_{BB} \) is the correction value [dB] when \( H \) is 10 m and \( h_p \) is 1.2 m and is given by

\[
\Delta L_{BB} = 10 \log \left\{ b_0 + b_1 \frac{\phi}{\Phi} + b_2 \cdot 10^{-0.0904 \xi \cdot d_{SP}} \right\},
\]

where \( b_0 = 0.046, b_1 = 1.01, \) and \( b_2 = 0.554 \). In Eq. (6.4), the term related to \( \phi/\Phi \) indicates the direct sound from the source to the prediction point. \( \phi \) and \( \Phi \) are the perspective angles [rad] from the prediction point to a part of the target road of 10 m length where the sound source \( S \) is the midpoint, as shown in Figs. 6.2 and 6.3, in the cases with and without detached houses, respectively.

The term related to \( 10^{-0.0904 \xi \cdot d_{SP}} \) indicates sounds other than the direct sounds. As shown in Fig. 6.4, \( d_{SP} \) is the horizontal distance between \( S \) and \( P \). A 15-m-wide rectangular area is assumed between \( S \) and \( P \), and the density of the houses \( \xi \) (the ratio of the location area of the detached houses to the rectangular area) is calculated.

Equations (6.3) and (6.4) were deduced from the results of scale-model experiments assuming residential areas in which many detached houses of standard size in Japan were located. In the experiments, the horizontal distances between the prediction points and the target roads were 20 to 50 m. The ratio of the total area of the detached houses to the location area was in the range from 0.16 to 0.34. The heights (\( H \)) of the detached houses were 4 to 10 m and the heights (\( h_p \)) of the receiver were 1.2 to 9.2 m. Therefore, this calculation method is valid in these ranges. Furthermore, \( h_p \) should be less than \( H \). If the heights of the detached houses are different from each other and the roofs are not flat, the mean height of the detached houses can be used as \( H \) [73].

### 6.2.2. Simplifying the computation of practical calculation method [74,75]

Equation (6.4) is expressed as a sum of the constant \( b_0 \), the component of direct sound, and the component other than the direct sound (referred to as \( E_{oth} \)). In the case of the buildings lying evenly in the target area, the error of \( \Delta L_{BB} \) would be maintained under 0.5 dB if \( E_{oth} \) was omitted by the following three judgement procedures.
(1) Judgement procedure using horizontal distance between the source and prediction point

When the distance from the source to the prediction point \(d_{SP}\) exceeds 254 m, \(E_{oh}\) can be set to zero and the density of the houses \((\xi)\) need not to be calculated.

This is an easy procedure because the judgement can be implemented only using \(d_{SP}\).

(2) Judgement procedure considering the direct sound

When \(d_{SP}\) is less than 254 m, the shortest omittable distance \(d_{SP}^*\) from the prediction point \(P\) to the source \(S\) is calculated as

\[
d_{SP}^* = -234 \left(\frac{\phi}{\phi'}\right)^3 + 659 \left(\frac{\phi}{\phi'}\right)^2 - 386 \left(\frac{\phi}{\phi'}\right) + 220, \tag{6.5}
\]

and when \(d_{SP}^*\) exceeds \(d_{SP}^*\), \(E_{oh}\) can be set to zero.

Even though the calculation using Eq. (6.5) is required, this judgement is useful since it can be implemented regardless of the visibility of the source from the prediction point.

(3) Judgement procedure when the source is invisible from the prediction point

When houses are uniformly distributed and \(\phi\) is zero, point sound sources are selected in order of increasing distance from the prediction point and used to calculate \(\xi \cdot d_{SP}\). Once \(\xi \cdot d_{SP}\) exceeds 22.1, \(E_{oh}\) can be set to zero for the sound source point and subsequent points.

This procedure enables \(E_{oh}\) to be set to zero and the calculation of \(\xi\) for all sources of \(\phi = 0\) to be omitted before the distance becomes \(d_{SP}^*\). Although this is a more complicated procedure than (1) and (2), it can be useful when the calculation cost should be minimized.

Note: Only the contribution of sounds propagating into the building complex is considered in this prediction model. When the height of the receiver is greater than those of the buildings or noise is predicted for a viaduct with a noise barrier or for a banked road, it is necessary to consider the contribution of sounds propagating over the buildings.

APPENDICES

Appendix A1  SOUND POWER SPECTRA OF VEHICLE NOISE

In this appendix, the frequency characteristics (power spectrum) of running vehicle noise on dense asphalt, porous asphalt, and KOUKINOU II pavements are described.

A1.1. Power Spectrum for Dense Asphalt Pavement

The A-weighted sound power level for each frequency band \((1/n\text{-octave band})\) on a dense asphalt pavement is given by the following method. For the frequency bands, the center frequencies for the octave bands are from 63 Hz to 4 kHz, and those for the 1/3-octave bands are from 50 Hz to 5 kHz. The A-weighted band power level \(L_{WA}(f_{ci})\) [dB] for the \(i\)th center frequency \(f_{ci}\) [Hz] is calculated as

\[
L_{WA}(f_{ci}) = L_{WA} + \Delta L_{WA}(f_{ci}), \tag{A1.1}
\]

where \(L_{WA}\) is the A-weighted sound power level of the road vehicle on a dense asphalt pavement [dB] (see Subsection 2.2.2) and \(\Delta L_{WA}(f_{ci})\) is the A-weighted relative power level for the frequency band of \(f_{ci}\) [dB]. Table A1.1 and Fig. A1.1 show the representative A-weighted relative power level \(\Delta L_{WA}(f_{ci})\) on a dense asphalt pavement.

A1.2. Power Spectrum for Porous Asphalt Pavement

The A-weighted band power level \(L_{WA}(f_{ci})\) for the center frequency \(f_{ci}\) [Hz] on a porous asphalt pavement is given by Eq. (A1.1). In the equation, \(L_{WA}\) is the A-weighted sound power level on porous asphalt (see Subsection 2.2.3), which was determined using the measurement data for the steady running condition on expressways where the elapsed time since the construction of the pavement was within 11 years, and \(\Delta L_{WA}(f_{ci})\) is the representative A-weighted relative power level shown in Table A1.2 and Fig. A1.1.
Table A1.2 A-weighted relative band power level \( \Delta L_{WA(f_c)} \) on porous asphalt pavement.

| Center frequency [Hz] | Octave band | 1/3-octave band |
|-----------------------|-------------|-----------------|
| 63                    | 63          | -25.0           |
| 80                    |             | -26.8           |
| 125                   | 125         | -17.0           |
| 160                   |             | -19.8           |
| 250                   | 250         | -9.9            |
| 315                   |             | -12.7           |
| 500                   | 500         | -4.5            |
| 630                   |             | -7.7            |
| 800                   | 800         | -4.4            |
| 1,000                 | 1,000       | -9.4            |
| 1,250                 |             | -11.2           |
| 2,000                 | 2,000       | -9.1            |
| 2,500                 |             | -16.0           |
| 4,000                 | 4,000       | -16.0           |
| 5,000                 |             | -23.7           |
| Overall               | 0.0         | 0.0             |

Table A1.3 A-weighted relative band power level \( \Delta L_{WA(f_c)} \) on KOUKINOU II pavement.

| Center frequency [Hz] | Octave band | 1/3-octave band |
|-----------------------|-------------|-----------------|
| 63                    | 63          | -28.5           |
| 80                    |             | -30.1           |
| 125                   | 125         | -20.5           |
| 160                   |             | -23.4           |
| 250                   | 250         | -13.9           |
| 315                   |             | -16.7           |
| 500                   | 500         | -8.0            |
| 630                   |             | -10.5           |
| 800                   | 800         | -2.6            |
| 1,000                 | 1,000       | -6.8            |
| 1,250                 |             | -7.1            |
| 2,000                 | 2,000       | -6.7            |
| 2,500                 |             | -15.1           |
| 4,000                 | 4,000       | -15.6           |
| 5,000                 |             | -24.2           |
| Overall               | 0.0         | 0.0             |

Fig. A1.1 Representative A-weighted relative sound power levels (in 1/3-octave bands) on each type of pavement.

A1.3. Power Spectrum for KOUKINOU II Pavement

The A-weighted band power level \( L_{WA(f_c)} \) for the center frequency \( f_c \) [Hz] on a KOUKINOU II pavement is given by Eq. (A1.1). In the equation, \( L_{WA} \) is the A-weighted sound power level on KOUKINOU II (see Subsection 2.2.4), which was determined using the measurement data for the steady running condition on expressways where the elapsed time since the construction of the pavement was within 6 years, and \( \Delta L_{WA(f_c)} \) is the representative A-weighted relative power level shown in Table A1.3 and Fig. A1.1.

Note 1: The engine load is large when the vehicle accelerates or when it runs on an uphill road. It is necessary to consider the increase of sound pressure level in the low-frequency range [11,76–78].

Note 2: According to recent results of measurements of the frequency characteristics of traffic noise, it is clear that the power level of recent vehicles tends to be lower than that given in ASJ RTN-Model 2013 at frequencies below 1 kHz [15].

Note 3: According to results of recent measurements, it is not necessary to determine the relative value for a pavement with newer than 1 year separately, since the frequency characteristics of traffic noise differ among the measurement points but do not differ with the elapsed years after the construction [17].

Appendix A2 SOUND POWER LEVELS OF HYBRID AND ELECTRIC VEHICLES

Hybrid and electric vehicles (HVs and EVs, respectively) are becoming popular and their production is rapidly increasing in Japan, as in many other countries.
At the end of March 2018, the numbers of registered HVs and EVs were about 7.50 million and 0.09 million, respectively. The percentage of registered vehicles of these types was more than 10% [79]. These vehicles are regarded as environment friendly due to their fuel efficiency and low-carbon emission. On the other hand, because of their reduced audibility by pedestrians, installation of an additional sound-emitting device, which is defined as an Acoustic Vehicle Alerting System (AVAS) by the UN Regulation, has been mandatory since 2018.

Figure A2.1 shows the measurement results of the noise of a running HV and two types of GEV [80]. These results represent the maximum A-weighted sound pressure levels measured at a distance of 2 m from the center of the lane. At speeds below 15 km/h, the levels of noise generated from HVs are 5 to 20 dB lower than those from GEVs. In addition, Table A2.1 shows a comparison of the regression equations of the A-weighted sound power level of HVs and GEVs, using the maximum A-weighted sound pressure levels of 451 HEVs (including two EVs) measured at general roads [15]. The A-weighted sound power level of HVs was 0.6 dB lower than that of GEVs during the steady running condition at 40 km/h or higher.

The noise reduction effect of these low-emission vehicles can be expected in the vicinity of signalized intersections or expressway tollgates, where the propulsion noise of vehicles predominates. Therefore, it is important to accumulate measurement data of HVs and EVs running at low speeds or accelerating.

Appendix A3 SOUND POWER LEVELS OF ROAD VEHICLES ON DENSE ASPHALT PAVEMENT DURING ACCELERATION

The A-weighted sound power levels during acceleration on a dense asphalt pavement, such as in the interchange sections (near an expressway tollgate or a junction), are given for each type of vehicle using Eqs. (2.1) and (2.2) (see Subsection 2.2.2); the coefficients \(a\), \(b\), and \(c\) for the acceleration running condition are given in Table A3.1. The coefficient \(b\), which represents the speed dependence, is 10 for all categories of vehicles.

A constant power level is applied until the vehicle reaches 1 km/h (the value obtained when \(V = 10\) km/h is substituted into the equation for the deceleration running condition). Acceleration at speeds exceeding 80 km/h for the section near an express tollgate and that exceeding 60 km/h for the section of a junction are treated as the steady running condition.

Appendix A4 SOUND POWER LEVELS OF ROAD VEHICLES ON POROUS ASPHALT GENERAL ROADS

The A-weighted sound power levels on general roads paved with porous asphalt are given for each type of vehicle using Eqs. (2.3) and (2.4) (see Subsection 2.2.3); the coefficients \(a\), \(b\), and \(c\) for acceleration running

At the end of March 2018, the numbers of registered HVs and EVs were about 7.50 million and 0.09 million, respectively. The percentage of registered vehicles of these types was more than 10% [79]. These vehicles are regarded as environment friendly due to their fuel efficiency and low-carbon emission. On the other hand, because of their reduced audibility by pedestrians, installation of an additional sound-emitting device, which is defined as an Acoustic Vehicle Alerting System (AVAS) by the UN Regulation, has been mandatory since 2018.

Figure A2.1 shows the measurement results of the noise of a running HV and two types of GEV [80]. These results represent the maximum A-weighted sound pressure levels measured at a distance of 2 m from the center of the lane. At speeds below 15 km/h, the levels of noise generated from HVs are 5 to 20 dB lower than those from GEVs. In addition, Table A2.1 shows a comparison of the regression equations of the A-weighted sound power level of HVs and GEVs, using the maximum A-weighted sound pressure levels of 451 HEVs (including two EVs) measured at general roads [15]. The A-weighted sound power level of HVs was 0.6 dB lower than that of GEVs during the steady running condition at 40 km/h or higher.

The noise reduction effect of these low-emission vehicles can be expected in the vicinity of signalized intersections or expressway tollgates, where the propulsion noise of vehicles predominates. Therefore, it is important to accumulate measurement data of HVs and EVs running at low speeds or accelerating.

Table A2.1 Regression equations of A-weighted sound power level of HVs and GEVs.

| Classification | Number of vehicles |
|----------------|-------------------|
| HV             | \(L_{WA} = 45.2 + 30\lg V\) |
| GEV            | \(L_{WA} = 45.8 + 30\lg V\) |

Table A3.1 Coefficients \(a\) and \(b\) for dense asphalt pavement (expressway, acceleration sections).

| Classification | Near an expressway tollgate \((1 \leq V \leq 80\text{ km/h})\) | Near a junction \((1 \leq V \leq 60\text{ km/h})\) |
|----------------|--------------------------------|--------------------------------|
|                | \(a\) | \(b\) | \(a\) | \(b\) |
| Three-category  | Light vehicles | 84.8 | 10 | 82.3 | 10 |
|                | Medium-sized vehicles | 89.6 | 10 | 84.8 | 10 |
|                | Large-sized vehicles | 92.5 | 10 | 91.3 | 10 |
| Two-category   | Light vehicles | 84.8 | 10 | 82.3 | 10 |
|                | Heavy vehicles | 91.3 | 10 | 88.8 | 10 |
| Motorcycles    | 87.7 | 10 | 85.2 | 10 |
condition are given in Table A4.1. The vehicle speed $V$ is in the range from 40 to 80 km/h for the steady traffic flow section and from 10 to 60 km/h for the non-steady traffic flow section. The coefficient $b$, which represents the speed dependence, is 30 and 10 for the steady- and non-steady traffic flow sections, respectively. The coefficient $c$ is always 0 for motorcycles.

**Appendix A5  CALCULATION OF FREQUENCY-DEPENDENT PROPAGATION**

In this appendix, a general energy-based calculation method for frequency-dependent sound propagation, which is not limited to road traffic noise, is presented.

### A5.1. Basic Equations for Propagation

Consider point source $S$ and prediction point $P$ on a flat ground surface as shown in Fig. A5.1. Generally, the propagation paths to be considered are the two paths in Fig. A5.1(a) when there is no barrier (no diffraction calculation is required), and the four paths in Fig. A5.1(b) when there is a barrier. In the prediction of road traffic noise, however, the numbers of paths to be considered are one and two without and with a barrier, respectively, because the sound source is placed on a road surface. The A-weighted sound pressure level $L_A$ [dB] is calculated using the following equations. $L_A$ in Eq. (A5.1) corresponds to that in Eq. (3.1).

$$L_A = 10 \log \sum_i 10^{L_A(f_c,i)/10},$$  \hspace{1cm} (A5.1)

$$L_A(f_c,i) = 10 \log \sum_{m=1}^M 10^{L_A(f_c,0)/10} + \Delta L_{g,ex}(f_c,i),$$  \hspace{1cm} (A5.2)

$$L_{A,m}(f_c,i) = L_{WA}(f_c,i) - 11 - 20 \log r_m + \Delta L_{diff,m}(f_c,i) + \Delta L_{air,m}(f_c,i).$$  \hspace{1cm} (A5.3)

Here, $f_{c,i}$ is the center frequency [Hz] of the $i$th band, $L_A(f_c,i)$ is the A-weighted sound pressure level [dB] for the frequency band of $f_{c,i}$, $L_{A,m}(f_c,i)$ is the A-weighted sound pressure level [dB] for propagation path $m$ (see Fig. A5.1) for the frequency band of $f_{c,i}$, $L_{WA}(f_c,i)$ is the sound power level [dB] for the frequency band of $f_{c,i}$, $r_m$ is the direct distance from the sound source or its mirror image to the prediction point or its mirror image, $\Delta L_{diff,m}(f_c,i)$ and $\Delta L_{air,m}(f_c,i)$ are the correction terms [dB] for propagation path $m$ for diffraction ($\Delta L_{diff,m}(f_c,i) = 0$ dB without a barrier) and atmospheric absorption, respectively, and $\Delta L_{g,ex}(f_c,i)$ is the correction term [dB] for the excess attenuation due to the ground. The calculation frequencies $f_{c,i}$ are the 1/3-octave band center frequencies from 100 Hz to 5 kHz. In the following, the subscript of frequency $f$ and subscript $m$ representing a propagation path will be omitted if there is no misunderstanding without them.

**Note:** In the road traffic noise prediction, firstly, $L_A$ is calculated with the moving sound source $S$ to obtain the unit pattern; secondly, $L_{EA}$ is obtained from the unit pattern using Eq. (1.11); lastly, $L_{Aeq,T}$ is calculated using Eq. (1.12).
A5.2. Correction for Diffraction $\Delta L_{\text{dif}}(f)$

Similar to the calculation procedures for road traffic noise propagation presented in Chapter 3, the fundamental correction terms for diffraction around a knife wedge and a wedge with an opening angle of 90°, $\Delta L_{\text{d,k}}(f)$ and $\Delta L_{\text{d,r}}(f)$ [dB], are calculated using Eqs. (A5.4) and (A5.5), respectively, and used for calculating correction terms for various types of diffraction.

A5.2.1. Fundamental correction term for diffraction around a knife wedge

The fundamental correction term $\Delta L_{\text{d,k}}(f)$ [dB] for diffraction around a knife wedge such as a simple barrier is calculated as [23, 24]

$$\Delta L_{\text{d,k}}(f) = \begin{cases} -13 - 10 \log N & N \geq 1 \\ -5 \mp 9.08 \sinh^{-1}(\sqrt{N})^{0.485} & -0.324 \leq N < 1 \\ 0 & N < -0.324 \end{cases}, \quad \text{(A5.4)}$$

where $N = \delta/\lambda$ is the Fresnel number, $\delta$ is the diffraction path difference [m] defined in Subsection 3.2.1, $\lambda = c/f$ is the wavelength [m], and $c$ is the sound speed [m/s] (343.7 m/s in 20°C atmosphere). The sign $\mp$ is negative for $N \geq 0$ and positive for $N < 0$.

Note 1: Equation (A5.4) was derived from a calculation chart [23] based on experimental values for diffraction around reflective barriers [24].

Note 2: In the experiment to derive Eq. (A5.4), the sound source was located in the range of about 60° from the front of the observation point. Hence, Eq. (A5.4) may overestimate the diffraction effect in the case of “grazing incidence” in which the source is positioned at a point far from the frontal prediction point. In such cases, calculation formulae [81] deduced by the approximation of the asymptotic solution of sound diffraction [82] are applicable.

A5.2.2. Fundamental correction term for diffraction around a wedge with an opening angle

The fundamental correction term $\Delta L_{\text{d,r}}(f)$ [dB] for diffraction around a wedge with an opening angle, such as a building and an embankment, is calculated as [25]

$$\Delta L_{\text{d,r}}(f) = \begin{cases} -10.5 - 10 \log N & N \geq 1 \\ -5 \mp 9.08 \sinh^{-1}(\sqrt{N})^{0.485} & -0.0718 \leq N < 1 \\ 0 & N < -0.0718 \end{cases}. \quad \text{(A5.5)}$$

Note 1: There are no frequency-dependent correction terms that correspond to the correction terms $C_{\text{dif,abs}}$, $C_{\text{dif,cob}}$, $C_{\text{dif,emb}}$ and so forth, described in Section 3.2. Hence, frequency-dependent calculations for diffraction cannot be performed. When these calculations are required, the frequency-dependent correction terms should be obtained through a wave-based numerical analysis or an experiment.

A5.2.4. Correction term for diffraction on road traffic noise

When the attenuation due to diffraction increases, the low-frequency components are dominant behind the barrier. If the attenuation due to diffraction exceeds approximately 30 dB, the equations for the fundamental correction terms for diffraction presented in Section 3.2 cannot be used. To predict road traffic noise under such conditions, the frequency-dependent fundamental correction terms for diffraction are calculated using Eq. (A5.4) or Eq. (A5.5), and the correction term for diffraction $\Delta L_{\text{dif}}$ is calculated using the following equation, where the frequency-dependent terms are weighted with the power spectrum of the sound source. In the following equation, $\Delta L_{\text{dif}}$ or $\Delta L_{\text{dif}}(f)$ is used as a general expression instead of various correction terms for diffraction, such as $\Delta L_{\text{dif,ab}}$ shown in Table 3.1.

$$\Delta L_{\text{dif}} = 10 \log \sum_i 10^{\Delta L_{\text{WA}}(f_i)/10} \quad \text{(A5.6)}$$

Here, $\Delta L_{\text{WA}}(f_i)$ is the A-weighted relative sound power level [dB] for the frequency band of $f_i$. When calculating the values for the 1/3-octave bands, the values in Appendix A1 are used.

A5.3. Correction for Atmospheric Absorption $\Delta L_{\text{a}}(f)$

A5.3.1. Equations

$\Delta L_{\text{a}}(f)$ is calculated as the product of attenuation per unit length $\alpha_{\text{a}}(f)$ [dB/m] and the propagation path length $r$ [m]:

$$\Delta L_{\text{a}}(f) = -\alpha_{\text{a}}(f) \cdot r. \quad \text{(A5.7)}$$

$\alpha_{\text{a}}(f)$ is calculated using the following equation from ISO 9613-1:1993 assuming atmospheric pressure of 101325 kPa [83]:

$$\alpha_{\text{a}}(f) = f^2 \cdot 10^{-10} \left( 1.60 + \frac{b_O f_O}{f_O^2 + f^2} + \frac{b_N f_N}{f_N^2 + f^2} \right), \quad \text{(A5.8)}$$

where $f_O$ and $f_N$ are the oxygen and nitrogen relaxation frequencies, and $b_O$ and $b_N$ are the coefficients related to the molecular absorption of oxygen and nitrogen, respectively. They are calculated as

$$f_O = 24 + 4.04 \times 10^4 h \frac{0.02 + h}{0.391 + h}, \quad \text{(A5.9)}$$

$$f_N = \frac{17.1}{\sqrt{T_C + 273}} \left( 9 + 18100 \times h \times e^{-\frac{3500}{T_C + 273}} \right). \quad \text{(A5.10)}$$
A5.3.2. Correction term for atmospheric absorption of road traffic noise

To calculate the attenuation due to the atmospheric absorption of road traffic noise under various temperature and humidity conditions, the frequency-dependent correction term \( \Delta L_{\mathrm{air}}(f_{ci}) \) is calculated using Eqs. (A5.7) to (A5.13), and the correction term for atmospheric absorption \( \Delta L_{\mathrm{air}} \) is calculated using the following equation, where the frequency-dependent terms \( \Delta L_{\mathrm{air}}(f_{ci}) \) are weighted with the power spectrum of the sound source:

\[
\Delta L_{\mathrm{air}} = 10 \log \left( \frac{\sum \frac{\Delta L_{\mathrm{air}}(f_{ci})}{10}}{\sum \frac{10^{\Delta L_{\mathrm{air}}(f_{ci})/10}}{10}} \right),
\]

where \( \Delta L_{WA}(f_{ci}) \) is the A-weighted relative sound power level [dB] for the frequency band of \( f_{ci} \). When calculating the values for 1/3-octave bands, the values in Appendix A1 are used.

A5.4. Correction for Excess Attenuation due to Ground \( \Delta L_{g,ex}(f) \)

\( \Delta L_{g,ex}(f) \) is the correction term of the sound pressure level [dB] relative to a perfectly reflective surface. It is simplified to \( \Delta L_{g,ex}(f) = 0 \) to avoid the underestimation of \( L_{A,refl}(f) \), whereas, generally, \( \Delta L_{g,ex}(f) \leq 0 \).

A5.5. Calculation of Sound Reflection

A5.5.1. Basic equations

As shown in Fig. A5.2, consider a case where point sound source \( S \), prediction point \( P \), and a reflecting surface with ends of \( O_1 \) and \( O_2 \) are located above flat ground. In the calculation of the reflected sound, set mirror images of \( S \) and \( P \) with respect to the ground surface and the reflecting surface. The A-weighted sound pressure level \( L_{A,refl} \) [dB] of the reflected sound is calculated using the following equations:

\[
L_{A,refl} = 10 \log \sum_i 10^{L_{A,refl}(f_{ci})/10},
\]

\[
L_{A,refl}(f_{ci}) = 10 \log \sum_{m=1}^M 10^{L_{A,refl,m}(f_{ci})/10}
\]

where \( f_{ci} \) is the frequency of the reflected sound for the frequency band of \( f_{ci} \).

A5.5.2. Correction for reflection \( \Delta L_{refl}(f) \)

Similar to the calculation procedures for reflection sound presented in Subsection 3.5.1, the fundamental correction term \( \Delta L_r(f) \) [dB] for reflection is calculated using the following equation and used for calculating correction terms for various types of reflection [44].

\[
\Delta L_r(f) = \begin{cases} 
10 \log \left( \frac{0.5}{(1 + (10N)^3)^2} \right) & N \geq 0 \\
10 \log \left( 1 - \frac{0.5}{(1 + (10|N|)^3)^2} \right) & N < 0 
\end{cases}
\]

A5.5.3. Calculation of correction terms for various types of reflection

The correction terms for various types of reflection
are calculated using $\Delta L_\text{c}(f)$ at each frequency through the procedures presented in Section 3.5.

### A5.4.4. Correction term for absorption of road traffic noise

To calculate the correction term for absorption materials other than those listed in Table 3.6 for road traffic noise, the term $\Delta L_{\text{abs}}$ [dB] is calculated by weighting with the power spectrum of the sound source,

$$
\Delta L_{\text{abs}} = 10 \log \left( \sum_i \frac{\Delta L_{\text{WA}(f)}}{10} \left(1 - \alpha(f_c,i)\right) \sum_i \frac{\Delta L_{\text{WA}(f)}}{10} \right), \quad (A5.19)
$$

where $\Delta L_{\text{WA}(f)}$ is the A-weighted relative sound power level [dB] for the frequency band of $f_c,i$. When calculating the values for 1/3-octave bands, the values in Appendix A1 are used. $\alpha(f_c,i)$ is the sound absorption coefficient of the reflecting surface in the frequency band of $f_c,i$.

### Appendix A6 WAVE-BASED NUMERICAL ANALYSIS

For complicated road structures such as an overhead road constructed over a flat road with parallel barriers and a semi-underground road with large overhangs, a limitation exists in the principle of applying the practical calculation methods described in the main body. For such cases, wave-based numerical methods, such as the boundary element method (BEM) and the finite-difference time-domain (FDTD) method, can be efficiently applied. If the road structure is modeled in a simple case of a uniform cross-sectional shape. Under the condition that a line source $Q_{\text{line}}$ exists over a range of perspective angles $\Psi$ [rad] as shown in Fig. A6.1, the band level of A-weighted sound pressure at a center frequency of $f$ [Hz], $L_A(f)$ [dB], is calculated as

$$
L_A(f) \approx L_{\text{WA},\text{line}}(f) + 10 \log \frac{\Psi}{\pi} - 3 - 10 \log l + \Delta L_{2D}(f), \quad (A6.1)
$$

where $L_{\text{WA},\text{line}}(f)$ is the A-weighted sound power level over a unit-length segment in $Q_{\text{line}}$ for a frequency band around a center frequency $f$ [Hz]. $L_{\text{WA},\text{line}}(f)$ is calculated using the following equation with the band level of A-weighted sound power $L_{\text{WA}}(f)$ [dB] (see Appendix A1) for a running vehicle:

$$
L_{\text{WA},\text{line}}(f) = L_{\text{WA}}(f) - 10 \log \frac{1000V}{N}, \quad (A6.2)
$$

where $V$ is the average running speed of vehicles [km/h] and $N$ is the traffic volume [vehicles/h]. $\Delta L_{2D}(f)$ is the insertion loss, which is obtained by the two-dimensional wave-based numerical analysis of an obstacle as a barrier. $\Delta L_{2D}(f)$ is calculated as

$$
\Delta L_{2D}(f) = 10 \log \left| \frac{\phi_{2D}(k)}{\phi_{2D,00}(k)} \right|^2, \quad (A6.3)
$$

where $\phi_{2D}(k)$ is the complex sound pressure at the wavenumber $k$ ($= 2\pi f/c$, $c$ is the sound speed) at the prediction point $P$ in a sound field with obstacles, and it is obtained by the two-dimensional BEM or FDTD method.
\[ \phi_{2D,00}(f) = \frac{i}{2} H_0^{(1)}(k_l), \] (A6.4)

where \( H_0^{(1)}(x) \) is the Hankel function of the first kind of order zero and \( c \) is the sound speed [m/s].

When using the two-dimensional FDTD method, a hemi-free field that has the sound source and the prediction point at the same points as those in the sound field with the road structure is assumed, and the FDTD calculation is executed for the hemi-free field. From the result, \( \phi_{2D,00}(f) \) is obtained.

Note: In two-dimensional wave-based numerical analysis, sound propagation from a cylindrical source (coherent line source) is dealt with, and therefore the sound propagation physically differs from the propagation from a series of point sources with a random phase (incoherent line source), which is the ideal physical model of a sound source of road traffic. However, according to investigations on the insertion loss of barriers and the effects of ground for a straight road source of road traffic. However, according to investigations on the propagation from a series of point sources with a random phase with, and therefore the sound propagation physically differs from the existing in the range between 

\[ \frac{1}{2} \cos \frac{k_2}{C_0}, \]

and +60° from a prediction point is sufficiently small, within about 2 dB. Therefore, the insertion loss calculated by two-dimensional wave-based numerical analysis can be practically applied to sound propagation in a three-dimensional sound field to obtain an approximate sound pressure level at a prediction point.

A6.1.2. Application of integral transform

Consider a sound field that has a uniform cross-sectional shape infinitely continuing in the \( z \)-direction and point sound source \( S \), as shown in Fig. A6.2. The complex sound pressure at receiving point \( P \) in this field, \( \phi_{3D}(x,y,z,k) \), is related to the complex sound pressure \( \phi_{2D}(x,y,k_{2D}) \) in a two-dimensional field, which has the cross-sectional shape as the original three-dimensional sound field, by the following equation \[89,90]:

\[ \phi_{3D}(x,y,z,k) = \frac{1}{\pi} \int_0^{+\infty} \phi_{2D}(x,y,\sqrt{k^2-k_z^2}) \cos k_z z \, dk_z, \] (A6.5)

where the integral parameter \( k_z \) is the \( z \)-directional component of the wavenumber \( k \). With the wavenumber in the two-dimensional field defined as \( k_{2D} = \sqrt{k^2-k_z^2} \)

\( \phi_{2D}(x,y,k_{2D}) \) is calculated as a function of the integral parameter \( k_z \), with which \( k_{2D} \) varies in the manner \( k \to 0 \to i \cdot \infty \). All \( \phi_{2D}(x,y,k_{2D}) \) are integrated according to Eq. (A6.5), then \( \phi_{3D}(x,y,z,k) \) for the three-dimensional field is obtained.

To obtain \( \phi_{2D}(x,y,k_{2D}) \), the BEM and FDTD method can be applied. When the BEM is applied, the values of \( \phi_{2D}(x,y,k_{2D}) \) at discrete wavenumbers \( k_{2D} \) are calculated and the integration term in Eq. (A6.5) is approximately obtained by summing the calculated values of \( \phi_{2D}(x,y,k_{2D}) \). To ensure sufficient accuracy, it is necessary to calculate two-dimensional solutions \( \phi_{2D}(x,y,k_{2D}) \) at many discrete wavenumbers with small intervals. In particular, near \( k_{2D} = 0 \), \( \phi_{2D}(x,y,k_{2D}) \) diverges to infinity \[91\], and therefore the intervals of the wavenumber should be sufficiently small.

When using the FDTD method, the values of \( \phi_{2D}(x,y,k_{2D}) \) at real and imaginary wavenumbers are obtained by the Fourier and Laplace transformations of an impulse response, respectively \[92\]. The sufficiently small interval of the wavenumbers can be maintained by increasing the data length of the impulse response by adding zeros after the obtained response and then applying the Fourier and Laplace transformations. However, this method cannot be applied to a sound field with absorptive boundaries.

A6.1.3. Three-dimensional wave-based numerical analysis

Conventionally, three-dimensional wave-based numerical analyses of outdoor noise propagation have not been carried out owing to the large computational cost. However, thanks to the recent progress of the computer environment and the development of efficient numerical methods, three-dimensional wave-based analyses are being put into practical use. For example, analyses using the fast multipole boundary element method (FMBEM) \[93,94\], which is a highly efficient BEM with the use of the fast multipole method (FMM) \[66,95,96\], and analyses using the FDTD method \[97\] have been reported.

A6.1.4. Notes on using BEM

(1) Size of boundary elements

The size of boundary elements should be set less than 1/5 of the wavelength \[98,99\]. If possible, a size of 1/8 of the wavelength or less is preferable.

(2) Avoidance of internal resonance

Careful attention should be paid to avoid the phenom-
enon that unexpectedly large errors occur at specific frequencies that depend on the dimensions of an obstacle owing to its internal resonance. This phenomenon is called the non-uniqueness problem or the fictitious eigenfrequency difficulty. Several calculation methods to avoid this problem have been reported [100–103].

(3) Analysis around thin objects
When the basic BEM is applied to an object that is thinner than the boundary element size, calculation error may occur owing to the proximity of the boundary elements on both sides of the object and the singularity of the kernel function of the boundary element integration. To deal with this problem, the normal derivative formulation in the BEM is often used with degenerate boundaries, i.e., zero-thickness boundaries [104]. When using the basic formulation, it is necessary to discretize the boundary with boundary elements, the width of which is the thickness of the object or less.

(4) Absorptive surfaces on top part of the barrier
When using edge-modified barriers (see Reference R2), sound absorption materials at the top part of the barriers are sometimes treated. In wave-based numerical analyses, the boundary condition of a sound absorption material is usually given as the specific acoustic impedance of the material surface, assuming the locally reactive condition (see A6.3.3). However, if the specific acoustic impedance at the top of the barrier is adopted as the absorption characteristics of the absorption material, the diffracted sound over the barrier may be underestimated, resulting in overestimation of the barrier effect. In such cases, it is desirable to carry out the calculation with an extended reaction model, in which the sound propagation inside the absorption material is simulated [105].

A6.1.5. Notes on using FMBEM [106]
(1) Proper use according to frequency range
When using the FMBEM, it is desirable to use two types of FMBEM: the FMBEM for low-frequency range (LF-FMBEM) [94] and the FMBEM for high-frequency range (HF-FMBEM) [93], from the viewpoint of computational efficiency. Here, the range where the non-dimensional wavenumber $kD$ is small is called the low-frequency range, and the range with large $kD$ is called the high-frequency range, where $D$ is the size of cells that group the boundary elements in the FMBEM. Hybrid methods of both types have also been proposed [107,108].

(2) Treatment of ground
In the BEM, the calculation boundaries can be limited to those of only objects above the ground surface by regarding the ground surface as an infinite rigid plane and including the contribution from the mirror image reflected by the ground surface in the fundamental solution (Green’s function). On the other hand, this technique cannot be applied directly to the FMBEM. Some efficient techniques in the FMBEM for plane-symmetric sound fields have been proposed [109,110].

A6.1.6. Notes on using FDTD method
(1) Selection of difference scheme
When using the simplest Yee algorithm [111], serious numerical error due to accumulating dispersion error occurs in the case where a large number of calculation steps of $10^3$ order or more are executed. To reduce the dispersion error, a higher-order difference scheme represented by the FDTD (2,4) scheme [112] should be applied.

Note: To reduce the numerical dispersion error, various differential schemes, such as the higher-order scheme [113] and the compact scheme [114], have been developed. Calculation methods with higher accuracy related to not only the spatial difference approximation but also temporal integration are being investigated [115].

(2) Spatial grid size of finite difference
The spatial grid size of the finite difference should be set to less than 1/20 of the wavelength for the Yee algorithm considering the relationship between the spatial grid size and the numerical dispersion error. 1/10 of the wavelength or more is applicable when using the higher-order difference scheme such as the FDTD (2,4) method. In the FDTD method, zigzag approximation is usually applied to simulate the object shape because the orthogonal grid system is adopted in the FDTD method. When the shape of the sound field is complicated, an adequate grid size to approximate the shape of the sound field should be set.

(3) Non-reflection boundary
When applying the FDTD method to road traffic noise prediction, it is necessary to set non-reflection termination on the boundaries surrounding the calculation area to realize a scattering condition ensuring that there are only outgoing waves. A perfectly matched layer (PML) [116,117], which is the most frequently applied boundary condition in the FDTD analysis, is desirable. In particular, for the calculation of the diffraction field, for example, the shadow zone behind a barrier or a building, the PML should be applied to avoid unexpected numerical reflections from the surrounding termination because the amplitude of the diffraction sound may be considerably smaller than that of the unexpected numerical reflection from the surrounding termination.

A6.2. Calculation Method of Meteorological Effect
Outdoor sound propagation is strongly affected by the vertical distribution of wind and temperature. The PE method is often used as a calculation method that enables meteorological effects to be considered [118,119].

A6.2.1. Application of PE method
The PE method is a numerical method in the frequency domain for solving the one-way wave equation deduced from the Helmholtz equation; the method treats only the
outgoing wave. Assume a rotationally symmetric sound field having a rotational axis \( z \), as shown in Fig. A6.3, and consider a two-dimensional coordinate system \((r, z)\), where \( z \) is the height from the ground and \( r \) is the horizontal distance from a point source. This two-dimensional sound field is discretized in a rectangular calculation grid, and the sound pressure distribution at the grid points on the \( z \)-axis is firstly set as the starting field condition. According to the range-marching solution procedure, the complex sound pressures at the grid points on the line \( r = \Delta r \) are calculated from the given starting field condition on the \( z \)-axis. In the same manner, complex sound pressures at grid points on the lines \( r = 2\Delta r, 3\Delta r, 4\Delta r, \ldots \) are successively obtained by the range-marching solution technique. This calculation method can consider complex ground impedance. Furthermore, meteorological effects can be taken into consideration by setting the values of the effective sound speed at respective grid points based on the vertical distribution of the vector wind speed and temperature. On the other hand, sound reflection and scattering by acoustical obstacles cannot be considered because the method originates from the one-way wave equation. As a result, the PE method is generally applied to long-range outdoor sound propagation in an open field without any obstructing objects. Two types of calculation method are known: the Crank-Nicolson PE (CN-PE) method, in which the difference equation is constructed by applying the Crank-Nicolson approximation to the differential term of the advection equation, and Green’s function PE (GF-PE) method, in which the plane wave expansions of the two-dimensional sound field solution are used to improve the calculation efficiency.

The PE method for road traffic noise prediction is limited to flat terrain where point sound sources are on the ground surface. When the sound sources are discretely arranged on a target road as shown in Fig. A6.3 and the unit pattern at a receiving point is calculated according to the calculation procedures for sound propagation at a single frequency (see Appendix A5), the correction for the excess attenuation \( \Delta L_{g,ex}(f) \) in Eq. (A5.2) is calculated by the following procedure [36].

As shown in Fig. A6.3, the calculation area for the PE method is the two-dimensional cross section including sound source \( S_i \) and prediction point \( P \). Let the height be \( z \), the wind speed \( V(z) \), the temperature \( T(z) \), and the angle between the wind direction and the cross section \( \theta \). The effective sound speed \( c_{eff}(z) \) at height \( z \) is calculated as

\[
c_{eff}(z) = 331.5 + 0.61T(z) + V(z)\cos\theta. \tag{A6.6}
\]

Assuming this effective sound speed distribution, the PE analysis at frequency \( f \) [Hz] is performed, and the complex sound pressure \( \phi_i(f) \) for propagation from the \( i \)th sound source \( S_i \) to the prediction point \( P \) is calculated.

For a sound field with rigid ground having the same geometrical configuration of \( S_i \) and \( P \) in a homogeneous atmosphere without wind and a vertical gradient of temperature, the complex sound pressure at frequency \( f \), \( \phi_{i,00}(f) \), is calculated by the PE method. After that, the value of the correction for excess attenuation \( \Delta L_{g,ex}(f) \) is obtained as

\[
\Delta L_{g,ex}(f) = 10\log \left| \frac{\phi_i(f)}{\phi_{i,00}(f)} \right|^2. \tag{A6.7}
\]

A6.2.2. Notes on using PE method

(1) Reflection and scattering from acoustical obstacles

The PE method is a wave-based numerical method for calculating sound propagation on a flat ground considering the meteorological effects and the ground effect with finite impedance based on the one-way wave equation. Therefore, sound reflection and scattering by acoustical obstacles cannot be considered in principle.

(2) Restriction of propagation direction

Whereas the PE method has high accuracy for sound propagation along flat ground, the accuracy is degraded at large elevation angles. The limitation of the applicable elevation angle for the CN-PE method is around 30°. For the GF-PE method, the limitation angle is around 75°.

(3) Grid spacing in finite difference

In the CN-PE method, the grid spacings \( \Delta r \) and \( \Delta z \) should be set to 1/10 or less of the wavelength. In the GF-PE method, \( \Delta r \) can be set to approximately 10 times the wavelength.

(4) Non-reflection termination

It is necessary to set an artificial gradually increasing attenuation layer on the upper boundary to simulate the hemi-free field condition. For the calculation of long-range sound propagation, the attenuation layer should be sufficiently thick (approximately 50 times the wavelength) because the sound is incident on the attenuation layer at a shallow angle in the distant region.
A6.3. Common Notes

Some points that should be commonly noted in the methods described in Sections A6.1 and A6.2 are shown here.

A6.3.1. Frequency range of calculation

The calculation is performed over six octave bands between 125 Hz and 4 kHz. For numerical analysis in the frequency domain by the BEM, discrete calculation frequencies should be set within a 1/9-octave interval [120].

Note: When the available computing time or memory is practically limited, the frequency range can be reduced to four octave bands between 250 Hz and 2 kHz, because the dominant components of road traffic noise exist in this frequency range.

A6.3.2. Source position

The sound source is located at the surface of a road.

Note: When using the BEM, sound sources cannot be set on the boundaries. In such cases, the sound sources may be set at points whose heights from the road surface are less than 1/20 of the wavelength [121].

A6.3.3. Setting of absorbing boundary conditions

Complex values of specific acoustic impedance are considered as the boundary conditions of all surfaces in wave-based numerical analysis. A hard boundary such as a absorbing material, their specific acoustic impedance should be set. For ground surfaces, the specific acoustic impedance ratio \( z \) is calculated using Eq. (A6.8) with the effective flow resistivity \( \sigma_e \) [(kPa s)/m\(^2\)] [122], and the specific acoustic impedance \( z \) [(Pa s)/m] is obtained from Eq. (A6.9) using the air density \( \rho \) [kg/m\(^3\)] and the sound speed \( c \) [m/s].

\[
\zeta = 1 + 5.50 \left( \frac{\sigma_e}{f} \right)^{0.632} + i \cdot 8.43 \left( \frac{\sigma_e}{f} \right)^{0.632} \quad (A6.8)
\]

\[
z = \rho c \cdot \zeta \quad (A6.9)
\]

Values of \( \sigma_e \) shown in Table A6.1 are used according to the type of ground surface. Measured values of the specific acoustic impedance of a porous asphalt pavement have been reported in the literature [123].

Note 1: The acoustic characteristics of absorbing materials are generally specified as absorption coefficients. To reflect such characteristics, in many cases, only the real part of the specific acoustic impedance is deduced from the absorption coefficient, and the imaginary part is ignored. When applying such a method to set the specific acoustic impedance, careful attention should be paid to the fact that the effects of absorption are sometimes overestimated [121].

Note 2: The specific acoustic impedance \( z \) of the ground surface obtained using Eqs. (A6.8) and (A6.9) is based on the time convention for the harmonic dependence \( e^{-\text{int}} \). When based on the time convention \( e^{\text{int}} \), the complex conjugate values in Eqs. (A6.8) and (A6.9) should be used.

Appendix A7 SIGNALIZED INTERSECTIONS

For noise prediction at signalized intersections, a precise noise calculation method based on dynamic traffic simulation considering the behavior of each running vehicle with corresponding traffic signal cycles was proposed [124]. In this appendix, other calculation methods, such as a practical method and a simplified method, are described (see Table A7.1).

A7.1. Practical Method [54]

For each signal cycle, noise is separately calculated for vehicles passing a green signal and for vehicles decelerating, stopping, and accelerating at a red signal for each lane. In the calculation, the mean A-weighted sound power level \( L_{WA} \) [dB] is applied as the power level of running vehicles, which is determined by taking account of the component ratios of different vehicle types.

For running vehicles at a green signal, \( L_{Aeq} \) is simply calculated assuming a steady traffic flow. For vehicles under a transient running condition at a red signal, \( L_{Aeq} \) is calculated from \( L_{EA} \), which is determined by the unit pattern of each vehicle, as shown in Fig. A7.1. Then, all vehicles stopping at a red signal are accounted for in the calculation of \( L_{Aeq} \). The total \( L_{Aeq} \) is obtained by summing the energies in the above results.

| Table A7.1 List of noise calculation methods at signalized intersection. |
|---|
| **Calculation method** | **Outline** |
| Practical method | A method of calculating \( L_{Aeq} \) separately for vehicles that pass a green signal under a steady condition and for vehicles that decelerate, stop, and accelerate when the signal is red under a transient running condition [54]. |
| Simplified method | A simple method of calculating \( L_{Aeq} \) by setting \( L_{WA} \) separately for a steady-state flow section and a compound section with steady-state and accelerating flow sections [54]. |
The A-weighted sound power levels near a signalized intersection and the methods used to set various conditions for the red-signal phase are given below.

### A7.1.1. Sound power level near a signalized intersection

1) **Acceleration running condition**

The acceleration running condition is defined as the transitional state from stopping at a signalized intersection to steady running. The speed range is from 1 to 60 km/h. The constant power level (the value obtained when \( V = 10 \) km/h is substituted into the equation for the deceleration running condition) is applied to speeds of less than 1 km/h. Acceleration at speeds exceeding 60 km/h is treated as a steady running condition.

2) **Deceleration running condition**

The deceleration running condition is defined as the transitional state from steady running to stopping at a signalized intersection. The speed range is more than 10 km/h. The sound power level at 10 km/h is applied at speeds of less than 1 km/h. Acceleration at speeds exceeding 60 km/h is treated as a steady running condition.

### A7.1.2. Method to set various conditions

1) **Mean A-weighted sound power level \( \overline{L_{WA}} \)**

For the component ratio \( q \) of heavy vehicles in the two-category classification, the mean A-weighted sound power level \( \overline{L_{WA}} \) is calculated as

\[
\overline{L_{WA}} = a_L + b \log V + 10 \log(1 + c \cdot q),
\]  

(A7.1)

where \( a_L \) is a constant given in the equation of sound power level for light vehicles [dB], \( b \) is a coefficient representing the speed dependence, \( V \) is the running speed [km/h], and \( c \) is the conversion coefficient of the sound power level from a heavy vehicle to a light vehicle, which is calculated using the following equation with the constant \( a_H \) in the equation for the sound power level for a heavy vehicle:

\[
c = 10^{(a_H - a_L)/10} - 1.
\]  

(A7.2)

In the case of a dense asphalt pavement, the values to be applied for \( a_L, a_H, \) and \( b \) are given in Table A7.2. In the case of a porous asphalt pavement, the \( \overline{L_{WA}} \) can be calculated using the values given in Table A4.1.

### Table A7.2

| Running condition | \( a_L \) | \( a_H \) | \( b \) |
|-------------------|----------|----------|-------|
| Acceleration      | 82.3     | 88.8     | 10    |
| Deceleration      | 45.8     | 53.2     | 30    |

### (2) Setting of traffic volume

The number of vehicles that stop at a red signal during one signal cycle \( N_R \) [number of vehicles/cycle] is set as

\[
N_R = N_C \cdot \frac{T_R}{T_C},
\]  

(A7.3)

where \( N_C \) is the number of vehicles that pass through the intersection in one signal cycle [number of vehicles/cycle], \( T_R \) is the duration of the red signal during one signal cycle [s], and \( T_C \) is the length of time of one signal cycle [s].

### (3) Accelerations of vehicles

The accelerations while accelerating and decelerating at signalized intersections are shown in Table A7.3.

### (4) Mean headway and source positions of vehicles that stop at red signal

The mean headway position \( d \) [m] of vehicles that stop at a red signal is calculated as

\[
d = d_L + (d_H - d_L) \cdot q,
\]  

(A7.4)

where \( d_L \) is the spacing of light vehicles that stop at a red signal (= 6) [m], \( d_H \) is the spacing of heavy vehicles that stop at a red signal (= 12) [m], and \( q \) is the component ratio of heavy vehicles. The source position of \( x_n \) [m] (distance from the stop line) of the \( n \)th vehicle that stops at a red signal is calculated as

\[
x_n = (n - 0.5)d.
\]  

(A7.5)

### (5) Mean running speed when turning left/right

The mean running speed when turning left or right is set to 20 km/h. However, speeds while accelerating to 20 km/h are calculated using the accelerations shown in Table A7.3.
the time \( T \) of each section is calculated as taking account of the traffic volume.

The length of the mixed section with accelerating and steadily running vehicles is determined by summing the section lengths \( l_{\text{stop}} \) [m] and \( l_{\text{accel}} \) [m], where \( l_{\text{stop}} \) is the distance from the front of the first vehicle to the rear of the last vehicle when vehicles stop at a red signal and \( l_{\text{accel}} \) is the distance traveled by the first vehicle when it accelerates to a constant speed after the signal turns green. The length of each section is calculated as

\[
l_{\text{stop}} = d \cdot N_R, \tag{A7.6}
\]

\[
l_{\text{accel}} = \frac{v^2}{2a_{\text{accel}}}, \tag{A7.7}
\]

where \( a_{\text{accel}} \) is the acceleration while accelerating \([m/s^2]\) given in Table A7.3 and \( v \) is the speed in the steadily running section \([m/s]\). A steady-running section is specified on both sides of the mixed section.

(2) Mean A-weighted sound power level \( L_{WA} \)

The mean sound power level \( L_{WA} \) for the steady-running section is calculated using Eq. (A7.1). On the other hand, \( L_{WA} \) for the mixed section with accelerating and steadily running vehicles is determined from the mean sound power level \( L_{W,AR} \) [dB] under the steady-running condition (when the signal is green) and from \( L_{W,A} \) [dB] under the accelerating condition, by averaging the power using the component ratio of the traffic volume that passes through the intersection at each signal phase. The mean sound power level is calculated as

\[
L_{WA} = 10 \lg \left( \frac{N_R \cdot 10^{L_{W,AR}/10} + (N_C - N_R) \cdot 10^{L_{W,A}/10}}{N_C} \right), \tag{A7.8}
\]

where \( L_{W,AR} \) is calculated by substituting the speed given to vehicles in the steady-running section with the speed in the equation for calculating the sound power level for accelerating vehicles.

A7.2. Simplified Method [54]

The noise is calculated assuming that all vehicles modeled in the practical method are represented by a single vehicle with a constant speed along a steady-running section. The road is divided into two sections. In one section, all vehicles run steadily, and in the other, some vehicles stop then accelerate at a red signal (a mixed section with accelerating and steadily running vehicles). The mean sound power level \( L_{WA} \) of a vehicle is separately given for each section. The concept of a mixed section with accelerating and steadily running vehicles and a steady-running section is illustrated in Fig. A7.2, and an illustration of a unit pattern is shown in Fig. A7.3. \( L_{\text{eq},T} \) is calculated using Eq. (1.6) in Chapter 1 of the main body by taking account of the traffic volume \( N_T \) [vehicles] during the time \( T \) [s] and \( L_{AE} \), which is obtained from the energy integration of the unit pattern.

(1) Setting of mixed section and steady-running section

The length of the mixed section with accelerating and steadily running vehicles is determined by summing the section lengths \( l_{\text{stop}} \) [m] and \( l_{\text{accel}} \) [m], where \( l_{\text{stop}} \) is the distance from the front of the first vehicle to the rear of the last vehicle when vehicles stop at a red signal and \( l_{\text{accel}} \) is the distance traveled by the first vehicle when it accelerates to a constant speed after the signal turns green. The length of each section is calculated as
cases with and without detached houses, respectively. The term related to $P_{i}(C_{18}/C_{1}/C_{8})$ indicates reflection sound components. In this calculation method, the geometrical reflections of the first and second orders from the detached houses, which are located between the target road and the prediction point and immediately behind the prediction point, are considered. As shown in Fig. A8.2, $\theta_i$ is the perspective angle [rad] from the first- or second-order mirror point, $P'$ or $P''$, of the prediction point $P$ to a portion of the 10-m-long target road, $d_{\text{road}}$ is the perpendicular distance between $S$ and $P$, and $d_{\text{ref},i}$ is the perpendicular distance between $S$ and $P'$ or $P''$ (horizontal distance from $P'$ or $P''$ to a foot on the perpendicular line at $S$).

The term related to $\frac{1}{n} \sum_{k=1}^{n} \left( \frac{0.351}{0.322 + \xi} \right)$ indicates the diffracted sound from the source $S$ to the prediction point $P$ via a vertex of a building $O$, as shown in Fig. A8.3. For the calculation of this term, a number ($n$) of discrete source points $S_k$ are set on a part of the 10-m-long target road, and the diffraction path difference $S_kO + OP - S_kP$ is calculated as $\delta_i$ [m]. When $P$ is visible from $S_k$, the diffraction sound is not calculated.

The term related to $10^{-0.0904\xi_{\text{disp}}}$ indicates sounds other than the direct, reflected, and single diffraction sounds. As shown in Fig. 6.4, a 15-m-wide rectangular area is assumed between $S$ and $P$, and the density of the houses (the ratio of the location area of the detached houses to the rectangular area) $\xi$ and the horizontal distance $d_{\text{SP}}$ between $S$ and $P$ are calculated.

**REFERENCES**

**Reference R1  NOISE REDUCTION EFFECT OF DOUBLE-LAYER POROUS ASPHALT PAVEMENT**

The double-layer porous asphalt pavement (DPA) adopted in Japan is made of porous asphalt formed in layers with the top layer having maximum chipping sizes of 5–8 mm and thicknesses of 15–20 mm and the bottom layer with a maximum chipping size of 13 mm and thicknesses of 30–50 mm [128–130]. Figure R1.1 shows the structures of DPA and a single-layer porous pavement (PA).

(1) **Noise reduction effect**

Figure R1.2 shows the maximum A-weighted sound pressure levels of a passenger car and a large-sized vehicle measured on test tracks with DPA, PA, and a dense asphalt pavement (DA) [131]. Figure R1.3 shows the noise reduction effect of DPA, which was calculated using the curves representing regression equations given in Fig. R1.2. It can be seen that the A-weighted sound pressure level on DPA decreases by 5–10 dB compared with that on DA and by 4–6 dB compared with that on PA.

(2) **Frequency characteristics of running noise**

Figure R1.4 shows the maximum A-weighted sound pressure levels in 1/3 octave bands on DPA, PA, and DA.
These data represent the sound spectra of the noise of vehicles running at a constant speed of 60 km/h measured on each pavement type (see Fig. R1.2). The sound pressure levels on DPA at a frequency over 500 Hz are much lower than those on DA. Moreover, the sound pressure levels of DPA in the frequency range from 200 Hz to 1 kHz are lower than those of PA.

(3) Aging variation in noise reduction effect
Aging variation in the noise reduction effect of DPA was measured on general roads [130,132]. According to these reports, the aging variation in the noise reduction effect of DPA is similar to that of PA.

Reference R2  SOUND PROPAGATION AROUND BARRIERS WITH OVERHANGS AND EDGE-MODIFIED BARRIERS

To reduce diffracted noise more efficiently than by using a standard simple barrier, edge-modified barriers or barriers with overhangs are sometimes built along roads. In this reference, methods for calculating sound propagation around these barriers are described. Here, a barrier with its top part simply folded is called a barrier with an overhang, and a barrier with acoustic devices at the top edge is called an edge-modified barrier.

Equations obtained through experiments have been reported for the five types of barrier shown in Fig. R2.1 [133]. For other types of barrier including newly developed ones, it is necessary to derive similar equations through scale-model experiments or full-scale experiments.

The correction for diffraction around edge-modified barriers and barriers with overhangs shown in Fig. R2.1 is calculated using the following equations for each corre-
sponding situation regarding the positions of source point S and prediction point P shown in Fig. R2.2.

(For barriers with overhangs)

\[ \Delta L_{\text{dif,ob}} = \Delta L_{\text{dif,hb}} + C_{\text{dif,ob}} \]  \hspace{1cm} (R2.1)

(For edge-modified barriers)

\[ \Delta L_{\text{dif,emb}} = \Delta L_{\text{dif,hb}} + C_{\text{dif,emb}} \]  \hspace{1cm} (R2.2)

Here \( \Delta L_{\text{dif,ob}} \) and \( \Delta L_{\text{dif,emb}} \) [dB] are the correction terms for diffraction around the barrier with an overhang and the edge-modified barrier; \( \Delta L_{\text{dif,hb}} \) [dB] is the correction term for a hypothetical simple barrier whose top edge corresponds to the intersection O of two straight lines SX and PY: a line through the point source and the source-side diffraction point, and a line through the prediction point and the receiver-side diffraction point, as shown in Fig. 3.8; and \( C_{\text{dif,ob}} \) and \( C_{\text{dif,emb}} \) are the correction terms for the overhang and acoustic device, respectively.

When the prediction point P is located in Region 1 or Region 2 as shown in Fig. R2.2, \( C_{\text{dif,ob}} \) and \( C_{\text{dif,emb}} \) are calculated using the following equations.

\[
\begin{align*}
C_{\text{dif,ob}} & = \left\{ \begin{array}{ll}
-A - B \lg \delta + C_{\text{Region2}} & \delta \geq 1 \\
-C - D \sinh^{-1} \delta^E + C_{\text{Region2}} & 0 \leq \delta < 1
\end{array} \right. \\
C_{\text{Region2}} & = \max \{ F \lg \theta + G, 0 \} 
\end{align*}
\]  \hspace{1cm} (R2.3)

\[
C_{\text{dif,emb}} = \max \{ A, B, C, D, E, F, G \} 
\]  \hspace{1cm} (R2.4)

Here \( \delta \) is the path difference for the hypothetical simple barrier [m], \( \theta \) is the angle between XY and XP in Fig. R2.2 [deg], and \( \max \{ a, b \} \) gives the larger value of \( a \) and \( b \). Values for coefficients \( A \) to \( G \) are given in Table R2.1.

Note 1: Because the equations for \( C_{\text{dif,ob}} \) and \( C_{\text{dif,emb}} \) are derived from the experimental results with absorptive barriers, they should not be corrected with the correction term \( C_{\text{dif,abs}} \) for the absorption effect of the standard metallic absorptive-type barrier, defined as Eq. (3.6).

Note 2: The prediction accuracy for barriers with overhangs in Region 3 has not been verified.

Note 3: Procedures for calculating the A-weighted sound pressure level using the correction term \( \Delta L_{\text{dif,ob}} \) or \( \Delta L_{\text{dif,emb}} \) in wave-based numerical analysis are shown in Ref. [134].
If a road is straight and infinitely long and the sound diffraction and the effects of the ground are ignored, \( L_{\text{Aeq}} \) can be determined using an analytical solution [135].

\[
L_{\text{Aeq}}; T \text{ can be calculated using the following equation involving the single-event sound exposure level } LE_A [\text{dB}] \text{ and the traffic volume } NT [\text{number of vehicles}] \text{ passing a prediction point during the time } T [\text{s}]:
\]

\[
L_{\text{Aeq}}; T = LE_A + 10 \log \left( \frac{NT}{T} \right) \tag{R3.1}
\]

Then, \( L_{\text{Aeq},T} \) can be calculated as

\[
L_{\text{Aeq},T} = L_{WA} - 10 \log l - 10 \log V + 10 \log NT + 10 \log \left( \frac{3.6}{2T} \right) . \tag{R3.3}
\]

Since \( L_{WA} \) is given for each vehicle category, \( L_{\text{Aeq},T} \) for the entire traffic is calculated by the energy summation of the obtained results for respective vehicle types.

### Reference R4 STUDY OF PREDICTION ACCURACY

The calculation models of sound power levels of road vehicles and calculation methods of sound propagation were updated so that the calculated value becomes more accurate to the measured road traffic noise. Since many assumptions are included in setting the power level of running-vehicle noise and in simplifying the calculation of noise propagation in ASJ RTN-Model 2018, it is necessary to examine the prediction accuracy of this model.

Here, we describe the results of an investigation in which actual measurement values are compared with values predicted using the previous model. In addition, it is necessary to note that several types of uncertainty are included in the actual measurement values. We also
examine the causes of errors that are likely to be significant when considering the prediction accuracy of ASJ RTN-Model 2018.

R4.1. Relationship between Predicted and Measured Values at General Road Section [136]

R4.1.1. Actual measurement data used in this examination

The actual measurement data were obtained at straight sections of general roads in fiscal year 2013 based on the manual of constant monitoring of motor vehicle traffic noise [137] by the Japanese Ministry of the Environment. The measurements were in accordance with JIS Z8731:1999, which is almost identical to ISO 1996-1:2016. The measurement conditions of these data are as follows.

1) Noise levels considered

$L_{Aeq}$ and $L_{AN}(L_{AS}, L_{AI0}, L_{AS0}, L_{AS0}, L_{AS5})$. The measurement duration was 10 min, and multiple measurement were performed over 24 h at each location.

2) Measurement point

1.2 m above the ground on a public/private boundary. The selected measurement points were away from juxtaposed roads or road intersections, and without obstructions or glass ground in the sound propagation path. The number of lanes was from 1 to 4.

3) Traffic volume

The traffic volume was determined with the three-category or two-category vehicle classification for each direction. The number of motorcycles was also counted separately. The traffic volumes of the target roads were less than 4,500 per hour, and the ratio of heavy vehicles varied widely (from 0% to 100%).

4) Running speed

Obtained for both directions. The measurement data of traffic flow with running speed less than 40 km/h were excluded from the examination.

R4.1.2. Calculation

The predicted values were obtained using the calculation procedures described in Reference R3; the A-weighted sound power levels $L_{WA}$ on a dense asphalt pavement in a steady traffic flow section were used. Multiple lanes of traffic traveling in the same direction were combined into a hypothetical single lane at the center of the traffic stream.

R4.1.3. Comparison of predicted and measured values

The relationship between the predicted and actual measurement values for daytime (6:00–22:00) and nighttime (22:00–6:00) is shown in Fig. R4.1. In the scatter diagrams, the line where the predicted and measured values coincide and its 3 dB range are also shown. The correlation coefficients were 0.81 for daytime and 0.85 for nighttime. The mean differences between the predicted and measured values ($\Delta$, predicted $L_{Aeq}$ minus actual measurement values) were +0.4 and −0.8 dB for daytime and nighttime, respectively, indicating excellent agreement between the two values. For daytime, 87% of the prediction was included within the ±3 dB range, where 78% was included for nighttime.

R4.2. Relationship between Predicted and Measured Values on Roadside of Expressway [138]

R4.2.1. Actual measurement data used in this examination

The actual measurement data were obtained at expressways with bank and cut road structures in fiscal years from 2014 to 2018. A summary of seven selected measurement points is shown in Table R4.1.
(1) Noise levels considered

$L_{Aeq}$ and $L_{A95}$ (the lower limit of the 90% percentile range). The measurement duration was 2 h for road 1–6, while the duration was 15 min for road 7.

(2) Measurement point

The roadside measurement points were 1.2 m above the ground surface. The reference measurement points for the bank roads (roads 1–6) were 1.2–2.8 m above the road surface at a distance of 7.5 m from the center of the closest cruising lane. For the cut road (road 7), the reference point was 3.0 m above the 2.0-m-high noise barrier on the top of the slope.

(3) Traffic volume

The traffic volume for the bank roads (roads 1–6) was determined with the three-category vehicle classification for each direction and each lane. Buses and motorcycles were separately counted. The traffic volume for the cut road (road 7) was counted by traffic counter with the two-category vehicle classification for each direction and each lane.

The traffic volumes of the target roads (roads 1–7) were from 800 to 4,000 per hour, and the ratio of heavy vehicles were varied from 17% to 32%.

(4) Running speed

For the bank roads (roads 1–6), the running speed of traffic was determined for each direction, each lane, and each type of vehicle by visual measurements. For the cut road (road 7), the running speed measured by the traffic counter for each direction and each lane was used. The average running speeds of the target traffic were from 80 to 110 km/h.

R4.2.2. Calculation

The predicted values were obtained by the calculation procedure described in Subsection 1.3.2 using actual measured traffic conditions.

The calculation position for each lane was located at the center of the lane. The corrections for the diffraction on the top of the slope of the bank structures were calculated by the method for the wedge with an opening angle. The correction for the noise barrier was calculated by the method for the knife wedge. The correction for the absorptive barrier was also involved. Regarding the correction of the ground effect for the slope surface, the coefficients for loose soil were used, while the correction was set to 0 dB for the ground of the measurement side since the surfaces were covered by an asphalt pavement. The correction for atmospheric absorption was also involved. Since the roadside measurement point of the cut road (road 7) was behind a noise barrier, two types of calculation were performed with and without taking account of the reflection from the ground (see Note 5 in Section 3.3).

R4.2.3. Comparison of predicted and measured values

The relationship between the predicted and actual measurement values for each road structure is shown in Fig. R4.2. For the bank roads, the reflection of the ground was considered. Since the measured $L_{Aeq}$ were at least 10 dB higher than $L_{A95}$, no correction of background noise was performed.

For the bank roads, the predicted values corresponded to within 3 dB of the measured values. With regard to the porous asphalt pavements, the mean differences between the predicted and measured values ($\Delta$, predicted value of $L_{Aeq}$ minus actual measurement values) were $+0.6$ and $+0.8$ dB at the reference and roadside points, respectively. The mean differences for the KOUKINOU II pavement, even though there was only one case, were $+0.8$ dB at the reference and $+1.5$ dB at the roadside points.

For the cut road, the mean differences between the predicted and measured values at the roadside point were $+0.3$ and $-1.6$ dB in the case with and without taking account of the ground reflection, respectively. The prediction considering the ground reflection showed better agreement with the actual measurement.

R4.3. Accuracy Verification of Practical Calculation Method for Areas behind Buildings [139]

In ASJ RTN-Model 2018, a practical calculation method is provided for predicting noise behind a dense building complex (Section 6.2). Two types of verification of the predicted and measured values were explained in this section: the correspondence of A-weighted sound pressure level using test vehicles and the correspondence of
A-weighted equivalent continuous sound pressure levels using road traffic census data.

R4.3.1. Verification using measurement value using test vehicles

Unit patterns in areas behind buildings were verified for the situation in which test vehicles run on a plane road or a cut road at a steady speed.

(1) In a residential area facing a plane road

The correspondence between the prediction and actual measurement values was examined in areas behind buildings facing a plane road. The test vehicles were independently passing by at a constant speed. The running speed and the A-weighted sound power level of the test passenger cars were estimated to be 35.6 km/h and 92.5 dB, respectively. Those of the test motorcycles were estimated to be 46.1 km/h and 97.4 dB, respectively.

The prediction and actual measurement values of the maximum A-weighted sound pressure level \( L_{A,F_{\text{max}}} \) at 9 points behind the buildings are shown in Fig. R4.3. Regardless of vehicle type, the differences between the prediction and actual measurement values were within approximately ±3 dB.

(2) In a residential area facing a cut road

The correspondence in areas behind buildings facing a cut road was examined. A test vehicle (passenger car) was independently passing by at a constant speed of 41.9 km/h, and its A-weighted sound power level was estimated to be 98.6 dB.

The prediction and actual measurement values of the maximum A-weighted sound pressure level \( L_{A,F_{\text{max}}} \) at 9 points behind the buildings are shown in Fig. R4.4. The calculations were performed with the correction of the diffraction on the top of the slope (shown as filled circles) and without correction in which the road surface level was equal to the ground of the residences (shown as open circles). The results demonstrate that the practical calculation method can be applied to areas facing a cut road with correction of the diffraction on the top of the slope and the attenuation by buildings. The differences between the prediction and actual measurement values were within approximately ±3 dB.

R4.3.2. Verification using road traffic census data

Equivalent noise levels were calculated in areas behind buildings facing plane roads, hereinafter called as Road-A...
and Road-B, to examine the prediction accuracy and to develop a noise map. In this calculation, road traffic census data were used for estimating the traffic conditions. As the results of the estimations for road-A, the hourly traffic volume consisted of 3,370 small-sized vehicles and 996 large-sized vehicles, and the average running speed was 36.7 km/h. The A-weighted sound power levels of the vehicles were determined to be 92.7 dB for the small-sized vehicles and 100.1 dB for the large-sized vehicles on the assumption that the vehicles were running at a steady speed, since the measurement point was distant from the signalized intersections and its traffic was steady. As the results of the estimations for Road-B, the hourly traffic volumes consisted of 768 small-sized vehicles and 64 large-sized vehicles, and the average passage speed was 19.9 km/h. The A-weighted sound power levels were determined to be 95.3 dB for the small-sized vehicles and 101.8 dB for the large-sized vehicles on the assumption that the vehicles are not running at a steady speed owing to the traffic signals along Road-B.

Figure R4.5 shows that the differences between the prediction and actual measurement values at the intended Road-A and Road-B were within approximately ±3 and ±5 dB, respectively.

**R4.4. Causes of Errors in ASJ RTN-Model 2018**

**R4.4.1. Setting of hypothetical traffic lanes**

In ASJ RTN-Model 2018, it is permitted to combine two or more lanes into a single hypothetical lane for simplicity of the calculation. According to a previous investigation [140], the difference in $L_{Aeq}$ caused by combining the lanes into a single lane was less than 1 dB, even in the case of a road with eight lanes, if the distance from the center of the nearest lane to the receiver was 5 m or more. However, the error increases markedly when the distance to the receiver is less than 5 m. Thus, when noise is predicted in the vicinity of roads with multiple lanes, it is recommended to increase the number of hypothetical lanes.

**R4.4.2. Road traffic conditions**

1. **Variations of vehicle running speed and sound power level**

   In ASJ RTN-Model 2018, the sound power level of a road vehicle is calculated under the assumption that all vehicles classified in each category run at the same speed (i.e., at the mean speed of all vehicles). According to the results of examination from a stochastic viewpoint [141], the change in $L_{Aeq}$ due to the variation of running speed is extremely small. Furthermore, the change in $L_{Aeq}$ is 1 dB or less if the standard deviation of the power level is 3 dB or less.

2. **Vehicle classification**

   In ASJ RTN-Model 2018, two types of vehicle classification are applied: the three-category classification (small-sized vehicles, medium-sized vehicles, and large-sized vehicles) and the two-category classification (light vehicles and heavy vehicles). It is preferable to apply the former classification. However, even when the two-category classification is applied, the errors in the predicted values caused by replacing the two-category classification with the three-category classification are 1 dB or less if the ratio of medium-sized vehicles to large-sized vehicles ranges from 10 to 80% [136].

**R4.4.3. Range of unit pattern calculation**

In the basic scheme of ASJ RTN-Model 2018, point sources are discretely set on lanes to obtain the unit pattern.
at the receiver, and then $L_{Aeq}$ is calculated. In this case, it is necessary to determine the range over which the point sources must be arranged. In other words, the range of the unit pattern calculation is essential. In Ref. [140], on the basis of the calculated unit patterns for flat roads, interchange sections, and the areas surrounding a tunnel portal, the errors in $L_{Aeq}$ caused by removing the low-level portions of the unit pattern (i.e., the portions where the A-weighted sound pressure level is 5, 10, or 15 dB smaller than the maximum) are examined. As a result, it was found that the errors are approximately 1 dB or less even when the low-level portions 10 dB below the maximum for flat roads and for interchange sections or 15 dB below the maximum for areas surrounding a tunnel portal are removed. However, since $L_{Aeq}$ strongly depends on the energy integration over the entire unit pattern, it is necessary to note that a significant error may occur owing to the lack of consecutive portions of the unit pattern. Hence, it is necessary to avoid the excessive removal of portions, even if the A-weighted sound pressure levels are sufficiently smaller than the maximum.

**R4.4.4. Problems encountered in actual measurements**

In addition to considering problems in the prediction calculation, it is necessary to consider the causes of uncertainties in the actual measurements of road traffic noise. Typical causes of uncertainties are discussed below. It is also necessary to consider the measurement duration necessary to stabilize the values of $L_{Aeq}$ statistically.

(1) **Effects of meteorological factors**

When sounds propagate outdoors, the effects of the temperature profile and wind in the atmosphere appear as propagation distance increases. Attenuation may also occur owing to atmospheric absorption, which depends on atmospheric temperature and humidity. Among these effects, the wind and temperature profiles are extremely complicated, and it is still difficult to take these effects into account in practical noise prediction. Thus, only the variation of road traffic noise as affected by wind, which is based on actual measurement results, is introduced in ASJ RTN-Model 2018, as described in Section 3.6. Sound propagation may also be affected by the temperature gradient. However, its effect can be ignored for propagation distances of up to approximately 200 m, unless extreme temperature inversion occurs. For attenuation caused by atmospheric absorption, a comparatively precise calculation is available, as described in Section 3.4.

(2) **Influence of background noise**

In the measurement of road traffic noise, other types of noise (background noise) always affect the measurement results to some extent. In particular, the effect of background noise is larger when the receivers are far from the road or noise reduction measures such as noise barriers are provided. Although several methods of estimating the degree of background noise have already been investigated, an approximate background noise level can be estimated by simultaneously measuring the percentile level, $L_{A90}$ or $L_{A95}$, along with $L_{Aeq}$.

**3) Effect of other factors**

Since road traffic noise may be measured under circumstances that are not taken into account in the prediction, not only the causes described above but also various other causes of errors must be considered, for instance, errors caused by traffic flow conditions that are different from those set in the prediction or a difference in the performance of noise reduction measures such as noise barriers due to their installation condition. For a porous asphalt pavement, although the noise reduction effect and its change with time after the installation are taken into account in ASJ RTN-Model 2018, the deterioration of its performance caused by the blockage of air pores may significantly depend on its location. In the case of a viaduct, not only structure-borne noise, which is already taken into consideration in ASJ RTN-Model 2018, but also noise from the expansion joints of the road may often be included in actual measurement values.

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