Road traffic noise prediction model “ASJ RTN-Model 2013”: 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-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 “Environment 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] and ASJ RTN-Model 2008 [10] were completed and published in April 2004 and April 2009, respectively.

ASJ Model 1998 and newer models were comprehensively adopted in the “Technical Method for Environmental Impact Assessment of Roads” and has been widely used for road traffic noise prediction (the assessment of future environments) in Japan [11,12]. 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 2008. After five years of research and investigation, the new model, “ASJ RTN-Model 2013,” has been completed and is published in this Journal.

Table 1.1 shows the organization and the members of the committee. In this report, the results of research and
investigation are summarized. Each study group contributed to the assigned chapters.

Summary of the revisions in the current version
The contents of ASJ RTN-Model 2013 are shown in Table 1.2. The current model is based on ASJ RTN-Model 2008 to which the following revisions were made.

(1) Sound source description
- The latest knowledge on the A-weighted sound power level of hybrid vehicles (HVs) and electric vehicles (EVs) are shown in Reference R1.
- The latest knowledge on the noise reduction effect of double-layer drainage asphalt pavement is shown in Reference R2.

(2) Calculation of sound propagation
- The correction due to sound attenuation by an absorptive barrier is newly added.
- The calculation method for frequency-dependent propagation is updated. The content is described in Appendix A2.
- For a calculation method based on the wave-based numerical analyses, the contents are updated. The details are shown in Appendix A4.

(3) Special road sections
- At interchange sections, the running speed and acceleration of vehicles passing a tollgate, where an electronic toll collection (ETC) system is installed, are provisionally determined on the basis of in situ measurements.
- For a simple calculation method using a directional point source model at a semi-underground road, the correction for the dimensions of a semi-underground road structure has been revised so that the calculation method becomes more versatile. Furthermore, a correction for the noise reduction effect of an absorptive louver installed on a semi-underground road is newly added.

(4) Effects of individual buildings and built-up areas
- In built-up areas, calculation methods using a point source model have been provided so far. In this model, calculation methods using a point source model are newly added.

ACKNOWLEDGEMENTS
On the occasion of releasing the new prediction model, the committee would like to express its sincere thanks to the National Institute for Land and Infrastructure Management and Nippon Expressway Research Institute Co., Ltd., who provided opportunities to conduct research activities concerning road traffic noise, financially supported our research project and contributed valuable documents. The committee would also like to thank the Ministry of the Environment, Metropolitan Expressway Co., Ltd., and Nagoya Expressway Public Corporation, for their participation in our meetings and for their valuable suggestions.

MAIN BODY

1. OUTLINE OF THE PREDICTION METHOD (GENERAL PROCEDURE)
In this chapter, the scope of ASJ RTN-Model 2013, 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 2013 are as follows. For conditions related to the structure-borne noise of viaducts, refer to Chap. 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 2013 are as follows.
(1) A-weighted sound pressure level \( (L_A) \)

The definition corresponds to \( L_{PAF} \), the F-time-weighted and A-frequency-weighted sound pressure level defined in ISO 1996-1:2003; the symbols \( p \) and \( F \) are omitted for simplicity of notation. It is also called the A-weighted sound level according to IEC 61672-1:2002.

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

The definition complies with ISO 1996-1:2003. The symbol \( T \) can be omitted and represented by the symbol \( L_{Aeq} \) if the time interval is not required to be stated.

(3) Single event sound exposure level \( (L_{AE}) \)

This represents the sound exposure level for a single noise event, for example, when one vehicle passes in front of a receiver. The value (unit: dB) is defined as ten times the common logarithm of the square of the A-weighted sound pressure, which is integrated over the entire time of the event and normalized by the reference time (1 s), i.e.,

\[
L_{AE} = 10 \log \left( \frac{1}{T_0} \int_{t_1}^{t_2} \frac{p_A^2(t) \, dt}{p_0^2} \right),
\]

where \( T_0 = 1 \) s (the reference time), \( p_A(t) \) is the instantaneous A-weighted sound pressure [Pa] at time \( t \) and \( p_0 = 20 \) \( \mu \)Pa (reference sound pressure). The time interval \( t_1 \) to \( t_2 \) [s] is the duration of the noise event.

(4) A-weighted sound power level of running vehicle \( (L_{WA}) \)

This is the decibel value of the A-weighted sound power \( P_A \) [W] (the sound energy emitted in 1 s) radiated from a single running vehicle. The sound power level is determined on the assumption that the vehicle is a point source. It is expressed as

\[
L_{WA} = 10 \log \frac{P_A}{P_0},
\]

where \( P_0 = 1 \) pW (reference sound power). When the sound power level is expressed as a 1/n-octave band component to show the frequency characteristics, it is referred to as the 1/n-octave band sound power level.

(5) 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 generally expressed as a function of time but may be treated as a function of distance along the traffic lane for practical calculation.

(6) 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.

(7) Vehicle classification

Two types of vehicle classification are applicable, that is, a four-category classification (passenger cars, small-sized vehicles, medium-sized vehicles and large-sized vehicles) and a two-category classification (light vehicles and heavy vehicles). In addition, motorcycles are classified as another category.

Note: The sound power levels of hybrid and electric vehicles (HVVs and EVs) are almost the same with that of gasoline engine vehicles (GEVs) at a running speed of 40 km/h or more. Thus, HVVs and EVs are included in the same classification as GEVs.

(8) 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.

(9) Type of pavement

This prediction model is applicable to road surfaces with a dense asphalt concrete pavement and a drainage asphalt concrete pavement with a porous structure. Hereafter, the former is referred to as a dense asphalt pavement and the latter as a drainage asphalt pavement (it might also be referred to as a high-performance pavement or a low-noise pavement).

Note: A drainage asphalt pavement with a maximum chipping size of 13 mm and a designed void content of 20% is considered to be the standard type in this prediction model. In addition, a double-layer drainage asphalt pavement, which has a self-cleaning effect on pore clogging and acoustic absorption properties for enhanced noise reduction, is developed.

(10) Noise barriers

There are two types of noise barriers, 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 with a glass fiber board (50 mm thick and 32 kg/m² dense) covered by a thin protective film. The box is constructed of aluminum plates with slits on the road side and a 1.6-mm-thick galvanized iron plate on the back, to optimize its sound insulation performance.

(11) 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.

(12) Effective (air) flow resistivity ($\sigma_a$)

This is the equivalent flow resistivity (unit: kPa·s/m²) deduced by theoretical curve fitting of frequency characteristics of the excess attenuation observed above a finite-impedance boundary such as the ground surface. This value is explicitly distinguished from the flow resistivity $\sigma$ measured directly from airflow velocity and pressure difference in the medium covering the ground in accordance with the impedance model proposed by Miki [13].

1.3. General Calculation Procedure and Basic Formulas

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

1.3.1. Principles and basic formulas 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 omni-directional point source passing along the road under consideration, and to calculate its time-integrated value over the duration of its passage. 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). Then, one of the sections is selected and a representative point (source point) is set at the center point of the section. In this case, the A-weighted sound power $P_{A,i}$ (or the A-weighted sound power level $L_{WA,i}$) emitted from the source (the vehicle) in the $i$th road section is set, and the A-weighted sound pressure (or the A-weighted sound pressure level) at the prediction point is calculated by applying a formula based on geometrical spreading (inverse-square law). (The running speed $v_i$ and sound power $P_{A,i}$ are assumed constant within the section.)

Then, to add the contributions from all road sections in terms of energy, the squared A-weighted sound pressure $P_{A,i}^2$ is considered to be proportional to the A-weighted sound energy density at the prediction point.

During the time when the sound source exists in the $i$th section $\Delta t_i$ [s], it is assumed to be located at the center position of the section. The A-weighted sound exposure arriving at the prediction point during the interval of duration $\Delta t_i$ (see Fig. 1.2) to give

$$E_{A,i} = p_{A,i}^2 \cdot \Delta t_i = p_{A,i}^2 \cdot \frac{\Delta l_i}{v_i}, \quad (1.3)$$

where $\Delta l_i$ is the length of the $i$th section [m] and $v_i$ is the running speed of the vehicle in the $i$th section [m/s].

The above calculation is performed for every section. Then, the total time-integrated value of the squared A-weighted sound pressure (A-weighted sound exposure) $E_A$ [Pa²·s] at the prediction point when a vehicle travels along the entire road is calculated as

$$E_A = \sum_i E_{A,i} = \sum_i p_{A,i}^2 \cdot \Delta t_i$$

$$= \sum_i p_{A,i}^2 \cdot \frac{\Delta l_i}{v_i} = \sum_i p_{A,i}^2 \cdot \frac{3.6 \Delta l_i}{V_i}, \quad (1.4)$$

where $V_i$ is the running speed of the vehicle in the $i$th section [km/h] ($v_i = V_i/3.6$).

Equation (1.4) is converted to a decibel expression leading to the single-event sound exposure level $L_{AE}$,

$$L_{AE} = 10 \log \frac{E_A}{E_0} = 10 \log \left( \frac{1}{T_0} \int_0^T 10^{L_{Aeq}/10} \cdot \Delta t_i \right), \quad (1.5)$$

where $E_0 = 4 \times 10^{-10}$ Pa²·s (reference sound exposure).

By applying the traffic volume $N_T$ (number of vehicles) during the time interval $T$ [s] to the single-event sound exposure level $L_{AE}$, the equivalent continuous A-weighted sound pressure level $L_{Aeq,T}$ is obtained as

$$L_{Aeq,T} = 10 \log \left( 10^{L_{AE}/10} \cdot \frac{N_T}{T} \right) = L_{AE} + 10 \log \frac{N_T}{T}. \quad (1.6)$$
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 position 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 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.

Note: At special road sections, where the vehicle running speed varies by acceleration-deceleration cycles or the propagation property rapidly changes with the arrangement of the sound source and the prediction point, it may be necessary to shorten the intervals of the discrete sources.

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 $L_{A,i}$ 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.

Fig. 1.3 Calculation procedure for predicting road traffic noise.
Calculation of the energy integration of the unit pattern and \( L_{\text{Aeq}} \)

The time-integrated value of the unit pattern (single-event noise exposure level \( L_{\text{AE}} \)) is calculated. By applying the traffic volume \( N_T \) [number of vehicles] during time interval \( T \) [s] to the above result, the equivalent continuous A-weighted sound pressure level \( L_{\text{Aeq},T} \) is obtained as the mean energy level during the time interval \( T \).

Calculations (1) to (6) are performed by lane and by vehicle type, then \( L_{\text{Aeq},T} \) is calculated by the energy summation of the obtained results to give the total noise level for the entire road at the prediction point.

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 2013, the calculation formula 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 calculation formula for the sound power level in the model is given as a function of the running speed, and the influences of other factors are considered in the correction terms.

#### 2.1. Classification of Road Vehicles

Road vehicles are basically classified into two or four categories, as shown in Table 2.1. The four-category classification places importance on noise radiation characteristics, while 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 [14]. 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:** The four-category classification nearly corresponds to that in road vehicle noise regulations in Japan, which is based on vehicle weight and engine output.

#### Table 2.1 Vehicle categories (excluding motorcycles).

<table>
<thead>
<tr>
<th>Two-category</th>
<th>Four-category</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light vehicles</td>
<td>Passenger cars</td>
<td>Motor vehicles used exclusively for carrying passengers with a capacity of 10 or fewer passengers</td>
</tr>
<tr>
<td></td>
<td>Small-sized vehicles</td>
<td>Motor vehicles with an engine displacement exceeding 0.050 lit. and an overall length of 4.7 m or less</td>
</tr>
<tr>
<td></td>
<td>Medium-sized vehicles</td>
<td>Motor vehicles with an overall length exceeding 4.7 m excluding large-sized vehicles (most vehicles in this category have 2 axles)</td>
</tr>
<tr>
<td></td>
<td>Heavy vehicles</td>
<td>Medium-sized buses with capacities from 11 to 29 passengers</td>
</tr>
<tr>
<td></td>
<td>Large-sized vehicles</td>
<td>Motor vehicles with a gross vehicle weight of over 8t or a maximum authorized payload of over 5t (most vehicles in this category have 3 or more axles)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large-sized buses with a capacity of 30 or more passengers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large-sized special motor vehicles</td>
</tr>
</tbody>
</table>

**Note:** The category for HVs and EVs is included in the same classification for GEVs. New knowledge regarding the sound power level of these vehicles is introduced in Ref. R1.

#### Table 2.2 Vehicle category (motorcycles).

<table>
<thead>
<tr>
<th>Category</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycles</td>
<td>Motorcycles and mopeds</td>
</tr>
</tbody>
</table>
\[ L_{WA} = a + b \log V + C, \] (2.1)

where \( L_{WA} \) is the sound power level [dB], \( V \) is the vehicle speed \([\text{km/h}]\), \( a \) and \( b \) are regression coefficients, and \( C \) is the correction term from a reference value (the power level when the vehicle runs on a dense asphalt pavement constructed within the last several years).

\( L_{WA} \) varies with the road conditions such as the pavement type and road gradient. Because there are various sound sources in a road vehicle and the noise generated from these sources is influenced 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

\[ C = \Delta L_{\text{surf}} + \Delta L_{\text{grad}} + \Delta L_{\text{dir}} + \Delta L_{\text{etc}}, \] (2.2)

where \( \Delta L_{\text{surf}} \) is the correction for a drainage asphalt pavement [dB], \( \Delta L_{\text{grad}} \) 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].

2.2.2. Sound power levels in steady and non-steady traffic flow sections

The values of coefficients \( a \) and \( b \) in Eq. (2.1) are provided separately for the steady- and non-steady traffic flow sections, which are defined as follows.

**Note 1:** The average sound power level under the running conditions including acceleration, deceleration and stopping can be obtained by applying the formula calculated for the non-steady traffic flow section described here.

**Note 2:** The several calculation formulas in the model were developed using the data obtained in 1991–1998. Since then, the committee has been accumulating new data on noise emission of road vehicles. As a result of comparing the sound power levels measured in the 1990s and in recent years, it was found that there are no significant differences between them. Hence, the calculation formulas in this model were not revised from those in the previous model, ASJ RTN-Model 2008 [15].

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 general road including signalized intersections, where vehicles frequently accelerate and decelerate. The vehicle speed \( V \) is in the range from 10 to 60 km/h.

A schematic illustration of the A-weighted sound power level in the steady and non-steady traffic flow sections is shown in Fig. 2.1, and the values of the coefficients \( a \) and \( b \) are given in Table 2.3. The coefficient \( b \), which represents the speed dependence of the noise

**Fig. 2.1** A-weighted sound power level in steady and non-steady traffic flow sections.

generated is 30 for the steady traffic flow section and 10 for the non-steady traffic flow section.

2.2.3. Sound power level in acceleration and deceleration sections

The A-weighted sound power levels during acceleration and deceleration are individually calculated as follows.

**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 formula for the deceleration running condition). 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.

A schematic illustration of the A-weighted sound power level is shown for the acceleration and deceleration running condition in Fig. 2.2(a) and the values of the coefficients \( a \) and \( b \) are given in Table 2.4.

**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.

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.

3) 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 formula 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 10 km/h.

A schematic illustration of the A-weighted sound power level for the acceleration and deceleration running conditions near a junction and signalized intersection is shown in Fig. 2.2(b) and the values of the coefficients $a$ and $b$ are given in Table 2.4.

### 2.3. Correction of Sound Power Level for Various Factors

In this section, the formulas used to calculate the correction for a drainage asphalt pavement, road gradient, sound radiation directivity and other factors are described.

#### 2.3.1. Correction for drainage asphalt pavement

The noise reduction effect due to a drainage asphalt pavement depends on the vehicle type, and also on the number of years since the pavement was constructed. The correction formula is based on measurement data. The correction value for the noise reduction due to a drainage asphalt pavement $\Delta L_{\text{surf}}$ is calculated as follows. In the case of a motorcycle, the correction value is 0 dB.

1) **For general roads**

1) **Stopping**

For both light and heavy vehicles,

$$\Delta L_{\text{surf}} = 0.$$  \hfill (2.3)

2) **Running at 60 km/h or less**

For light vehicles,

$$\Delta L_{\text{surf}} = -5.7 + 7.3 \lg(y + 1).$$  \hfill (2.4)

For heavy vehicles,

$$\Delta L_{\text{surf}} = -3.9 + 3.6 \lg(y + 1).$$  \hfill (2.5)

$y$ denotes the number of years since the pavement was constructed.

**Note:** If $L_{\text{WA}}$ calculated using $\Delta L_{\text{surf}}$ is less than $L_{\text{WA}}$ under the stopping condition, the latter value is used.

(2) **For expressways**

1) **Running at less than 60 km/h**

For light vehicles,

$$\Delta L_{\text{surf}} = -5.7 + 6.4 \lg(y + 1).$$  \hfill (2.6)

For heavy vehicles,

$$\Delta L_{\text{surf}} = -3.9 + 3.6 \lg(y + 1).$$  \hfill (2.7)

2) **Running at 60 km/h or more**

For light vehicles,

$$\Delta L_{\text{surf}} = 3.2 - 5 \lg V + 6.4 \lg(y + 1).$$  \hfill (2.8)

For heavy vehicles,

**Table 2.4** Coefficients $a$ and $b$ near an expressway tollgate, a junction and a signalized intersection.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Expressway tollgate</th>
<th>Junction and signalized intersection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deceleration (10 km/h ≤ $V$ ≤ 140 km/h)</td>
<td>Acceleration (1 km/h ≤ $V$ ≤ 80 km/h)</td>
</tr>
<tr>
<td></td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>Passenger cars</td>
<td>46.4</td>
<td>84.5</td>
</tr>
<tr>
<td>Small-sized vehicles</td>
<td>47.6</td>
<td>85.7</td>
</tr>
<tr>
<td>Medium-sized vehicles</td>
<td>51.5</td>
<td>85.6</td>
</tr>
<tr>
<td>Large-sized vehicles</td>
<td>54.4</td>
<td>92.5</td>
</tr>
<tr>
<td>(b) Two-category</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classification</td>
<td>Expressway tollgate</td>
<td>Junction and signalized intersection</td>
</tr>
<tr>
<td></td>
<td>Deceleration (10 km/h ≤ $V$ ≤ 140 km/h)</td>
<td>Acceleration (1 km/h ≤ $V$ ≤ 80 km/h)</td>
</tr>
<tr>
<td></td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>Light vehicles</td>
<td>46.7</td>
<td>30</td>
</tr>
<tr>
<td>Heavy vehicles</td>
<td>53.2</td>
<td>10</td>
</tr>
<tr>
<td>(c) Motorcycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Classification</td>
<td>Expressway tollgate</td>
<td>Junction and signalized intersection</td>
</tr>
<tr>
<td></td>
<td>Deceleration (10 km/h ≤ $V$ ≤ 140 km/h)</td>
<td>Acceleration (1 km/h ≤ $V$ ≤ 80 km/h)</td>
</tr>
<tr>
<td></td>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>49.6</td>
<td>30</td>
</tr>
</tbody>
</table>
\( \Delta L_{\text{surf}} = 5.0 - 5 \log V + 3.6 \log(y + 1). \)  \hspace{1cm} (2.9)

**Note 1:** These formulas for \( \Delta L_{\text{surf}} \) are based on data for the steady running condition on expressways and general roads, where the pavement had been constructed up to 15 and 7 years previously, respectively [16]. The formulas are also applicable to sections of non-steady running, acceleration running and deceleration running.

**Note 2:** The noise reduction effect of a double-layer drainage pavement is introduced in Ref. R2.

### 2.3.2. Correction for road gradient

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

\[
\Delta L_{\text{grad}} = 0.14l_{\text{grad}} + 0.05l_{\text{grad}}^2, \quad 0 \leq l_{\text{grad}} \leq l_{\text{grad,max}}, \quad (2.10)
\]

where \( l_{\text{grad}} \) is the gradient of the road [%] and \( l_{\text{grad,max}} \) is the maximum applicable gradient; their values at various vehicle speeds are shown in Table 2.5. 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 [17,18].

### 2.3.3. 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 influenced by the body shape, vehicle noise has directivity [19,20]. 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

\[
\Delta L_{\text{dir}} = \begin{cases} 
(a + b \cdot \cos \varphi + c \cdot \cos 2\varphi) \cos \theta & \varphi < 75^\circ \\
0 & \varphi \geq 75^\circ 
\end{cases}, \quad (2.11)
\]

where the coordinate system is shown in Fig. 2.3 and the coefficients \( a, b \) and \( c \) are given in Table 2.6. This equation is applicable to both dense asphalt and drainage pavements, and 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):

\[ \theta = \tan^{-1}(\sin \varphi \tan \theta) \quad \varphi \neq 0. \quad (2.12) \]

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.

### 2.3.4. 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.

### 2.4. Frequency Characteristics of Road Vehicle Noise

The frequency characteristics of road vehicle noise on dense asphalt and drainage asphalt pavements are described in Appendix A1.

**Note:** A comparison between the sound power spectrum adopted in the model and that measured in recent years showed no significant differences between them [21].

| Table 2.5 Maximum applicable gradients at different speeds. |
|-----------------|-----------------|
| Speed [km/h]    | \( i_{\text{grad,max}} [\%] \) |
| 40              | 7               |
| 50              | 6               |
| 60              | 5               |
| 80              | 4               |
| 100             | 3               |

Fig. 2.3 Illustration of coordinate system used for considering sound radiation directivity.

| Table 2.6 Coefficients of correction term for sound radiation directivity. |
|-----------------|-----------------|
| Classification  | Coefficients    |
|                 | \( a \) | \( b \) | \( c \) |
| Light vehicles  | -1.8  | -0.9  | -2.3  |
| Heavy vehicles  | -2.6  | -1.1  | -3.4  |
### Table 3.1 Symbols of correction terms for various types of diffraction.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Symbol</th>
<th>Summary</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental term</td>
<td>$\Delta L_d$</td>
<td>Fundamental term for various types of diffraction</td>
<td>Eq. (3.3)</td>
</tr>
<tr>
<td>Simple barrier (single diffraction)</td>
<td>$\Delta L_{\text{dif, sb}}$</td>
<td>Single diffraction around a simple barrier or top of slope, considering an infinite half-screen</td>
<td>Eq. (3.4)</td>
</tr>
<tr>
<td></td>
<td>$C_{\text{dif, abs}}$</td>
<td>Absorption effect of the standard metallic absorptive-type barrier</td>
<td>Eq. (3.5)</td>
</tr>
<tr>
<td>Finite length barrier</td>
<td>$\Delta L_{\text{dif, fb}}$</td>
<td>Single diffraction around a simple barrier of finite length</td>
<td>Eq. (3.6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Eq. (3.7)</td>
</tr>
<tr>
<td>Thick barrier or embankment</td>
<td>$\Delta L_{\text{dif, dd}}$</td>
<td>Double diffraction around a thick barrier, including an embankment or building</td>
<td>Eq. (3.8)</td>
</tr>
<tr>
<td>Multiple barriers</td>
<td>$\Delta L_{\text{dif, db}}$</td>
<td>Double or triple diffractions due to multiple barriers with a spacing of 5 m or more</td>
<td>Eqs. (3.9)–(3.12)</td>
</tr>
<tr>
<td>Barrier with overhang</td>
<td>$\Delta L_{\text{dif, emb}}$</td>
<td>Diffraction around a barrier with an overhang on the edge</td>
<td>Subsection 3.2.6</td>
</tr>
<tr>
<td>Edge-modified barrier</td>
<td></td>
<td>Diffraction around a barrier with acoustic device on the top edge to reduce diffracted sound</td>
<td>Reference R3</td>
</tr>
<tr>
<td>Low-height barrier</td>
<td>$\Delta L_{\text{dif, low}}$</td>
<td>Single diffraction around a low-height barrier with a height of 1 m or less in a flat terrain; calculated as the insertion loss relative to a barrier with a height of 0 m.</td>
<td>Eq. (3.13)</td>
</tr>
<tr>
<td>Transmission through barrier</td>
<td>$\Delta L_{\text{dif, trans}}$</td>
<td>Summation of diffraction over a barrier and transmission through a barrier</td>
<td>Eq. (3.14)</td>
</tr>
</tbody>
</table>

### 3. METHOD OF CALCULATING SOUND PROPAGATION

An engineering method of calculating outdoor noise propagation considering the decay by distance owing to geometrical spreading (inverse-square law), the diffraction effect, ground absorption and attenuation of sound 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 the method of calculating the reflection and transmission of sound are also described. The overall values (i.e., the summation of all frequency components) of the A-weighted sound pressure level are directly calculated using the method described in this chapter.

The methods of calculating the propagation for each frequency component are described in Appendix A2. For complicated boundary shapes or absorption characteristics, the two-dimensional wave-based numerical analyses described in Appendix A4 or the scale-model experiments [22] can be applied.

#### 3.1. Basic Formula

The A-weighted sound pressure level $L_{A,i}$ [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

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

where $L_{WA,i}$ 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]. $\Delta L_{\text{cor},i}$ 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

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

where $\Delta L_{\text{dif},i}$ is the correction for diffraction [dB], $\Delta L_{\text{grnd},i}$ is the correction for the ground effect [dB] and $\Delta L_{\text{air},i}$ 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 $\Delta L_{\text{dif}}$

The correction for diffraction due to acoustical obstacles such as noise barriers, $\Delta L_{\text{dif}}$, is calculated using $\Delta L_d$ as a function of the diffraction path difference $\delta$. Correction terms for various types of diffraction are listed in Table 3.1. Note that the symbol $\Delta L_{\text{dif}}$ is a generic term used to represent the correction terms in Table 3.1.

**Note:** When the noise reduction effect of diffraction exceeds 30 dB, it may not be so large as to be indicated by the calculated values because of the influence of actual wind conditions.
values in Maekawa’s chart to a chart for values of overall determined by curve-fitting to convert the frequency-dependent

The frequency characteristics of noise from a running vehicle (see Appendix A1). Values of $\Delta L_{\text{spec}}$ are described in Appendix A1.

![Diagram](image1)

(a) For $S$ invisible from $P$

$\delta = L - R$

(b) For $S$ visible from $P$

$\delta = -(L - R)$

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

3.2.1. Fundamental correction term for diffraction, $\Delta L_d$

The fundamental correction term for diffraction, $\Delta L_d$ [dB], is calculated as a function of the path difference $\delta$ [m] (see Fig. 3.1) for diffraction considering the point source $S$, diffraction point $O$ and prediction point $P$:

$$\Delta L_d = \begin{cases} 
-20 - 10 \log(c_{\text{spec}} \delta) \\
5 - 17.0 \cdot \sinh^{-1}(c_{\text{spec}} \delta)^{0.414} & c_{\text{spec}} \delta \geq 1 \\
\min(0, -5 + 17.0 \cdot \sinh^{-1}(c_{\text{spec}} \delta)^{0.414}) & 0 \leq c_{\text{spec}} \delta < 1, \\
-c_{\text{spec}} \delta & c_{\text{spec}} \delta < 0
\end{cases}$$

(3.3)

where $\delta$ is defined as a negative value when $S$ is visible from $P$. The function $\min[a, b]$ gives the smallest value of $a$ and $b$. The coefficient $c_{\text{spec}}$ is defined as shown in Table 3.2. $\Delta L_d$ is illustrated in Fig. 3.2 as a function of $\delta$.

**Note 1:** Equation (3.3) is determined using Maekawa’s engineering chart for diffraction [23,24] and the frequency characteristics of the noise from a running vehicle (see Appendix A1). Values of $c_{\text{spec}}$ are determined by curve-fitting to convert the frequency-dependent values in Maekawa’s chart to a chart for values of overall $L_{\text{pa}}$.

**Note 2:** The frequency characteristics of noise from a running vehicle on a drainage asphalt pavement are described in Appendix A1.

**Note 3:** The type of viaduct is not considered in the calculation of structure-borne noise from a viaduct because the difference in the frequency characteristics of noise due to the viaduct type is sufficiently small.

**Note 4:** The directivity of vehicle noise can be considered in the calculation for diffraction by applying the directivity correction of the power level (see Sect. 2.3.3) to the direction from the point source $S$ to the diffraction point $O$.

3.2.2. Single diffraction by simple barriers, $\Delta L_{\text{dif, sb}}$

The correction term $\Delta L_{\text{dif, sb}}$ for diffraction around a single diffraction point, such as diffraction around a simple plane barrier or the top of a slope, is calculated as follows. Small obstacles such as curbstones, guardrails and guard ropes along the road are neglected.

$$\Delta L_{\text{dif, sb}} = \begin{cases} 
\Delta L_d & \text{except for standard metallic absorptive-type barrier} \\
\Delta L_d + C_{\text{dif, abs}} & \text{standard metallic absorptive-type barrier}
\end{cases}$$

(3.4)

where $C_{\text{dif, abs}}$ is the correction term for the absorption effect of the standard metallic absorptive-type barrier and is calculated as [25]

<table>
<thead>
<tr>
<th>Classification of noise</th>
<th>$c_{\text{spec}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise from running vehicles Density asphalt pavement</td>
<td>0.85</td>
</tr>
<tr>
<td>Drainage asphalt pavement Age of less than 1 year</td>
<td>0.75</td>
</tr>
<tr>
<td>Structure-borne noise from viaducts (Independent of viaduct type)</td>
<td>0.60</td>
</tr>
</tbody>
</table>

![Table 3.2](image2)

![Diagram](image3)

(a) Noise from a running vehicle

(b) Noise from a viaduct structure

Fig. 3.2 $\Delta L_d$ as a function of path difference $\delta$.

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

(3.5)
3.2.3. Barriers with a finite length, $\Delta L_{\text{diff,fb}}$

Two methods are provided for obtaining the correction term for the diffraction around a barrier with a finite length: one is the “one-path” method considering only the diffraction over the top edge of the barrier, and the other method involves the summation of diffractions over the top edge and around the side edges.

(1) One-path method

If line segment SP from the point source S to the prediction point P crosses a finite barrier, as shown in Fig. 3.3, $\Delta L_{\text{diff,fb}}$ is calculated using Eq. (3.4). If not, the propagation from S to P is calculated for a terrain without a barrier; for vehicles running on a viaduct, the sidewalls along the road are considered as barriers.

(2) Summation of upper and side diffractions [26,27]

A finite barrier ABCD along a road is considered, as shown in Fig. 3.4. A plane including the barrier is divided into 9 regions ($\Gamma_1$ to $\Gamma_8$) with 4 straight lines. The correction term for the diffraction of the barrier ABCD, $\Delta L_{\text{diff,fb}}$, is calculated with the following equations.

1) For viaduct road, bank road and cut road

$$\Delta L_{\text{diff,fb}} = \Delta L_{1-5}$$

$$= 10 \lg \left( 10^{\Delta L_{125}/10} + (10^{\Delta L_{0+4}/10} - 10^{\Delta L_{125}/10}) \cdot (10^{\Delta L_{06}/10} + 10^{\Delta L_{06}/10}) \right)$$

(3.6)

$\Delta L_{\text{fb}}$ [dB] is calculated as $\Delta L_{\text{g}}$ in the case where regions $\Gamma_1$, $\Gamma_2$, and $\Gamma_8$ in Fig. 3.4 are open and other regions are closed to form a simple half-screen.

2) For flat road

$\Delta L_{\text{diff,fb}}$ is calculated as the insertion loss of the finite barrier ABCD, given by

$$\Delta L_{\text{diff,fb}} = \Delta L_{1-5} - \Delta L_{0-5}.$$  

(3.7)

See Subsection 3.2.8 to calculate the correction term for insertion loss.

3.2.4. Thick barriers, $\Delta L_{\text{diff,dd}}$

The correction term $\Delta L_{\text{diff,dd}}$ for the double diffraction around an acoustical obstacle such as an embankment or a building is calculated considering two diffraction points X and Y, as shown in Fig. 3.5, regardless of the surface acoustic impedance or the opening angle of the wedge, as [28]

$$\Delta L_{\text{diff,dd}} = \begin{cases} \Delta L_{\text{XP}} & P \in I, II \\ \Delta L_{\text{XP}} + \Delta L_{\text{YP}} + 5 & P \in III, \delta_{\text{XP}} \geq \delta_{\text{YP}} \\ \Delta L_{\text{SP}} + \Delta L_{\text{SY}} + 5 & P \in III, \delta_{\text{SP}} < \delta_{\text{YP}} \end{cases}$$

(3.8)

where $\Delta L_{\text{ABC}}$ is $\Delta L_d$ for the diffraction path ABC with the path difference $\delta_{\text{ABC}}$

If the point source S is above the top of the obstacle, $\Delta L_{\text{diff,dd}}$ is defined as the smallest value (i.e., the value with the largest absolute value) of the two values of $\Delta L_d$ for a single diffraction around X and Y.

3.2.5. Multiple barriers [29]

(1) Double barriers, $\Delta L_{\text{diff,db}}$

The correction term $\Delta L_{\text{diff,db}}$ for the diffraction around a pair of barriers with a spacing of 5 m or more, shown in Fig. 3.6, is calculated as

$$\Delta L_{\text{diff,db}} = \begin{cases} \Delta L_{\text{XSP}} + \Delta L_{\text{XYP}} & \delta_{\text{XP}} \geq \delta_{\text{YP}} \\ \Delta L_{\text{YSP}} + \Delta L_{\text{XY}} & \delta_{\text{XP}} < \delta_{\text{YP}} \end{cases}$$

(3.9)

(2) Triple barriers, $\Delta L_{\text{diff,tb}}$

The correction term $\Delta L_{\text{diff,tb}}$ for the diffraction around
Barriers with an overhang, that is, a barrier with its top edge folded, is given as the correction term for the summation of the diffraction around a barrier and the receiver-side edge, respectively.

Note: Careful attention is required in the calculation of $\Delta L_{\text{dif,emb}}$, by the method shown in Fig. 3.8 if the hypothetical barrier is extremely high. For a barrier with an overhang with a depth of 1 m or less, the barrier is approximated as a thick barrier, as shown in Fig. 3.9, in order to apply the method described in Subsection 3.2.4.

3.2.7. Edge-modified barriers, $\Delta L_{\text{dif,emb}}$

Barriers with acoustic devices, such as absorbers, installed on their top edge to reduce diffracted sound behind the barrier are referred to as edge-modified barriers. The noise-reducing efficiency of the device depends on its size and sound reduction mechanism; it is difficult to establish a generalized scheme to calculate propagation. Device-dependent efficiency is considered using the procedures in Reference R3.

3.2.8. Low-height barriers, $\Delta L_{\text{dif,low}}$

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

$$\Delta L_{\text{dif,low}} = \Delta L_{d,1} - \Delta L_{d,0},$$

where $\Delta L_{d,1}$ and $\Delta L_{d,0}$ are $\Delta L_d$ for $O_1$ (top edge of the barrier) and $O_0$ (an intersection of the barrier and the ground) shown in Fig. 3.10, respectively.

3.2.9. Transmission through barriers, $\Delta L_{\text{dif,trans}}$

If the transmission through a barrier is considered in the geometry shown in Fig. 3.11, the correction term $\Delta L_{\text{dif,trans}}$ for the summation of the diffraction around a barrier and the transmission is calculated as
where $\Delta L_{\text{dif,trans}}$ is $\Delta L_{d,1}$ for the top edge $O_1$, $\Delta L_{\text{dif,slit}}$ [dB] is the correction term for slit diffraction and $R_{A,\text{RTN}}$ [dB] is the sound reduction index of the barrier considering the $A$-weighted spectra of the noise of a running vehicle. Examples of $R_{A,\text{RTN}}$ for typical barrier panels in Japan are given in Table 3.3.

$\Delta L_{\text{dif,slit}}$ denotes the energy of sound propagating through the slit opening $O_0$–$O_1$, corresponding to the barrier with the sound reduction index $R_{A,\text{RTN}} = 0$ [dB], as shown in Fig. 3.12; 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. 3.13.

$$\Delta L_{\text{dif,slit}} = 10 \log (10^{\frac{\Delta L_{d,1}}{10}} + 10^{\frac{\Delta L_{\text{dif,slit}} - R_{A,\text{RTN}}}{10}}). \tag{3.14}$$

where $\Delta L_{\text{dif,slit}}$ is the correction term for slit diffraction and $R_{A,\text{RTN}}$ is the sound reduction index of the barrier considering the $A$-weighted spectra of the noise of a running vehicle. Examples of $R_{A,\text{RTN}}$ for typical barrier panels in Japan are given in Table 3.3.

The coefficient $K_i$ is a 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 $r_i > r_{c,i}$.

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

$\Delta L_{\text{dif,trans}} = 10 \log (10^{\frac{\Delta L_{d,i}}{10}} + 10^{\frac{\Delta L_{\text{dif,slit}} - R_{A,\text{RTN}}}{10}}). \tag{3.14}$

where $\Delta L_{\text{dif,trans}}$ is $\Delta L_{d,1}$ for the top edge $O_1$, $\Delta L_{\text{dif,slit}}$ [dB] is the correction term for slit diffraction and $R_{A,\text{RTN}}$ [dB] is the sound reduction index of the barrier considering the $A$-weighted spectra of the noise of a running vehicle. Examples of $R_{A,\text{RTN}}$ for typical barrier panels in Japan are given in Table 3.3.

$\Delta L_{\text{dif,slit}}$ denotes the energy of sound propagating through the slit opening $O_0$–$O_1$, corresponding to the barrier with the sound reduction index $R_{A,\text{RTN}} = 0$ [dB], as shown in Fig. 3.12; 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. 3.13.

$$\Delta L_{\text{dif,slit}} = 10 \log (10^{\frac{\Delta L_{d,1}}{10}} + 10^{\frac{\Delta L_{\text{dif,slit}} - R_{A,\text{RTN}}}{10}}). \tag{3.14}$$

where $\Delta L_{\text{dif,slit}}$ is the correction term for slit diffraction and $R_{A,\text{RTN}}$ is the sound reduction index of the barrier considering the $A$-weighted spectra of the noise of a running vehicle. Examples of $R_{A,\text{RTN}}$ for typical barrier panels in Japan are given in Table 3.3.

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$$\Delta L_{\text{dif,slit}} = 10 \log (10^{\frac{\Delta L_{d,1}}{10}} + 10^{\frac{\Delta L_{\text{dif,slit}} - R_{A,\text{RTN}}}{10}}). \tag{3.14}$$

where $\Delta L_{\text{dif,slit}}$ is the correction term for slit diffraction and $R_{A,\text{RTN}}$ is the sound reduction index of the barrier considering the $A$-weighted spectra of the noise of a running vehicle. Examples of $R_{A,\text{RTN}}$ for typical barrier panels in Japan are given in Table 3.3.

$\Delta L_{\text{dif,slit}}$ denotes the energy of sound propagating through the slit opening $O_0$–$O_1$, corresponding to the barrier with the sound reduction index $R_{A,\text{RTN}} = 0$ [dB], as shown in Fig. 3.12; 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. 3.13.

$$\Delta L_{\text{dif,slit}} = 10 \log (10^{\frac{\Delta L_{d,1}}{10}} + 10^{\frac{\Delta L_{\text{dif,slit}} - R_{A,\text{RTN}}}{10}}). \tag{3.14}$$

where $\Delta L_{\text{dif,slit}}$ is the correction term for slit diffraction and $R_{A,\text{RTN}}$ is the sound reduction index of the barrier considering the $A$-weighted spectra of the noise of a running vehicle. Examples of $R_{A,\text{RTN}}$ for typical barrier panels in Japan are given in Table 3.3.

$\Delta L_{\text{dif,slit}}$ denotes the energy of sound propagating through the slit opening $O_0$–$O_1$, corresponding to the barrier with the sound reduction index $R_{A,\text{RTN}} = 0$ [dB], as shown in Fig. 3.12; 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. 3.13.

$$\Delta L_{\text{dif,slit}} = 10 \log (10^{\frac{\Delta L_{d,1}}{10}} + 10^{\frac{\Delta L_{\text{dif,slit}} - R_{A,\text{RTN}}}{10}}). \tag{3.14}$$

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$\Delta L_{\text{dif,slit}}$ denotes the energy of sound propagating through the slit opening $O_0$–$O_1$, corresponding to the barrier with the sound reduction index $R_{A,\text{RTN}} = 0$ [dB], as shown in Fig. 3.12; 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. 3.13.

$$\Delta L_{\text{dif,slit}} = 10 \log (10^{\frac{\Delta L_{d,1}}{10}} + 10^{\frac{\Delta L_{\text{dif,slit}} - R_{A,\text{RTN}}}{10}}). \tag{3.14}$$

where $\Delta L_{\text{dif,slit}}$ is the correction term for slit diffraction and $R_{A,\text{RTN}}$ is the sound reduction index of the barrier considering the $A$-weighted spectra of the noise of a running vehicle. Examples of $R_{A,\text{RTN}}$ for typical barrier panels in Japan are given in Table 3.3.

$\Delta L_{\text{dif,slit}}$ denotes the energy of sound propagating through the slit opening $O_0$–$O_1$, corresponding to the barrier with the sound reduction index $R_{A,\text{RTN}} = 0$ [dB], as shown in Fig. 3.12; 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. 3.13.

$$\Delta L_{\text{dif,slit}} = 10 \log (10^{\frac{\Delta L_{d,1}}{10}} + 10^{\frac{\Delta L_{\text{dif,slit}} - R_{A,\text{RTN}}}{10}}). \tag{3.14}$$

where $\Delta L_{\text{dif,slit}}$ is the correction term for slit diffraction and $R_{A,\text{RTN}}$ is the sound reduction index of the barrier considering the $A$-weighted spectra of the noise of a running vehicle. Examples of $R_{A,\text{RTN}}$ for typical barrier panels in Japan are given in Table 3.3.

$\Delta L_{\text{dif,slit}}$ denotes the energy of sound propagating through the slit opening $O_0$–$O_1$, corresponding to the barrier with the sound reduction index $R_{A,\text{RTN}} = 0$ [dB], as shown in Fig. 3.12; 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. 3.13.
three typical types of ground surface are described in the following. \( \Delta L_{\text{grad,j}} = 0 \) [dB] for surfaces paved with asphalt concrete.

Note 1: When the propagation path becomes long, sound attenuation may not be as large as indicated by the calculated value because of the meteorological effect due to wind and temperature [32].

Note 2: Equation (3.17) 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 [33].

(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 \( H_{a,j} \) [m] [34].

1) Loose soil

\[
K_i = \begin{cases} 
3.93 \sqrt{H_{a,j}} + 0.081 + 15.1 & 0.6 \leq H_{a,j} < 1.5 \\
20.0 & H_{a,j} \geq 1.5 
\end{cases}
\]  
(3.18)

2) Grassland

\[
K_i = \begin{cases} 
6.98 \sqrt{H_{a,j}} - 0.537 + 9.85 & 0.6 \leq H_{a,j} < 1.5 \\
2.48 \sqrt{H_{a,j}} - 1.42 + 16.0 & 1.5 \leq H_{a,j} < 4.0 \\
20.0 & H_{a,j} \geq 4.0 
\end{cases}
\]  
(3.19)

3) Compacted ground

\[
K_i = \begin{cases} 
4.97 H_{a,j} - 0.472 H_{a,j}^2 + 5.0 & 0.6 \leq H_{a,j} < 3.0 \\
1.53 \sqrt{H_{a,j}} - 2.94 + 15.3 & H_{a,j} \geq 3.0 
\end{cases}
\]  
(3.20)

The average height of the propagation path \( H_{a,j} \) 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. 3.14.

\[
H_{a,j} = \frac{(H_{i-1} + H_i)}{2}
\]  
(3.21)

For a slope along a cut road, \( H_2 \) is always 1 m even if \( H_2 \) for the slope is 1 m or less [31].

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

\[
r_{c,j} = g(Z_i) \cdot (H_{a,j})^{(Z_i)},
\]  
(3.22)

where \( Z_i \) is given by

\[
Z_i = \frac{|H_{i-1} - H_i|}{(H_{i-1} + H_i)},
\]  
(3.23)

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

\[
f(Z_i) = \begin{cases} 
2.09 & 0.0 \leq Z_i < 0.4 \\
2.09 - 0.124(Z_i - 0.4) + 0.711(Z_i - 0.4)^2 - 2.47(Z_i - 0.4)^3 & 0.4 \leq Z_i < 0.8 \\
2.00 - 1.72(Z_i - 0.8) + 21.6(Z_i - 0.8)^2 - 189(Z_i - 0.8)^3 & 0.8 \leq Z_i \leq 1.0 
\end{cases} \quad (3.24)
\]

2) Grassland

\[
f(Z_i) = \begin{cases} 
2.3 & 0.0 \leq Z_i < 0.4 \\
2.3 - 0.387(Z_i - 0.4) + 0.920(Z_i - 0.4)^2 - 5.47(Z_i - 0.4)^3 & 0.4 \leq Z_i \leq 1.0 
\end{cases} \quad (3.25)
\]

3) Compacted ground

\[
f(Z_i) = \begin{cases} 
2.3 & 0.0 \leq Z_i < 0.2 \\
2.3 + 0.170(Z_i - 0.2) - 1.38(Z_i - 0.2)^2 - 0.648(Z_i - 0.2)^3 & 0.2 \leq Z_i \leq 1.0 
\end{cases} \quad (3.26)
\]

\[g(Z_i) = a + bZ_i + cZ_i^2 + dZ_i^3, \quad (3.27)\]

The values of coefficients \(a, b, c\) and \(d\) in this equation for each type of ground are listed in Table 3.4. Note that \(r_{c,i}\) for \(H_{a,j} < 1.1\) over a compacted ground surface is calculated as

\[r_{c,i} = g(Z_i) \cdot (1.1)^{f(Z_i)} \cdot 10^{0.47Z_i^{-1.1}h(Z_i)}, \quad (3.28)\]

where

\[h(Z_i) = 0.517 - 0.0592Z_i - 1.30Z_i^2 + 1.19Z_i^3. \quad (3.29)\]

Note 1: The calculation described above does not cause any excess attenuation if the ground surface is divided into small segments with a length shorter than \(r_{c,i}\). Refer to the approximate calculation method of excess attenuation accumulated over small-segmented surfaces [35].

Note 2: Diffraction and the ground surface effect are not independent phenomena; they essentially affect each other. Consider a barrier built along a road for example; correction for diffraction is increased, but simultaneously, the attenuation due to the ground surface effect is decreased for a larger height of the propagation path. The ground surface effect in this situation is given as the summation of ground surface effects along the propagation paths over the two ground surfaces in front of and behind the barrier. Note that specular reflection from the ground surfaces around the prediction point may be considered by introducing a mirror-image sound source if the ground surface is paved so that the reflection is not negligible.

### 3.4. Correction for atmospheric absorption effect, \(\Delta L_{\text{air}}\)

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

\[\Delta L_{\text{air}} = -6.84 \left( \frac{r}{1000} \right) + 2.01 \left( \frac{r}{1000} \right)^2 - 0.345 \left( \frac{r}{1000} \right)^3, \quad (3.30)\]

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

### Table 3.4 Coefficients of \(g(Z_i)\).

<table>
<thead>
<tr>
<th>Ground</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loose soil</td>
<td>35.1</td>
<td>3.26</td>
<td>-61.2</td>
<td>30.3</td>
</tr>
<tr>
<td>Grassland</td>
<td>23.8</td>
<td>1.69</td>
<td>-38.2</td>
<td>23.3</td>
</tr>
<tr>
<td>Compacted ground</td>
<td>18.6</td>
<td>0.946</td>
<td>-32.5</td>
<td>32.2</td>
</tr>
</tbody>
</table>

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 [36]. Equations for atmospheric states other than the standard state can be derived similarly.

### 3.5. Method of Calculating 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. 3.15(a); the source S and the 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. 3.15(b). The specular reflection is calculated as

\[L_{\text{A,refl}} = L_{\text{WA}} - 8 - 20 \log r + \Delta L_{\text{refl}} + \Delta L_{\text{abs}}, \quad (3.31)\]

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] (hereafter referred to as the “correction for reflection”) 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'OP and the direct path SP:

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

(3.32)

The values in Table 3.2 are applied to the coefficient $c_{\text{spec}}$. $\Delta L_r$ is shown as a function of $\delta$ in Fig. 3.16.

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

The correction term $\Delta L_{\text{refl}}$ for reflection from a semi-infinite plane in Fig. 3.15(a) is calculated considering the hypothetical barrier in Fig. 3.15(b). For S' invisible from P in Fig. 3.15(b),

$$
\Delta L_{\text{refl}} = \Delta L_r,
$$

(3.33)

otherwise, for S' visible from P in Fig. 3.15(b),

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

(3.34)

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

As shown in Fig. 3.17(a), we consider the source S, the prediction point P and the flat reflective plane $O_1-O_2$ with a finite width and an infinite length (i.e., a strip). The sound reflected from the strip is equivalently considered as the contribution from the mirror-image source S' to the prediction point P through slit opening $O_1-O_2$ with the same width as the strip (see Fig. 3.17(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. 3.17(c). The correction term $\Delta L_{\text{refl,slit}}$ is calculated as

$$
\Delta L_{\text{refl,slit}} = 10 \lg \left[10^{\Delta L_{\text{refl},1}/10} - 10^{\Delta L_{\text{refl},2}/10}\right],
$$

(3.35)

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

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

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

As shown in Fig. 3.18, we 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. $D_{\text{pk}}$ is defined as the summation of the sound contributions from regions $\Gamma_1$, $\Gamma_2$ and $\Gamma_3$. 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 (region $\Gamma_0$) to the energy passing through all regions [37]:

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

(3.36)

where $D_0$ is the relative contribution through the region $\Gamma_0$, and $D_{1-8}$ is the relative contribution through the regions $\Gamma_1$ to $\Gamma_8$, i.e., $D_0 + D_{1-8} = 1$. $D_{1-8}$ is calculated as [26]

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

(3.37)

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

(3.38)
the sound reflected from the whole reflecting plane at P is calculated as
\[
L_{A,\text{refl}} = L_{WA} - 13 + 10 \log \left( \frac{\cos \theta_1 \cdot \cos \theta_2}{r_1^2 \cdot r_2^2} \right) + \Delta L_{\text{abs}}.
\]
(3.41)

Note: When the reflection angle \( \theta_2 \) approaches 90°, the energy of the reflected sound approaches zero in Eq. (3.41), leading to significant error; careful attention is required.

3.5.3. Correction for sound absorption, \( \Delta L_{\text{abs}} \)

The correction term for the sound absorption \( \Delta L_{\text{abs}} \) is calculated as
\[
\Delta L_{\text{abs}} = 10 \log (1 - \alpha_{A\text{,RTN}}),
\]
(3.42)
where \( \alpha_{A\text{,RTN}} \) is the absorption coefficient considering the spectrum of typical road traffic noise. A measured value of \( \alpha_{A\text{,RTN}} \) is preferred; the typical values of the average absorption coefficient against oblique incidence [39,40] in Table 3.5 are applicable if measured values of \( \alpha_{A\text{,RTN}} \) are not provided.

3.6. Meteorological Effects

Meteorological factors such as wind, temperature gradient and atmospheric turbulence affect sound propagation. The change in \( L_{A\text{eq}} \) due to the effect of wind, \( \Delta L_{m,\text{line}} \) [dB], for a straight road is estimated independently of road structure, the presence of noise barriers and the ground surface condition as
where $l$ is the horizontal distance from the center of the road to the prediction point [m] and $U_{vec} = U \cos \theta$ is the vector component of the average wind speed $U$ [m/s] for the angle $\theta$ between the wind direction and a line perpendicular to the road through the prediction point. $U_{vec}$ is positive in the downwind direction and negative in the upwind direction. Examples of $\Delta L_{m,\text{line}}$ obtained from Eq. (3.43), rounded to the nearest 0.5 dB, are given in Table 3.6.

Note: Equation (3.43) is tentatively given on the basis of on-site measurements of road traffic noise taking into consideration of the empirical equations derived from experiments on the effect of wind in propagation around a point source [41].

### 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, road structures 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 various 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 calculation method for noise 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 using the method

![Fig. 4.1 Schematic configuration of an interchange and the behavior of a vehicle.](image-url)
described in Chap. 2. Then, the sound propagation from each source to a prediction point is calculated using the method described in Chap. 3. As a result of the calculation, a unit pattern as a function of time is obtained by taking into consideration the relationship between the position of a running vehicle and the elapsed running time. As an example, a schematic illustration of the position, running condition and speed of a vehicle, 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 at a 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 and its initial speed, acceleration, final speed and standstill time. The method of the calculation of $L_{Aeq}$ from the obtained unit pattern is the same as that for general roads.

### 4.1.2. Acceleration of vehicles

For a vehicle accelerating or decelerating at an interchange, the accelerations shown in Table 4.1 are used in the calculation [6,42]. For the accelerating motorcycles, the values for passenger cars are applied in it.

### 4.1.3. Service time at tollgate

The service time at a tollgate is defined as the standstill time for vehicles, and is required for issuing tickets at the entrance and collecting fare at the exit. The times indicated in Table 4.2 are applied [43].

**Note:** If an electronic toll collection (ETC) system is installed at the tollgate, acceleration and passing speed through the tollgate, which are set on the basis of in situ measurement results, are used in the calculation [44].

### 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 level under accelerating or decelerating running conditions is calculated by the method described in Item (2) of Subsection 2.2.3. When a vehicle accelerates or decelerates, fixed accelerations of $0.4 \text{ m/s}^2$ when accelerating and $-1.3 \text{ m/s}^2$ when decelerating are used in the calculation regardless of the vehicle type.

**Note:** The above acceleration when accelerating was obtained by local measurements. The acceleration when decelerating was measured; the accelerations obtained by measurements in the vicinity of signalized intersections (see Appendix A3) are expediently adopted for junctions.

### 4.3. Signalized Intersections

Along an urban road, there are many signalized intersections, and individual vehicles 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 on such a road is obviously 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 \( L_{\text{AEq}} \) for each road is calculated on the basis of a non-steady traffic flow, and the results are summed in energy [45].

**Note:** In the vicinity of an actual signalized intersection, the running condition of individual vehicles changes as the signal phase changes. Corresponding to the change in the running behavior, the sound power level of the vehicle varies greatly. 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 semi-precise method (practicable method) [46], which calculates the noise in the vicinity of the signalized intersection from the unit pattern of individual vehicles, or one can apply a simple method [46] that is a simplification of the semi-precise method. The outline of these calculation methods are described in Appendix A3.

### 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., sound directly emitted from a vehicle in a tunnel, and multiple-reflected and diffused sounds inside the tunnel, respectively. The former is assumed to be radiated from an imaginary point source in a tunnel through the portal, and the latter is assumed to be radiated from an imaginary plane source with a size corresponding to that of the portal surface [47].

**Note:** This calculation model is basically applicable to semicircular or rectangular portals; however, its applicability to portals of other shapes is being studied [48]. This model can also be applied to a tunnel whose interior 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

\[
L_A = 10 \log(10^{L_{\text{ATD}/10}} + 10^{L_{\text{ATR}/10}}),
\]

where \( L_{\text{ATD}} \) is the A-weighted sound pressure level of the direct sound from an imaginary point source [dB] and \( L_{\text{ATR}} \) is that of other reflected and diffused sounds (imaginary plane source) [dB].

4.4.2. Location and sound power level of imaginary point source

The sound power level of the imaginary 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 the absorption in the tunnel, \( a \), and the actual distance from the portal to the vehicle \( x \) [m] as

\[
x' = ax.
\]

If the tunnel is composed of several sections with different absorption coefficients \( a \) is calculated as

\[
\begin{align*}
L_{\text{A,TD}} &= L_{\text{WA}} - 20 \log r + \Delta L_{\text{dif}} + \Delta L_{\text{grnd}}, \\
L_{\text{A,TR},i} &= L'_{\text{WAR}} - 8 - 20 \log r_i + \Delta L_{\text{dif},i} + \Delta L_{\text{grnd},i}, \\
L_{\text{WAR}} &= L_{\text{WAR}} - 10 \log N,
\end{align*}
\]

where \( N \) is the number of elements into which the plane source is divided, \( L_{\text{WAR}} \) is the A-weighted sound power level of the plane source [dB] and \( L'_{\text{WAR}} \) is the A-weighted sound power level when the divided elements of the plane source are considered as point sources [dB].
\[
a = \frac{\sum (a_i x_i)}{\sum x_i}, \quad (4.7)
\]

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

The sound power level of the imaginary plane source \(L_{WA,R} [\text{dB}]\) set at the portal plane position is calculated by subtracting the A-weighted sound power \(P_{A,D} [\text{W}]\) of the directly radiated sound from the A-weighted sound power \(P_{A,T} [\text{W}]\) of all sounds radiated from the portal. It is calculated as

\[
L_{WA,R} = 10 \log \left( \frac{P_{A,T} - P_{A,D}}{10^{-12}} \right). \quad (4.8)
\]

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

\[
P_{A,T} = \frac{P_A}{2} \left\{ 1 - \frac{ax}{\sqrt{h^2 + (ax)^2}} \right\}, \quad (4.9)
\]

\[
P_{A,D} = \frac{P_A}{2} \left\{ 1 - \frac{x}{\sqrt{h^2 + x^2}} \right\}, \quad (4.10)
\]

where \(P_A\) is the A-weighted sound power of the actual source [W].

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

\[
P_{A,T} = \frac{P_A}{\pi} \tan^{-1} \left\{ \frac{wh}{\sqrt{(ax)^2 + (w^2 + h^2) \cdot (ax)^2}} \right\}, \quad (4.11)
\]

\[
P_{A,D} = \frac{P_A}{\pi} \tan^{-1} \left\{ \frac{wh}{\sqrt{x^4 + (w^2 + h^2) \cdot x^2}} \right\}, \quad (4.12)
\]

### 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 4.3 are used in the calculation in accordance with the type of pavement on the road surface.

<table>
<thead>
<tr>
<th>Wall surface condition</th>
<th>Dense asphalt pavement</th>
<th>Drainage asphalt pavement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without absorptive material</td>
<td>0.04</td>
<td>0.1</td>
</tr>
<tr>
<td>Absorption measure on sidewalls</td>
<td>—</td>
<td>0.4</td>
</tr>
<tr>
<td>Absorption measure on entire wall</td>
<td>0.6</td>
<td>—</td>
</tr>
</tbody>
</table>

Note: The relationship between \(a\) and the mean absorption coefficient of the inner wall of a tunnel, \(\alpha_{A,\text{RTN}}\) (refer to Subsection 3.5.3), has been investigated, and \(a\) can be estimated by applying the mean absorption coefficient \(\alpha_{A,\text{RTN}}\) [47,48].

### 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. 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 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, the wave-based numerical analysis (see Appendix A4) or a scale-model experiment [22] is available.

Note: Correction for the noise mitigation effect of absorptive louvers [49], 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 (mirror-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 formula**

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

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

(4.13)

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 $\alpha_{\text{A,RTN}}$ is the absorption coefficient of the sidewall surface (see Subsection 3.5.3).

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

$$L_{A,i} = L_{WA} - 8 - 20 \log r_i + \Delta L_{\text{cor,i}} + \Delta L_{\text{refl,slit,i}}. \quad (4.14)$$

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], $\Delta L_{\text{cor,i}}$ is the correction for sound attenuation during the propagation from the $i$th mirror-image source to the prediction point [dB] and $\Delta L_{\text{refl,slit,i}}$ 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 by 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 formula**

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

$$L_A = L_{WA,\text{su}} + 10 \log [a + (1 - a) \cos^n \phi] - 8 - 20 \log r, \quad (4.15)$$

$$n(\theta) = n_{\text{max}} \sin^\beta \theta, \quad (4.16)$$

where $a$, $n_{\text{max}}$, and $\beta$ are the parameters for the directivity of each imaginary point source and $r$ is the distance from the imaginary point source $S'$ to the prediction point P [m]. $L_{WA,\text{su}}$ is the apparent sound power level of the imaginary directional point source $S'$ determined from the direction of $\phi = 0$ [degree], and is given by

$$L_{WA,\text{su}} = L_W + \Delta L_{\text{dim, su}} + \Delta L_{\text{dir, su}} + \Delta L_{\text{abs, su}} + \Delta L_{\text{louver}}, \quad (4.17)$$

where $L_W$ is the A-weighted sound power level of a running vehicle [dB], $\Delta L_{\text{dim, su}}$ is the correction for the dimensions of a semi-underground road structure [dB], $\Delta L_{\text{dir, su}}$ is the correction for the directivity of an imaginary source, $\Delta L_{\text{abs, su}}$ is the correction for the absorption in a 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 [50]

$$\Delta L_{\text{dim, su}} = 10 \log \left\{ \frac{2}{\pi} \tan^{-1} \frac{W}{2H} + \frac{\pi WH}{3L^2} \frac{1}{L - W} + \frac{1}{L \alpha_{\text{A,RTN}} + 1} \right\}. \quad (4.18)$$

The values given in Table 4.4 for $a$, $n_{\text{max}}$, $\beta$ and $\Delta L_{\text{dir, su}}$ for each dimension, derived from the results of scale-model experiments and numerical analysis based on wave theory, are used in the calculation [51,52]. $\alpha_{\text{A,RTN}}$ is 0 dB when the dense asphalt pavement. In the case of the drainage asphalt pavement, values determined from in situ measurement results are used as $\alpha_{\text{A,RTN}}$ [53]. $\Delta L_{\text{abs, su}}$ is 0 dB when the wall surface of the inner structure has a reflective finish and it is $-1$ dB when the surface has an absorptive finish. An example of a directivity pattern calculated using the values in Table 4.4 is shown in Fig. 4.7. $\Delta L_{\text{louver}}$ is 0 dB when absorptive louvers are not installed. When such louvers are installed, $\Delta L_{\text{louver}}$ determined from the results of an in situ measurement and scale model experiment is used [54].

**3) Correction for noise attenuation by 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 the prediction point P is calculated as

$$L_A = L'_{A} + \Delta L_{\text{dir, ab}}, \quad (4.19)$$

where $L'_{A}$ is the A-weighted sound pressure level calculated at the 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). $\Delta L_{\text{dif},\text{sb}}$ is the correction for attenuation calculated using 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 continuously straight for a sufficient distance, discrete imaginary point sources along the line can be treated as a line source. Based on this concept, a method of obtaining directivity as a function of only $\psi$ is being studied [55].

4.6. Flat/Overhead Roads and Double-Deck Viaducts

4.6.1. Types of underside of viaducts and calculation models

The underside of a viaduct may be smooth and flat or
prediction point P is calculated using the following formula:
\[ L_A = 10 \log(10^{L_{A,0}/10} + 10^{L_{A,1}/10} + 10^{L_{A,2}/10} + 10^{L_{A,3}/10}), \]
(4.20)
where \( L_{A,0}, L_{A,1}, L_{A,2} \) and \( L_{A,3} \) are the A-weighted sound pressure levels of direct sound, reflection from the underside of the viaduct, and reflections from the underside and ground \((S' \text{ to } P' \text{ and } S'' \text{ to } P)\), respectively. Among them, \( L_{A,1}, L_{A,2} \) and \( L_{A,3} \) are calculated using the following formula:
\[ L_{A,i} = L_W - 8 - 20 \log r_i + \Delta L_{\text{dif},sb,i} + \Delta L_{\text{refl,slit},i} + \Delta L_{\text{abs}} \quad (i = 1 \text{ to } 3), \]
(4.21)
where \( \Delta L_{\text{dif},sb,i} \) is the correction for the attenuation by the noise barrier for the \( i \)th mirror-image source [dB], \( \Delta L_{\text{refl,slit},i} \) is the correction for the reflection calculated by the slit method [dB] and \( \Delta L_{\text{abs}} \) is the correction for the sound attenuation due to the absorptive surface [dB]. In some practical cases, it is necessary to consider double diffractions at the top of the noise barrier and the open edge of the slit. For convenience, however, the edge of the slit is neglected in the calculation of \( \Delta L_{\text{refl,slit},i} \) and the noise barrier is neglected in the calculation of \( \Delta L_{\text{refl,slit},i} \). In the case where the underside of a viaduct is absorptive, the correction for the absorption \( \Delta L_{\text{abs}} \) is applied (refer to Subsection 3.5.3).

Since the range of the effect of 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). 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 fourth term of Eq. (4.20) is neglected, and \( L_{A,1} \) and \( L_{A,2} \) in Eq. (4.21) are calculated by setting \( \Delta L_{\text{dif},sb,1} = 0 \) and \( \Delta L_{\text{dif},sb,2} = 0 \).

Note 1: If the road width on a viaduct increases, the effects of higher-order sound reflection cannot be neglected. In this case, higher-order reflections between the underside of the viaduct and the ground should be considered by setting additional mirror-image sources by the above-mentioned methods \((S' \text{ to } P', \text{ etc.})\).

Note 2: Even if the underside of a viaduct is treated with an absorptive material, it may not be absorptive at the beam of a pier. In the calculation of reflected sound, it is desirable to make some considerations, such as the use of an absorption coefficient calculated using a weighted average of the proportions of the area of the underside with or without absorptive panels.

4.6.2. Calculation by the slit method (image sources method)

As shown in Fig. 4.10, consider a case when a noise barrier is installed on one side of a flat road. For an ordinary viaduct road with 4 to 6 lanes, consider the four major sound paths of (a) direct sound \((S \text{ to } P)\), (b) reflection from the underside of a viaduct road \((S' \text{ to } P)\), and (c) reflections from the underside and ground \((S' \text{ to } P' \text{ and } S'' \text{ to } P)\). The A-weighted sound pressure level \( L_A \) [dB] at the prediction point P is calculated using the following formula on the basis of the total contribution from these sound paths:
\[ L_A = 10 \log(10^{L_{A,0}/10} + 10^{L_{A,1}/10} + 10^{L_{A,2}/10} + 10^{L_{A,3}/10}), \]
where \( L_{A,0}, L_{A,1}, L_{A,2} \) and \( L_{A,3} \) may have 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 follows. For ordinal noise calculation, the former method is generally applied, whereas the latter is applied if the unevenness is negligible [56]. The following method is applicable to cases in which a noise barrier is not installed on a flat road, or a noise barrier is installed only on one side of the road. When noise barriers are installed on both sides of a flat road, neither the slit method nor the scattered reflection method is applicable 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 based on the wave theory (refer to Appendix A4) or a scale-model experiment [22] is applied.

4.6.3. Calculation by the scattered reflection method

As shown in Fig. 4.11, a scattered-reflection surface \( \Sigma \) with the width of the viaduct is assumed beneath girders on the underside of the viaduct above the source and the
prediction point. Similarly to the slit method, we consider the four major paths of (a) direct sound (S to P), (b) reflection from the underside of a viaduct (S to P through \( \Sigma \)) and (c) reflections from the underside and ground (S to P’ through \( \Sigma \) and S to P through \( \Sigma' \)). The A-weighted sound pressure level \( L_A [dB] \) at the prediction point P is calculated using Eq. (4.20). However, \( L_A;1 \), \( L_A;2 \) and \( L_A;3 \) are calculated as

\[
L_A;i = L_{W_A} - 13 + 10 \log \left( \frac{\cos \theta_1 \cdot \cos \theta_2 \cdot D_\sigma}{r_1^2 \cdot r_2^2} \right) d\sigma
+ \Delta L_{abs} \quad (i = 1 \text{ to } 3),
\]

\[
D_\sigma = 10^{\frac{L_{dif,sb}}{10}}, \quad (4.22)
\]

where \( \Delta L_{dif,sb} \) is the correction [dB] for sound attenuation due to a noise barrier when a point source is set at the center of an element \( \Delta \sigma \). The reflection angle \( \theta_2 \) is the angle between the normal vector \( \mathbf{n} \) and the propagation path, as shown in Fig. 4.12. The symbol \( \int_S \) denotes surface integration over \( \Sigma \).

If a noise barrier is not installed on the roadside of a flat road, only the path from S to P’ through \( \Sigma \) is specified as the reflection path from the underside and ground. In the actual calculation, the fourth term of Eq. (4.20) can be neglected, and \( L_A;2 \) in the third term is calculated using Eq. (4.22) with \( D_\sigma = 1 \). Sources may be combined into a representative hypothetical lane.

**Note 1:** In Eq. (4.22), the scattered-reflection surface \( \Sigma \) is divided into several elements for numerical integration. In the calculation, an error may occur depending on the size of the elements. It is desirable to determine the effect of the size of the divided elements. Normally each element should be a square with sides less than 2 m.

**Note 2:** For a qualitative prediction, geometrical ray tracing is a well-known method that is useful for studying the arrival range of reflections from the underside and ground.

### 5. STRUCTURE-BORNE NOISE OF VIADUCTS

When vehicles run on a viaduct road, noise is generated owing to the vibration of the structure, which is referred to as structure-borne noise of the viaduct. The level of noise depends on the type of viaduct and the speed and weight of vehicles. The noise calculation method is described below [57,58].

#### 5.1. Scope

**1. Type of viaduct**

General steel viaducts and concrete viaducts, as shown in Table 5.1, are applied in the calculation.

**Note:** For other types of viaducts, a study of each viaduct based on site investigations are necessary [59].

**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**

This model is 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 omni-directional point source is assumed as an equivalent moving sound source that is synchronized with the running vehicle. The moving point

![Fig. 4.11 Propagation paths in the scattered-reflection method.](image)

![Fig. 4.12 Definition of reflection angle \( \theta_2 \) in the scattered-reflection method.](image)
source is set on the surface of the underside of the viaduct (at the bottom edge of the main girders for a girder structure or the bottom surface of a slab for a void slab structure) in a hypothetical lane 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 in 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

$$L_{W A, str} = a + 30 \log V,$$  \hspace{1cm} (5.1)

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

**Note:** The coefficient $a$ is the power average value calculated backward from individual measured data using Eq. (5.1). This procedure is the same as that for determining the calculation formula for the sound power level of running vehicles.

### 5.2.3. Calculation of unit pattern

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

$$L_{A, str} = L_{W A, str}/C_0 - 8 - 20 \log r + \Delta L_{dif},$$  \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 for the sound diffraction effect due to the shielding by the slab or girder structure [dB] (see Subsection 3.2.2).

**Note 1:** It is not necessary to consider the contribution of the sound reflection from the ground surface in the above calculation method, because its effect is already taken into account when determining the constant $a$ in the formula 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 Maekawa’s chart 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 A BEHIND SINGLE BUILDING AND IN BUILT-UP AREAS

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

6.1. Noise Behind Single Building [60,61]

As a method of calculating noise around a single building along the sides of roads, the following prediction model is considered. 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 and the noise reflected by the sidewalls of the building. Thus, $L_{A_{eq}}$ behind a single building is calculated by applying the methods of calculating the correction for diffraction caused by a finite-length barrier (Subsection 3.2.3) and reflected sounds (Subsection 3.5.1), and finally summing the direct sounds (or diffracted sounds) and the reflected sounds (see Fig. 6.1). 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

$$L_{A_{j}} = 10 \log(10^{L_{A_{0j}}/10} + 10^{L_{A_{1j}}/10}), \quad (6.1)$$

$$L_{A_{0j}} = L_{W_{A_{j}}} - 8 - 20 \log r_{0,j} + \Delta L_{bldg,j}, \quad (6.2)$$

$$L_{A_{1j}} = L_{W_{A_{j}}} - 8 - 20 \log r_{1,j} + \Delta L_{b-refl,j}, \quad (6.3)$$

where $L_{A_{j}}$, $L_{A_{0j}}$, and $L_{A_{1j}}$ are the A-weighted sound pressure levels [dB] of the total contribution from the sound source $S_j$, the direct sound component (or diffracted sound component) from $S_j$, and the reflected sound component due to the sidewalls of the building, respectively. $\Delta L_{bldg,j}$ is the correction for the diffraction by the building [dB] and $\Delta L_{b-refl,j}$ is the correction for reflection made owing to the finite size of the building walls. $r_{0,j}$ and $r_{1,j}$ are the distances [m] between the sound source $S_j$ and the receiver $P$, and between the image sound source $S'_j$ and the receiver $P$, respectively.

6.1.1. Correction for diffraction by a single building, $\Delta L_{bldg}$

(1) One-path method

In this method, only the diffraction by the top of a single building is considered, and diffraction by the sides of the building is ignored. As shown in Fig. 6.2, when line segment SP crosses the building, the building is treated as an infinite-length barrier with the depth $D$ [m] in the calculation of the unit pattern, and $\Delta L_{bldg}$ is calculated similarly to $\Delta L_{dif,dd}$ by using Eq. (3.8). 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.

(2) Method considering the diffraction by both top and sides of a building

As shown in Fig. 6.3, when line segment SP crosses a single building, $\Delta L_{bldg}$ is calculated as

$$\Delta L_{bldg} = 10 \log(10^{\Delta L_{upper}/10}$$

$$+ (1 - 10^{\Delta L_{upper}/10})(10^{\Delta L_{left}/10} + 10^{\Delta L_{right}/10})), \quad (6.4)$$

where $\Delta L_{upper}$, $\Delta L_{left}$, and $\Delta L_{right}$ are the corrections [dB] for diffractions caused by the top, left- and right-hand-side walls of the building, respectively. Then, Eq. (3.8) is used for the corrections, assuming the building to be an infinite-length barrier with a certain thickness and a path difference in the minimum path of diffraction around this thick barrier.

![Fig. 6.1](image_url) Calculation of noise behind a single building.

![Fig. 6.2](image_url) Calculation of $\Delta L_{bldg}$ by one-path method.

![Fig. 6.3](image_url) Calculation of $\Delta L_{bldg}$ considering diffraction by both top and sides of a building.
6.1.2. Correction for sound reflected by sidewalls of the building, \( \Delta L_{b-refl} \)

Figure 6.4 shows the configuration of the sound source S, receiver P and a building. A vertical plane corresponding to the sidewall of a building (reflection plane) is assumed. If both S and P are on the same side of the building, as shown in Fig. 6.4(a), the image sound source \( S' \) corresponding to the sound source S for the vertical plane is set and the reflected sound is considered. Otherwise, if the sound source S is not on the same side as the receiver P, as shown in Fig. 6.4(b), it is not necessary to consider the reflected sound and the second term on the right side of Eq. (6.1) is omitted.

The correction term \( \Delta L_{b-refl} \) [dB] is calculated using both the correction \( \Delta L_{refl,rect} \) [dB] for reflection by a rectangle in the specular reflection method (Subsection 3.5.1) and the correction \( \Delta L_{dif,low} \) [dB] for diffraction by a low barrier (Subsection 3.2.8), as

\[
\Delta L_{b-refl} = \Delta L_{refl,rect} - \Delta L_{0.5}, \tag{6.5}
\]

where \( \Delta L_{refl,rect} \) [dB] is calculated using Eqs. (3.36) to (3.40) and \( \Delta L_{0.5} \) [dB] is the correction calculated as \( \Delta L_{refl} \) using Eqs. (3.32)–(3.34) with the domains \( \Gamma_6 \) to \( \Gamma_8 \) shown in Fig. 3.18 assumed to be imaginary barriers. When it is necessary to consider sound absorption on the building walls, the correction for absorption, \( \Delta L_{abs} \), described in Subsection 3.5.3 is applied.

6.2. Noise behind Building Complexes

In this prediction model, two methods involving a point source model and a line source model are provided as methods of predicting noise behind dense building complexes. 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 build-up areas with buildings of different sizes and different conditions of building locations.

6.2.1. Calculation method using a point source model [62,63]

When detached houses are located in an area facing a flat 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

\[
L_{A,i} = L_{W,A,i} - 8 - 20 \log r_i + \Delta L_B, \tag{6.6}
\]

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]. \( \Delta L_B \) 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

\[
\begin{align*}
\Delta L_B &= p \cdot \Delta L_{BB} + q \\
p &= 0.017(H - h_p - 8.8) + 1 \tag{6.7} \\
q &= -0.063(H - h_p - 8.8),
\end{align*}
\]

where \( H \) 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

\[
\begin{align*}
\Delta L_{BB} &= 10 \log \left\{ a_0 + a_1 \cdot \frac{\phi}{\Phi} \right. \\
&\quad + a_2 \sum_i \left( \frac{\theta_i}{\Phi} \cdot \frac{d_{\text{road}}}{d_{\text{refl,i}}} \right) \\
&\quad + a_3 \cdot \frac{1}{n} \sum_{k=1}^n \left( 0.251 \cdot \frac{1}{1 + 0.522d_k} \right) \\
&\left. + a_4 \cdot 10^{-0.090d_{\text{road}}} \right\}, \tag{6.8}
\end{align*}
\]

where \( a_0 = 0.039, a_1 = 1.16, a_2 = 0.201, a_3 = 0.346 \) and \( a_4 = 0.288 \).

In Eq. (6.8), 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 Fig. 6.5, in the cases with and without detached houses, respectively. The term related to \( \sum_i (\theta_i/\Phi) d_{\text{refl,i}} \) indicates reflection sound components.

In this calculation method, the geometrical reflec-
tions 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. 6.6, \( \theta_i \) is the perspective angle [rad] from the first- or second-order mirror points, \( P' \) or \( P'' \), of the prediction point \( P \), to a portion of the of 10-m-long target road, \( d_{\text{road}} \) is the perpendicular distance between \( P \) and the road, 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 \( \frac{1}{n} \sum_{i=1}^{n} \left( \theta_i + 0.0904 d_{\text{ref},i} \right) \) indicates the diffracted sound from the source \( S \) to the prediction point \( P \) via a vertex of a building \( O \), as shown in Fig. 6.7. For the calculation of this term, a number \( n \) of discrete source points \( S_k \) are set on a part of 10-m-long target road and the diffraction path difference \( S_k O + OP - S_k P \) is calculated as \( \delta_k \) [m]. When \( P \) is visible from \( S_k \), the diffraction sound is not calculated.

The term related to \( 10^{-0.0904 d_{\text{sp}}} \) indicates sounds other than the direct, reflected and single diffraction sounds. As shown in Fig. 6.8, 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.

Equations (6.7) and (6.8) are deduced from the results of scale-model experiments assuming residential areas in which many detached houses of standard size in Japan are located. In the experiments, the horizontal distances between the prediction points and the target roads are 20 to 50 m, respectively. The ratio of the total area of the detached houses to that of the location area is in the range from 0.16 to 0.34. The heights \( (H) \) of the detached houses are 4 to 10 m and the heights \( (h_P) \) of the receiver are 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 \( H \) [64].

6.2.2. Calculation method based on a line source model

When many detached houses are located at an area facing a straight road, the equivalent continuous A-weighted sound pressure level \( L_{\text{Aeq}} \) behind building complexes is obtained by adding the value of the correction \( \Delta L_{\text{bldgs}} \) related to the sound attenuation due to the building complexes to the equivalent continuous A-weighted sound pressure level \( L_{\text{Aeq},0} \) without any detached houses, assuming that the road traffic noise is a line sound source. In this prediction model, there are two methods of calculating \( \Delta L_{\text{bldgs}} \) [dB]: using the correction value at a specific receiver and using the mean correction for the assessed section of the target road, as shown blow.
(1) $L_{\text{Aeq}}$ at specific receivers behind building complexes comprising detached houses \[65,66\]

1) Basic equation

When many detached houses are located along the sides of a flat or bank road, $L_{\text{Aeq}}$ at specific receivers behind the building complex is calculated by using the equivalent continuous A-weighted sound pressure level $L_{\text{Aeq,0}}$ without any detached houses and the correction $\Delta L_{\text{bldgs}}$ for attenuation due to the detached houses. It is expressed as

$$L_{\text{Aeq}} = L_{\text{Aeq,0}} + \Delta L_{\text{bldgs}}.$$  \hspace{1cm} (6.9)

2) For flat roads

When the target road is a flat road (where the road surface is located at the same level as the building area), the correction for attenuation due to the detached houses \[\Delta L_{\text{bldgs,flat}}\] in Eq. (6.9) is calculated as

$$\Delta L_{\text{bldgs,flat}} = \rho \cdot \Delta L_{\text{bldgs,h}} + q.$$  \hspace{1cm} (6.10)

$$\Delta L_{\text{bldgs,h}} = \begin{cases} a \log \frac{3\phi}{2\pi} (1-b) + b & (\phi \neq 0) \\ a \log b - 32.8 \xi - 0.242H \\ + 0.358 d_{\text{road}} + 3.60 & (\phi = 0) \end{cases}$$  \hspace{1cm} (6.11)

$$a = 74.2 e^{-0.174 d_{\text{road}}} + 4.74,$$  \hspace{1cm} (6.12)

$$b = 8.82 e^{-0.236 d_{\text{road}}}.$$  \hspace{1cm} (6.13)

$$p = -2.05 \times 10^{-2} (h_p - 1.2) + 1,$$  \hspace{1cm} (6.14)

$$q = -0.684/h_p + 0.570.$$  \hspace{1cm} (6.15)

Here, $h_p$ is the height of the receiver $P$ [m], $\phi$ is the perspective angle to the target road [rad], $\xi$ is the building density of the detached houses, $d_{\text{road}}$ is the horizontal distance from the receiver $P$ to the target road [m] and $H$ is the height of the buildings [m].

$\phi (= \phi_1 + \phi_2 + \cdots)$ is the sum of angles subtended by sections of the target road that can be seen from the receiver $P$, considered within an isosceles triangle with the apex $P$ and an apex angle of $2\pi/3$ (default triangle) symmetrical to the perpendicular line from the receiver $P$ to the road (see Fig. 6.9). $\xi$ is the ratio of the sum of the areas of the detached houses within the default area to the area of the default triangle (see Fig. 6.10).

3) For bank roads

When the target road is a bank road (where the road surface is located at a higher level than the building area), the correction for the attenuation due to the detached houses \[\Delta L_{\text{bldgs,bank}}\] is added to $\Delta L_{\text{bldgs}}$ in Eq. (6.9) is calculated using the following equations, in which the height $h_s$ [m] of the target road (sound source) is considered:

$$\Delta L_{\text{bldgs,bank}} = m \cdot \Delta L_{\text{bldgs,flat}} + n,$$  \hspace{1cm} (6.16)

$$m = r(h_p - 1.2) + s,$$  \hspace{1cm} (6.17)

$$n = r(h_p - 1.2) + u,$$  \hspace{1cm} (6.18)

$$r = -8.21 \times 10^{-4} (h_s - 0.3)^2 + 9.09 \times 10^{-3} (h_s - 0.3) - 1.88 \times 10^{-2},$$  \hspace{1cm} (6.19)

$$s = 2.19 \times 10^{-3} (h_s - 0.3)^2 - 4.59 \times 10^{-2} (h_s - 0.3) + 1,$$  \hspace{1cm} (6.20)

$$t = 5.16 \times 10^{-3} (h_s - 0.3)^2 - 5.97 \times 10^{-2} (h_s - 0.3) + 5.66 \times 10^{-2},$$  \hspace{1cm} (6.21)

$$u = -4.03 \times 10^{-2} (h_s - 0.3)^2 + 4.49 \times 10^{-1} (h_s - 0.3),$$  \hspace{1cm} (6.22)

where $\Delta L_{\text{bldgs,flat}}$ is obtained by substituting 1.2 for $h_p$ in Eq. (6.10).

Equations (6.10) and (6.16) are only valid when the receiver $P$ is 20 to 50 m in horizontal distance from the target road, the perspective angle $\phi$ is in the range from 0 to 0.92, the heights ($H$) of the detached houses are 4 to 10 m, the heights ($h_s$) of the sound source are 0.3 to 8.3 m and the heights ($h_p$) of the receiver are 1.2 to 8.2 m. 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 $H$ [64].

Note: The arrangement of the detached houses outside the default triangle should also satisfy the above conditions.
(2) Mean $L_{Aeq}$ for assessed section of target road behind building complexes [67–70]

The mean energy of the equivalent continuous A-weighted sound pressure level $L_{Aeq}$, in an assessed section (section length: $l$ [m]) at a certain distance from a target road is calculated using the equivalent continuous A-weighted sound pressure level $L_{Aeq,0}$ when there is no building complex, and the mean value of the correction $\Delta L_{bldgs}$ in the section of the road for diffraction due to the building complex, as indicated by the following equation:

$$L_{Aeq} = L_{Aeq,0} + \Delta L_{bldgs}.$$  
(6.23)

To calculate the correction $\Delta L_{bldgs}$ for the attenuation due to a building complex, when no noise barriers are installed along a flat road, the target building block (section length: $l$ [m]) for the prediction and assessment of noise is set up as shown in Fig. 6.11. The buildings are divided into those adjacent to the road and other buildings, and these groups of buildings are modeled by using parameters $w_2$, $\alpha$ and $\beta$. Consequently, $\Delta L_{bldgs}$ is calculated using the following equation. In the calculation, the attenuation by the ground surface is ignored.

$$\Delta L_{bldgs} = 10 \log \alpha - 0.78 \left( \beta \frac{\beta}{1 - \beta} \right)^{0.63} \times w_2^{0.86}.$$  
(6.24)

The parameters for the calculation are described in detail in Table 6.1.

Only the contribution of sounds propagating over the buildings. The relevant methods are described in the literature [67,69,70].

Note: Even if the location condition of the detached houses exceeds the scope of the application described above, the calculation method described in Sect. 6.1 is applicable when several buildings are individually located with sufficient intervals and the effect of multiple reflections between the buildings can be ignored. For example, the case where the sum of the perspective angles from the prediction point P to the target road is larger than approximately 90° corresponds to this condition.

APPENDICES

Appendix A1  SOUND POWER SPECTRA OF VEHICLE NOISE

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

A1.1. Power Spectrum for Dense Asphalt Pavement

The A-weighted sound power level for each frequency band (1/n-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 \( L_{WA}(f_{c,i}) \) [dB] for the \( i \)th center frequency \( f_{c,i} \) [Hz] is calculated as

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

where \( L_{WA} \) is the A-weighted sound power level of the road vehicle on a dense asphalt pavement [dB] (see Chapter 2) and \( \Delta L_{WA}(f_{c,i}) \) is the A-weighted relative power level for the frequency band of \( f_{c,i} \) [dB], which is given as

\[
\Delta L_{WA}(f_{c,i}) = \Delta L_W(f_{c,i}) + \Delta L_A(f_{c,i}) + \Delta L_{adj}. \tag{A1.2}
\]

Here, \( \Delta L_W(f_{c,i}) \) is the correction term for the frequency \( f_{c,i} \) [dB], which is given by Eqs. (A1.3) and (A1.4), \( \Delta L_A(f_{c,i}) \) is the A-weighted correction value for the frequency \( f_{c,i} \) [dB] (refer to JIS C 1509-1:2005) and \( \Delta L_{adj} \) is the correction value used to adjust the energy synthesis value of the A-weighted relative band power level to 0 dB (see Eq. (A1.5)).

1) For steady running, non-steady running and deceleration running conditions

\[
\Delta L_W(f_{c,i}) = -20 \log \left[ 1 + \left( \frac{f_{c,i}}{2500} \right)^2 \right]. \tag{A1.3}
\]

2) For acceleration running and steady running conditions on uphill roads

The engine load is large when the vehicle accelerates or when it runs on an uphill road. Under such running conditions, the sound pressure level in the low-frequency range increases. When this effect is considered, the correction term \( \Delta L_{W,V}(f_{c,i}) \) [dB] given by the following formula is added to Eq. (A1.3).

\[
\Delta L_{W,V}(f_{c,i}) = 30 \log \left( 1 + \frac{630}{f_{c,i}} \right). \tag{A1.4}
\]

\( \Delta L_{adj} \) [dB] is given as

\[
\Delta L_{adj} = -10 \log \sum_i 10^{9(\Delta L_W(f_{c,i}) + \Delta L_A(f_{c,i}))/10}. \tag{A1.5}
\]

The relative band power level calculated by Eqs. (A1.3) and (A1.4) is shown in Fig. A1.1. Moreover, \( \Delta L_{WA}(f_{c,i}) \) [dB] under the steady running, non-steady running and deceleration running conditions is given in Table A1.1.

**Note:** A spectrum model of dense asphalt pavement has been widely used as a typical spectrum of noise from a running vehicle. However, according to recent results of measurements of the frequency characteristics of vehicles, it is clear that at frequencies above 2 kHz, the power level of recent vehicles tends to be lower than that given in ASJ RTN-Model 2003 [71–73].

### A1.2. Power Spectrum on Drainage Asphalt Pavement

The A-weighted band power level at the center frequency of vehicle noise on drainage asphalt pavement is given by the following formula. This formula is based on measurement data obtained from expressways where the pavement was constructed 15 years previously [74]:

\[
L_{WA}(f_{c,i}) = L_{WA} + \Delta L_{WA,drain}(f_{c,i}). \tag{A1.6}
\]

where \( L_{WA} \) is the A-weighted sound power level of a running vehicle on drainage asphalt pavement [dB] (see Chap. 2) and \( \Delta L_{WA,drain}(f_{c,i}) \) is the correction term used to obtain the A-weighted relative band power level at the
frequency \( f_{ci} \) of the vehicle on drainage asphalt pavement and is calculated by

\[
\Delta L_{W,\text{adj}}(f_{ci}) = \Delta L_W(f_{ci}) + \Delta L_{\text{drain}}(f_{ci}) + \Delta L_A(f_{ci}) + \Delta L_{\text{adj}}. \tag{A1.7}
\]

Here, \( \Delta L_W(f_{ci}) \) is the correction term at the frequency \( f_{ci} \) [dB] (Eqs. (A1.3) and (A1.4)), \( \Delta L_{\text{drain}}(f_{ci}) \) is the correction term for drainage pavement at the frequency \( f_{ci} \), which is shown in Table A1.2, \( \Delta L_A(f_{ci}) \) is the A-weighted correction value at the frequency \( f_{ci} \) [dB] (refer to JIS C 1509-1: 2005) and \( \Delta L_{\text{adj}} \) is the correction value [dB] used to adjust the synthesis energy of the A-weighted relative band power level to 0 dB and is given as

\[
\Delta L_{\text{adj}} = -10 \log \sum_i 10^{(\Delta L_W(f_{ci}) + \Delta L_{\text{drain}}(f_{ci}) + \Delta L_A(f_{ci}))/10}. \tag{A1.8}
\]

The A-weighted relative band power levels under the steady running condition, the non-steady running condition and the deceleration running condition are shown in Table A1.3 and Fig. A1.2.

**Appendix A2 CALCULATION OF FREQUENCY-DEPENDENT PROPAGATION**

In this appendix, the calculation of frequency-dependent propagation is described. Assuming the road vehicle to be a point source at the center of the \( i \)th road segment, as mentioned in Sect. 1.3, the A-weighted sound pressure level \( L_{A,i} \) [dB] at the prediction point is calculated as

\[
L_{A,i} = 10 \log \sum_n 10^{L_{A,i}(f_n)/10}, \tag{A2.1}
\]
where \( L_{A,i}(f_n) \) is the A-weighted sound pressure level [dB] at the \( n \)th frequency \( f_n \) [Hz]. The obtained \( L_{A,i} \) is substituted into Eq. (1.5) to calculate \( L_{A,E} \), which is converted to \( L_{A,eq} \) using Eq. (1.6).

Two methods of calculating \( L_{A,i}(f_n) \) are described in the following sections: an engineering method and a precise method. Both methods employ the same concept: effects such as sound diffraction around a barrier are considered in the contribution from each propagation path illustrated in Fig. A2.1 or Table A2.1, and finally, the contributions from all paths are summed. The engineering method is chosen when the ground effect is neglected and all calculations are executed in the real-number region; otherwise, the precise method is chosen when the ground effect is considered with complex-number calculations.

The calculation frequencies \( f_n \) are defined as the center frequencies of 1/3-octave bands from 100 Hz to 5 kHz for the engineering method, or as frequencies with intervals of 1/9 octave or less in 1/3-octave bands from 100 Hz to 5 kHz for the precise method [75].

In the following description, \( L_{WA}(f) \) denotes the A-weighted power level [dB] in the 1/n octave band of noise from a running vehicle (see Appendix A1). The effect of drainage asphalt pavement is considered as a change in \( L_{WA}(f) \) and is not considered in sound propagation.

### A2.1. Engineering Method

#### A2.1.1. Basic formula for sound propagation

Sound propagation from a point source \( S \) to a prediction point \( P \) at the frequency \( f \) [Hz] is considered to be the summation of contributions from \( M \) paths and is calculated as

\[
L_{A,i}(f) = 10 \log_{10} \sum_{m=1}^{M} 10^{L_{A,m}(f)/10} + \Delta L_{ex}(f). \tag{A2.2}
\]

\[
L_{A,m}(f) = L_{WA}(f) - 11 - 20 \log r_m + \Delta L_{diff,m}(f) + \Delta L_{air,m}(f). \tag{A2.3}
\]
Here, the suffix \( m \) denotes an index for the \( m \)th propagation path (\( M = 2 \) in the absence of noise barriers or \( M = 4 \) in the presence of a noise barrier), \( L_{A,m}(f) \) is the A-weighted sound pressure level for the contribution of the \( m \)th path, \( r_m \) is the direct distance of the \( m \)th path, \( \Delta L_{\text{dif},m}(f) \) is a correction term for diffraction [dB] (0 dB, in the absence of a barrier), \( \Delta L_{\text{air},m}(f) \) is a correction term for atmospheric absorption [dB] and \( \Delta L_{\text{ex}}(f) \) is a correction term for excess attenuation due to the ground [dB].

**A2.1.2. Correction for sound diffraction \( \Delta L_{\text{dif},m}(f) \)**

For the calculation of the correction term for sound diffraction in the \( m \)th path \( \Delta L_{\text{dif},m}(f) \), the following two methods are used. For noise from moving sources such as road traffic, the contribution from the source located immediately in front of the prediction point predominates; therefore, the accuracy of the calculation for the source located around the frontal point is particularly important to assess \( L_{Aeq} \). In such a case, Maekawa’s empirical formula [23,24] is used for calculating the correction term for diffraction. In the following description, \( \Delta L_{\text{dif},m}(f) \) is expressed as \( \Delta L_{\text{dif}} \).

\[
\Delta L_{\text{dif}}(f) = \begin{cases} 
-13 - 10\log N & N \geq 1 \\
-5 + 8\sinh^{-1}(|N|^{0.485})/\sinh^{-1}(1) & -0.324 \leq N < 1.0 \\
0 & N < -0.324
\end{cases}
\]  
(A.24)

where \( N = 2\delta/\lambda \) is the Fresnel number for the \( m \)th path, \( \delta \) is the diffraction path difference [m] (defined similarly to that in Fig. 3.1), and \( \lambda = c/f \) is the wavelength [m] (\( c \) is the sound speed [m/s], 343.7 m/s in 20°C atmosphere).

The sign \( \pm \) is negative for \( N \geq 0 \) and positive for \( N < 0 \).

On the other hand, Eq. (A.24) overestimates the diffraction effect when the source is positioned near a barrier or in the case of “grazing incidence,” in which a source is positioned at a point far from the frontal point of a prediction point. In such cases, the following method which gives an approximation value of the asymptotic solution of sound diffraction by a reflective barrier is applicable [76,77]. Here, the following equation is valid in only the case where the source \( S \) is invisible from the prediction point \( P \).

\[
\Delta L_{\text{dif}} = 10\log(D_{SP} + D_{SP}^{'})^2
\]  
(A.25)

\[
D_{SP} = \frac{1}{2\pi\sqrt{N_{SP} + 0.18}} \sqrt{1 + \left( \frac{1}{2\pi(N_{SP}^{0.6} + 0.18^{0.6})^{1/0.6}} \right)^2}
\]  
(A.26)

\[
D_{SP}^{'\prime} = \frac{1}{2\pi\sqrt{N_{SP} + 0.18}} \sqrt{1 + \left( \frac{1}{2\pi(N_{SP}^{0.6} + 0.18^{0.6})^{1/0.6}} \right)^2}
\]  
(A.27)

Here, \( N_{SP} = 2\delta_{SP}/\lambda \) is the Fresnel number, \( \delta_{SP} \) is the diffraction path difference [m] (defined as \( \delta_{SP} = R_{d,SP} - R_{g,SP} \) in Fig. A2.2), and \( \lambda = c/f \) is the wavelength [m] (\( c \) is the sound speed [m/s]). \( N_{SP} \) is calculated similarly with replacing \( S \) for the mirror source \( S' \).

**A2.1.3. Correction for atmospheric absorption \( \Delta L_{\text{air},m}(f) \)**

\( \Delta L_{\text{air},m}(f) \) is calculated as the product of attenuation per unit length \( \alpha(f) \) [dB] and the propagation path length \( r_m \) for the \( m \)th path [m]:

\[
\Delta L_{\text{air},m}(f) = -\alpha(f) \cdot r_m.
\]  
(A.2.8)

\( \alpha(f) \) is calculated by the following equation using ISO 9613-1:1993, assuming an atmospheric pressure of 101.325 kPa [78].

\[
\alpha(f) = f^2 \times 10^{-10} \left( 1.60 + \frac{b_O f_O}{f_O + f^2} + \frac{b_N f_N}{f_N + f^2} \right)
\]  
(A.2.9)

Here, \( f_O \) and \( f_N \) are the oxygen and nitrogen relaxation frequencies, respectively, and \( b_O \) and \( b_N \) are the coefficients related to the molecular absorptions of oxygen and nitrogen, respectively. They are calculated as

\[
f_O = 24 + 4.04 \times 10^4 h_0 0.02 + h_0 0.391 + h_0
\]  
(A.2.10)

\[
f_N = \frac{17.1}{\sqrt{T_C + 273}} \left[ 9 + 18100 \times h \times e^{-\frac{3500}{T_C + 273}} \right]
\]  
(A.2.11)

\[
h = 41200 \times h_1 \times 10^{-\frac{8070}{(T_C + 273)^3.39}}
\]  
(A.2.12)

\[
b_O = 1.11 \times 10^9 \times e^{-\frac{3240}{T_C + 273}} \left( \frac{293}{T_C + 273} \right)^{2}
\]  
(A.2.13)

\[
b_N = 9.28 \times 10^9 \times e^{-\frac{3500}{T_C + 273}} \left( \frac{293}{T_C + 273} \right)^{2}
\]  
(A.2.14)

where \( T_C \) is the atmospheric temperature [°C] and \( h \) is the relative humidity [%].
A2.1.4. Correction for excess attenuation due to ground, ΔL_{ge,ex}(f)

\[ ΔL_{ge,ex}(f) \] is the correction of the sound pressure level relative to a perfectly reflective surface. It is simplified to \( ΔL_{ge,ex}(f) = 0 \) to avoid the underestimation of \( L_{A,f}(f) \), whereas, generally, \( ΔL_{ge,ex}(f) ≤ 0 \).

Note: To evaluate \( ΔL_{ge,ex}(f) \), the wave-based numerical analysis described in A4.2 can be applied to the estimation of the ground and meteorological effects. However, the method is applicable to only the case where a point source sets on the flat ground surface.

A2.2. Precise Method

The wave-based calculation method used to consider diffraction around a barrier, absorption by the ground surface and the effect of the terrain including a slope along a road is described in the following.

An infinite straight road with the cross-sectional terrain illustrated in Table A2.1 is considered. A point source \( S \) is set on the road surface. Symbols A and D in the illustrations denote infinite distances. Only the terrain and barrier shown in the figures are considered; other factors such as the reflection from the barrier on the opposite side of the road must be calculated separately.

A2.2.1. Basic formula

The sound field behind a barrier is considered to be the summation of contributions from \( M \) propagation paths. \( L_{A,f}(f) \) [dB] at the prediction point \( P_1 \) at the frequency \( f \) [Hz] is calculated as [79]

\[
L_{A,f}(f) = L_{WA}(f) - 8 + 10 \log \left[ \sum_{m=1}^{M} \frac{D_m \cdot R_m \cdot G_m \cdot A_m}{r_{0,m}} \right].
\]

(A2.15)

Here, \( r_{0,m} \) is the direct distance of the \( m \)th path [m], \( D_m \) is the coefficient for diffraction around the barrier, \( R_m \) is the reflection coefficient of the ground surface, \( G_m \) is a coefficient representing the size of the reflecting surface and \( A_m \) is a coefficient for atmospheric absorption. In the following, the imaginary unit is denoted as \( i \) and angular frequency is denoted as \( \omega \); the temporal factor \( e^{-i \omega t} \) is omitted for simplicity of notation.

A2.2.2. Coefficient for diffraction around a simple barrier, \( D_m \)

The coefficient \( D_m \) for diffraction around a thin reflective semi-infinite barrier is calculated as

\[
D_m = D(N_m)e^{ikr_m},
\]

(A2.16)

\[
D(N) = \begin{cases} 
1 & 0 \leq N < 1 \\
\frac{1}{2} \left( 1 + \sqrt{\frac{N}{0.30}} \right) & -0.30 \leq N < 0 \\
1 & N < -0.30
\end{cases}
\]

(A2.17)

\[ kr_m \sin \theta \gg 1 \] (80); the error due to the violation of this
Table A2.2 Examples of ground surface and their effective flow resistivity.

<table>
<thead>
<tr>
<th>Ground surface</th>
<th>Effective flow resistivity ( \sigma_e ) [kPa s/m(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete, asphalt</td>
<td>20,000</td>
</tr>
<tr>
<td>Compacted soil</td>
<td>1,250</td>
</tr>
<tr>
<td>Lawn, rice field, grassland</td>
<td>300</td>
</tr>
<tr>
<td>Soft farmland, furrowed rice</td>
<td>75</td>
</tr>
</tbody>
</table>

Table A3.1 List of noise calculation methods at signalized intersection.

<table>
<thead>
<tr>
<th>Calculation method</th>
<th>Outline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practicable method (Semi-precise method)</td>
<td>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 [46].</td>
</tr>
<tr>
<td>Simplified method</td>
<td>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 [46].</td>
</tr>
</tbody>
</table>

A2.2.4. Coefficient for finiteness of reflecting surface, \( G_m \)

A coefficient \( G_m \) is defined to estimate the relationship between the size of the reflecting surface and its relative contribution. The definition of \( G_m \) for each path is given in Table A2.1. In the case of the slit method (see Fig. 3.17) applied to the analysis of the reflecting surface AB in Fig. A2.4, the coefficient \( \Gamma_{X-AB-P} \) representing the contribution from the barrier-top edge X to the mirror-image receiver P' through the slit AB is defined as

\[
\Gamma_{X-AB-P} = D_{diff}(N_{XAP}) - D_{diff}(N_{XBP'}). \tag{A2.25}
\]

where

\[
D_{diff}(N) = \begin{cases} 
0 & \text{if } 0 < N \\
\frac{1}{2} \left( 1 \mp \sqrt{\frac{|N|}{0.30}} \right) & \text{if } |N| \leq 0.30 \\
1 & \text{if } N < -0.30
\end{cases} , \tag{A2.26}
\]

where the sign \( \mp \) is negative for \( N \geq 0 \) and positive for \( N < 0 \).

A2.2.5. Coefficient for atmospheric absorption, \( A_m \)

A coefficient \( A_m \) for atmospheric absorption is calculated, using \( \alpha(f) \) defined in Sect. A2.1.3, as

\[
A_m = 10^{-\alpha(f) \cdot \rho_0 / 20} . \tag{A2.27}
\]

Appendix A3 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 [84]. In this appendix, other calculation methods such as a practicable method (semi-precise method) and its simplified method are described (see Table A3.1).

A3.1. Practicable Method [46]

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 \( L_{AE} \), which is determined by the unit pattern of each vehicle, as shown in Fig. A3.1. Then, all vehicles stopping at a red signal are accounted for in the calculation of \( L_{Aeq} \). Total \( L_{Aeq} \) is obtained by summing the energies in the above results. The methods used to set various conditions for the red-signal phase are given below.

(1) 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

\[
N_R = N_C \cdot \frac{T_R}{T_C} , \tag{A3.1}
\]

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

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

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

where \( a_L \) is a constant given in the formula of sound power level for light vehicles \([\text{dB}]\), \( b \) is a coefficient representing the speed dependence, \( V \) is the running speed \([\text{km/h}]\) 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 formula with the constant \( a_H \) in the formula for the sound power level for a heavy vehicle:

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

Note: It is also possible to calculate the mean A-weighted sound power level for the four-category classification using the difference among the constant values for four categories, similarly to Eq. (A3.3).

Acoustics

Accelerations of vehicles

The accelerations while accelerating and decelerating at signalized intersections are shown in Table A3.2.

Table A3.2  Accelerations while accelerating and decelerating at signalized intersections.

<table>
<thead>
<tr>
<th>Running condition</th>
<th>Acceleration ([\text{m/s}^2])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerated</td>
<td>1.0</td>
</tr>
<tr>
<td>Decelerated</td>
<td>-1.3</td>
</tr>
</tbody>
</table>

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

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

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

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

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 accelerations shown in Table A3.2.
where $a_{\text{accel}}$ is the acceleration while accelerating [m/s$^2$] given in Table A3.2 and $v$ is the speed in the steady-running section [m/s]. A steady-running section is specified on both sides of the compound section.

(2) Mean sound power level $L_{WA}$

The mean sound power level $L_{WA}$ for the steady-running section is calculated using Eq. (A3.2). On the other hand, $L_{WA}$ for the compound section with accelerating and steadily running vehicles is determined from the mean sound power level $L_{WA,B}$ [dB] under the steady-running condition (when the signal is green) and from $L_{WA,R}$ [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

$$L_{WA} = 10 \lg \frac{N_R \cdot 10^{L_{WA,B}/10} + (N_C - N_R) \cdot 10^{L_{WA,R}/10}}{N_C},$$  
(A3.8)

where $L_{WA,R}$ is calculated by substituting the speed given to vehicles in the steady-running section for that speed in the formula for calculating the sound power level for accelerating vehicles.

### Appendix A4 WAVE-BASED NUMERICAL ANALYSIS

For complicated road structures, such as an overhead road constructed over a flat road with parallel barriers or a semi-underground road with large overhangs, the practical calculation methods described in the main body have limitations. For such cases, wave-based numerical analyses, such as the boundary element method (BEM) or the finite-difference time-domain (FDTD) method, can be effective. If the road structure is modeled as a simple case with a uniform cross-sectional shape for a sufficiently long distance, two calculation methods are practically applicable. One is a simple two-dimensional numerical analysis. In this method, a coherent line source is assumed, and it requires a smaller computational resource than three-dimensional numerical analysis. The other is 2.5-dimensional numerical analysis (see Fig. A4.2), by which sound pressure from a point source is calculated; consequently, a unit pattern can be obtained by setting discrete point sources on a straight line. These methods are described in Sect. A4.1.

On the other hand, outdoor sound propagation is strongly affected by meteorological factors, namely, vector wind speed and temperature. To consider such meteorological factors, the parabolic equation (PE) method can be applied. By this method, one can calculate refracted sound propagation due to the vertical distributions of vector wind speed and temperature, and the ground effect over a finite-impedance surface. However, the applicable sound field is restricted to a simple hemi-free field having a flat terrain without any obstacles such as barriers and buildings. Application of the PE method is described in Sect. A4.2. Notes that should be commonly paid attention to all methods described in this appendix are shown in Sect. A4.3.
Note: When using wave-based numerical analysis, it is necessary to discretize the space or boundaries of the sound field using a large number of elements or cells with sizes smaller than the wavelength. Therefore, the three-dimensional wave-based computation of road traffic noise propagation in a realistic three-dimensional area over a wide frequency range is extremely difficult because of its excessively high computational cost. To moderate this limitation, some novel algorithms with a high efficiency of memory storage and a high computational speed are being developed [85,86]. However, no practical application of the three-dimensional wave-based computation in a wide frequency range to road traffic noise problem has been realized so far.

A4.1. Calculation Methods for Complicated Road Structures

The methods described in this section can be applied to a straight road having a uniform cross-sectional shape for a sufficiently long distance. Reflections from independent piers or crossbeams supporting an overhead road or the overhang of a semi-underground road structure and sound propagation through the gaps between buildings along a street canyon cannot be analyzed by these calculation methods. In such cases, where a three-dimensional geometry must be considered, the scale-model experiment [22] can be applied.

A4.1.1. Two-dimensional wave-based numerical analysis

Under the condition that the line source $Q_{\text{line}}$ exists over a range of perspective angles, $\Psi$ [rad], as shown in Fig. A4.1, the band level of $A$-weighted sound pressure at a center frequency of $f$ [Hz], $L_A(f)$ [dB], is calculated as

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

(A4.1)

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

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

(A4.2)

where $V$ is the average running speed of vehicles [km/h] and $N$ is the traffic volume [number of 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

$$\Delta L_{2D}(f) = 10 \log \frac{\phi_{2D}(k)}{\phi_{2D,0}(k)},$$

(A4.3)

where $\phi_{2D}(k)$ is the complex sound pressure at the wavenumber $k = 2\pi f/c$ at the prediction point P in a sound field with obstacles, and it is obtained by the two-dimensional BEM or FDTD method [87,88]. $\phi_{2D,0}(f)$ is the complex sound pressure in a sound field without obstacles (two-dimensional hemi-free field). When using the two-dimensional BEM (with the temporal term $e^{-i\omega t}$), $\phi_{2D,0}(f)$ is calculated as

$$\phi_{2D,0}(f) = \frac{i}{2} H_0^{(1)}(kf),$$

(A4.4)

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 with the sound source and prediction point at the same points as the sound field with the road structure is assumed and the FDTD calculation is carried out for the hemi-free field. Based on the result, $\phi_{2D,0}(f)$ is obtained.

Note: In two-dimensional wave-based numerical analysis, sound propagation from a cylindrical source (coherent line source) is dealt with; therefore, the sound propagation physically differs from that 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. According to investigations on the insertion loss of barriers and the effects of the ground for a straight road with sufficient length [89–91], however, the difference between the insertion loss calculated by two-dimensional wave-based numerical analysis and that theoretically calculated for an incoherent line source existing in the range between $-60$ and $+60$ degrees 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 the analysis of sound propagation in a three-dimensional sound field to obtain an approximate sound pressure level at a prediction point.

A4.1.2. 2.5-Dimensional wave-based numerical analysis

A sound field that has a uniform cross-sectional shape continuously continuing in the $z$-direction and a point sound source, $S$, (see Fig. A4.2) is referred to as a “2.5-dimensional sound field.” The complex sound pressure at the receiving point P in the 2.5-dimensional sound field, $\phi_{2.5D}(x,y,z,k)$, is related to the complex sound pressure $\phi_{2D}(x,y,k_{2D})$ in a two-dimensional field, to which the cross-sectional shape of the 2.5-dimensional sound field is modeled, using the following equation [92,93].

$$\phi_{2.5D}(x,y,z,k) = \frac{1}{\pi} \int_0^{+\infty} \phi_{2D}(x,y,\sqrt{k^2 - k_{2D}^2}) \cos k_z dz,$$

(A4.5)

The integral parameter $k_z$ is the $z$-directional component of the wavenumber $k$. With the wavenumber in a two-dimensional field defined as $k_{2D} = \sqrt{k^2 - k_z^2}, \phi_{2D}(x,y,k_{2D})$ for $k_{2D}$ varying as $k_{2D} : k \to 0 \to i \cdot \infty$ is calculated as a function of the integral parameter $k_z$, and all the calculated $\phi_{2D}(x,y,k_{2D})$ values are integrated using Eq. (A4.5); then, $\phi_{2.5D}(x,y,z,k)$ for the 2.5-dimensional field is obtained.

To obtain $\phi_{2.5D}(x,y,k_{2D})$, the BEM and the FDTD method can be applied. When the BEM is applied,
φ_{2D}(x,y, k_{2D}) at discrete wavenumbers k_{2D} are calculated and the integration term in Eq. (A4.5) is approximately obtained by summing the calculated φ_{2D}(x,y, k_{2D}) values. To ensure sufficient accuracy, it is necessary to calculate two-dimensional solutions φ_{2D}(x,y, k_{2D}) at many discrete wavenumbers at small intervals. In particularly near k_{2D} = 0, φ_{2D}(x,y, k_{2D}) diverges to infinity [94]; therefore, wavenumber intervals should be sufficiently small.

When using the FDTD method, φ_{2D}(x,y, k_{2D}) values at real and imaginary wavenumbers are obtained by the Fourier and Laplace transformations of an impulse response [95]. Sufficiently small intervals of the wavenumbers can be maintained by increasing data length of the impulse response by adding zero after the obtained response and then applying the Fourier and Laplace transformations. However, this method cannot be applied to a sound field with an absorptive boundary.

**A4.1.3. Notes on using BEM**

(1) **Size of boundary elements**

The size of boundary elements should be set to be less than 1/5 of the wavelength [96,97]. 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 avoiding large errors unexpectedly occurring at specific frequencies that depend on the dimensions of an obstacle owing to its internal resonance. Several calculation methods to avoid such internal resonances have been reported in the literature [98–100].

(3) **Absorptive surface on top of barriers**

When using edge-modified barriers (see reference R3), absorptive materials are sometimes applied at the top of the barriers. Diffracted sound over such barriers is underestimated if the complex normal impedance (see A4.3.3) is adopted for the top of the barrier as the absorption characteristics of the absorption material [101].

**A4.1.4. Notes on using FDTD method**

(1) **Selection of difference scheme**

When using the simplest Yee algorithm [102], serious numerical error due to the accumulation of dispersion error occurs in the case where 1,000 calculation steps or more are executed. To reduce the dispersion error, a higher-order difference scheme represented by the FDTD (2,4) scheme [103] should be applied.

**Note:** To reduce numerical dispersion error, various differential schemes such as the higher-order scheme [104] and the compact scheme [105] have been developed. Calculation methods with higher accuracy related to not only the spatial difference approximation but also temporal integration are being investigated [106].

(2) **Spatial grid size of finite difference**

The spatial grid size of the finite difference should be set less than 1/20 of the wavelength in the Yee algorithm considering the relationship between spatial grid size and numerical dispersion error. 1/10 of the wavelength or more is applicable when using higher-order difference schemes such as the FDTD (2,4) method. In the FDTD method, zigzag approximation is usually applied to simulate an object’s 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) [107, 108], which is most frequently applied 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 diffracted sound may be considerably smaller than that of the unexpected numerical reflection from the surrounding termination.

**A4.2. Calculation Methods for Meteorological Effects**

Outdoor sound propagation is strongly affected by the vertical distributions of vector wind speed and temperature. The PE method is often used for calculation which enables the consideration of such meteorological effects [109,110].

**A4.2.1. 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. For a rotational symmetric sound field having a rotational axis z, as shown in Fig. A4.3, we can consider a two-dimensional coordinate system (r,z) consisting of the z-axis, which is the height from the ground, and the r-axis, which is the horizontal distance from a point.

---

**Fig. A4.3 PE analysis for calculation of a unit pattern.**
source. The two-dimensional sound field is discretized in rectangular calculation grids, and the sound pressure distribution at the grid points on the $z$-axis is first set as the starting field condition. According to the range-marching-solution procedure, the complex sound pressures at the grid points on the line $r = \Delta r$ is calculated from the given starting field condition on the $z$-axis. Similarly, complex sound pressures at grid points on the line $r = 2\Delta r$, $3\Delta r$, $4\Delta r$, ... are successively obtained based on the range-marching-solution technique. This calculation method can consider complex ground impedance. Furthermore, meteorological effect can be taken into consideration by setting the effective sound speeds at respective grid points based on the vertical distributions of 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 obstructive objects.

To apply the PE method to road traffic noise analysis, discrete sound sources are set on the target road, as shown in Fig. A4.3, and the unit pattern at the prediction point $P$ is calculated according to the procedure described in Sect. A2.1. The application being limited in the case where a point source is located on a flat ground, the value of the correction for excess attenuation, $\Delta L_{g,ext}(f)$, in Eq. (A2.2) is calculated by the following procedure [32]. In a two-dimensional plane including the sound source $S_i$ and the prediction point $P$, the complex sound pressure at $P$ at the frequency $f$, $\phi_i(f)$, is calculated by the PE method under the condition of the vertical distribution of the effective sound speed $c_{\text{eff}}(z)$, which is obtained from the vertical distributions of the vector wind speed $\vec{v}(z)\cos\theta$ and the temperature $T(z)$. The effective sound speed $c_{\text{eff}}(z)$ is defined as

$$c_{\text{eff}}(z) = 331.5 + 0.61T(z) + \vec{v}(z)\cos\theta. \quad (A4.6)$$

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

$$\Delta L_{g,ext}(f) = 10\lg \left( \frac{\phi_i(f)}{\phi_{i,00}(f)} \right)^2. \quad (A4.7)$$

A4.2.2. 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 and ground effects 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

Although the PE method has high accuracy for sound propagation along a flat ground, the accuracy degrades at large elevation angle. The applicable elevation angle for the Crank-Nicholson PE (CN-PE) method is approximately 30 degrees. For the Green’s Function PE (GF-PE) method, the applicable elevation angle is approximately 75 degrees.

(3) Grid spacing in finite difference

The grid spacing for $\Delta r$ and $\Delta z$ should be less than 1/10 of the wavelength in the CN-PE method. In the GF-PE method, $\Delta r$ can be extended to 10 times the wavelength.

(4) Non reflection termination

It is necessary to set an artificial layer of gradually increasing attenuation on the upper boundary to simulate a 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 small angle in the distant region.

A4.3. Common Notes

Some points that should be commonly noted in the methods described in Sect. A4.1 and A4.2 are presented here.

A4.3.1. Frequency range of calculation

The calculation is performed for 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 [75].

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.

A4.3.2. Source position

The sound source is located at the surface of the 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 [111].

A4.3.3. Setting absorptive boundary conditions

Complex values of normal acoustic impedance are considered as the boundary conditions of all surfaces in wave-based numerical analysis. A hard boundary such as a concrete surface can be treated as rigid (the value of normal acoustic impedance is infinity). For boundaries treated with an absorptive material, their normal acoustic impedance should be set. A formula for calculating the normal acoustic impedance of several kinds of ground is given in
Appendix A2 (see Eq. (A2.24)). Measured values of the normal acoustic impedance of a drainage asphalt pavement are available in the literature [112].

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 acoustic impedance is deduced from the absorption coefficient and the imaginary part is neglected. When applying such a method to set the normal acoustic impedance, careful attention should be paid to the fact that the effects of absorption are sometimes overestimated [111].

Note 2: In the case where the acoustic impedance $z$ of the ground is set using $\beta$ in Eq. (A2.24), $z = 1/\beta$ for the temporal term $e^{-\beta t}$ and $z = 1/\beta^*$ (denotes complex conjugate) for the temporal term $e^{\beta t}$.

REFERENCES

Reference R1  SOUND POWER LEVELS OF HYBRID AND ELECTRIC VEHICLES

Hybrid and electric vehicles (HVs and EVs) are becoming popular and their production is rapidly increasing in Japan, as in many other countries. At the end of March 2012, the numbers of registered HVs and EVs were about 2.03 million and 0.02 million, respectively. Although the percentage of registered vehicles of these types was about 3% of all vehicles, the market share of low-emission vehicles is expected to grow in the future [113,114]. The levels of propulsion noise generated from HVs and EVs are much lower than those from gasoline engine vehicles (GEVs) particularly at low running speeds. Therefore, a guideline for adding an artificial warning sound device was established to help make pedestrians more aware of these quiet vehicles approaching at speeds less than 20 km/h [115].

Figure R1.1 shows the measurement results of the noise of a running HVs and two types of GEVs [116]. 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, to compare the A-weighted sound power level of HVs with that of GEVs, noise measurement was carried out on a dense asphalt pavement [15]. The weight and tire size of these vehicles were almost the same. The sound power levels of both types of vehicle with the same engine type and displacement are shown in Fig. R1.2. It can be seen that the sound power levels of HVs are almost 5 dB lower than those of GEVs at a speed of 20 km/h in the acceleration section. However, during the steady running condition at 50 km/h or more (130 m from the starting line), there is no significant difference in the sound power level between HVs and GEVs. According to another report [117], EVs also tend to be much quieter than GEVs at low running speeds.

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.

**Note:** In FY 2011, the percentage of registered HVs and EVs among all road vehicles was low, and the numbers of the types of commercially available road vehicles were only 37 for HVs and 18 for EVs, respectively [118]. Although the number of registered low-emission vehicles is still small, the committee will conduct noise measurement to gather the sound power levels of HVs and EVs to assess road traffic noise in future environments.

**Reference R2 NOISE REDUCTION EFFECT OF DOUBLE-LAYER DRAINAGE PAVEMENT**

The double-layer drainage pavement (DDP) 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 a bottom layer with a maximum chipping size of 13 mm and thicknesses of 30–50 mm [119–121]. Figure R2.1 shows the structures of DDP and a single-layer drainage pavement (DP).

**1) Noise reduction effect**

Figure R2.2 shows the maximum A-weighted sound pressure levels of a passenger car and a large-sized vehicle measured on the test tracks with DDP, DP and a dense asphalt pavement (AP) [122]. Figure R2.3 shows the noise reduction effect of DDP, which was calculated using the regression formulas given in Fig. R2.2. It can be seen that the A-weighted sound pressure level on DDP decreases by 5–10 dB for compared with that on AP and by 4–6 dB compared with that on DP.

Figure R2.4 shows the initial noise reductions calculated from the differences between the A-weighted sound power levels measured on DDP and those measured on DP or AP [123]. The sound power level of a test passenger car on DDP is reduced by 4–8 dB for AP, and by 1–3 dB for DP. In addition, examples of the tire/road noise level measured on DDP using a special test truck [124] are described in Ref. 120.

**2) Frequency characteristics of running noise**

Figure R2.5 shows the maximum A-weighted sound pressure levels in 1/3 octave bands on DDP, DP and AP [122]. 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. R2.2). The sound pressure levels on DDP at a frequency over 500 Hz are much lower than those on AP. Moreover, the sound pressure levels of DDP in the frequency range from 200 Hz to 1 kHz are lower than those of DP.

Figure R2.6 shows the sound spectra of the A-weighted sound power level measured using a test passenger car.
under initial road surface conditions after each pavement was laid [123]. The sound pressure levels on DDP at a frequency over 400 Hz tend to be lower than those on DP.

(3) Annual change in noise reduction effect

Annual changes in the noise reduction effect of DDP were measured on general roads [121,125]. As a result, it was found that the annual change in the noise reduction effect of DDP is similar to the correction $\Delta L_{\text{surf}}$ for DP described in Sect. 2.3.1.

Reference R3 SOUND PROPAGATION AROUND 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 of calculating sound propagation around these barriers are described.

The calculation methods described in Sect. R3.1 should be applied for propagation calculations using the procedures described in Chap. 3 of the main body for the five barriers (whose specifications are provided by the Japanese expressway company NEXCO) shown in Fig. R3.1, or...
scale-model experiments similar to those in Ref. 126 are available for considering edge-modified barriers. The procedures in Sect. R3.2 are applied for the calculation of frequency-dependent propagation as in Appendix A2.2.

R3.1. Method of Calculation Based on Scale-Model Experiments

A method of calculating the correction term for diffraction around the barriers shown in Fig. R3.1 using empirical formulas derived from scale-model experiments [126] is described. The correction term for diffraction in each region shown in Fig. R3.2 is calculated as follows.

(1) For prediction point P in region 1

Instead of using $\Delta L_{\text{diff,sh}}$ in Subsection 3.2.2, $\Delta L_{\text{diff,emb}}$ [dB] in the following equation is applied as

$$\Delta L_{\text{diff,emb}} = \Delta L_{\text{diff,sh}} + \Delta L_c. \quad (R3.1)$$

$\Delta L_{\text{diff,sh}}$ [dB] is calculated as a correction term for a hypothetical simple barrier, as described in Subsection 3.2.6 and Fig. 3.8. The additional correction term $\Delta L_c$ [dB] is calculated as

$$\Delta L_c = \begin{cases} -A - B \log \delta + \Delta L_{\text{Zone}2} & \delta \geq 1 \\ -C - D \sinh^{-1}(|\delta|^\theta) + \Delta L_{\text{Zone}2} & 0 \leq \delta < 1 \end{cases}, \quad (R3.2)$$

where $\delta$ is the path difference for the hypothetical barrier [m], and values for coefficients $A$ to $E$ are given in Table R3.1.

(2) For prediction point P in region 2

Similarly to the previous section, Eq. (R3.1) is applied with $\Delta L_c$ [dB] calculated as

$$\Delta L_c = \begin{cases} -A - B \log \delta + \Delta L_{\text{Zone}2} & \delta \geq 1 \\ -C - D \sinh^{-1}(|\delta|^\theta) & 0 \leq \delta < 1 \end{cases}.$$

(3) For prediction point P in region 3

Instead of using Eq. (R3.1), the method described in Subsection 3.2.2 is applied to a simple barrier with a top edge at the source-side diffraction point X. Note: The prediction accuracy for a barrier with an overhang, i.e., types (4) and (5) in Fig. R3.1, has not been verified.

R3.2. Method of Calculation Based on Efficiency Determination using Actual Products

A series of procedures to determine the efficiency of an arbitrary product of an edge-modified barrier and to substitute the determined result into frequency-dependent propagation calculations [127] is described.

R3.2.1. General concept

Instead of using the diffraction coefficient $D_m$ (where $m$ denotes the path index) for a thin simple barrier in Subsection A2.2.2, the diffraction coefficient $D_{\text{emb},m}$ for an edge-modified barrier is calculated as follows. As shown in Fig. R3.3, $D_{\text{thick},m}$ denotes the coefficient of diffraction...
around a thick barrier enveloping the maximum height and thickness of the edge-modified barrier and $D_{\text{edge},m}$ denotes a coefficient representing the intrinsic sound reduction by the edge-modifying device. $D_{\text{emb},m}$ is defined as the product of these two coefficients [127].

$$D_{\text{emb},m} = D_{\text{thick},m} \cdot D_{\text{edge},m} \quad (\text{R3.5})$$

A folded barrier without any acoustical device other than the overhang (see Fig. 3.9) is approximated as a thick barrier with $D_{\text{emb},m} = D_{\text{thick},m}$. Equation (R3.5) is applicable for edge-modifying devices with a thickness (i.e., width in cross-sectional drawings) of approximately 1 m or less [30].

**R3.2.2. Diffraction due to a thick barrier, $D_{\text{thick},m}$**

$D_{\text{thick},m}$ is defined as the coefficient of diffraction around a thick barrier with a thickness equivalent to that of an edge-modified barrier. The calculation for a thick barrier described in Subsection 3.2.4 is applied at each frequency:

$$D_{\text{thick},m} = \begin{cases} 
D(N_{\text{SXP},m})e^{i\theta_{m}} & \text{P \in I, II} \\
2D(N_{\text{SXP},m})D(N_{\text{XY},m})e^{i\theta_{m}} & \text{P \in III, } N_{\text{SXP},m} \geq N_{\text{SYP},m} \\
2D(N_{\text{SYP},m})D(N_{\text{SXY},m})e^{i\theta_{m}} & \text{P \in III, } N_{\text{SXP},m} < N_{\text{SYP},m} 
\end{cases} \quad (\text{R3.6})$$

where $N_{\text{SXP},m}$ denotes the Fresnel number (see Subsection A2.1.2) along SXP in Fig. 3.5 for the $m$th path. $D(N)$ is calculated using Eq. (A2.9). $l_m = SX + XP$ [m] for P in regions I and II in Fig. 3.5, whereas $l_m = SX + XY + YP$ [m] for P in region III.

**R3.2.3. Device-dependent effect, $D_{\text{edge},m}$**

The determination of the efficiency of an actual product of the edge-modifying device is carried out and the results are substituted into the coefficient $D_{\text{edge},m}$ [127]. Figure R3.4 shows a schematic diagram of efficiency determination. The transfer function from the sound source S to the receiver P is measured for two barriers: a semi-infinite barrier with an edge-modifying device and a thick semi-infinite barrier with a thickness equivalent to that of the edge-modifying device. Usually, these barriers cannot be considered as semi-infinite because of reflections from the ground or surrounding buildings; the transfer functions for semi-infinite barriers are approximately obtained by measuring impulse responses and excluding the reflections from the temporal waveform of the impulse responses. The source and receiver are aligned in a plane perpendicular to the lengthwise direction of the barrier at angles $\theta_S$ and $\theta_P$, respectively, from the vertical surface of the barrier. The measured transfer functions are converted to the frequency characteristics of sound pressure levels, and the difference

**Table R3.1 Coefficients for the correction term $\Delta L_e$.**

<table>
<thead>
<tr>
<th>Pavement</th>
<th>Barrier</th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
<th>$E$</th>
<th>$F$</th>
<th>$G$</th>
<th>Applicable range of $\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense asphalt</td>
<td>Large branch-type</td>
<td>5.0</td>
<td>3.0</td>
<td>2.1</td>
<td>3.29</td>
<td>0.414</td>
<td>5.31</td>
<td>-1.4</td>
<td>0.11–10</td>
</tr>
<tr>
<td>Standard branch-type</td>
<td>1.88</td>
<td>-0.3</td>
<td>0.0003–11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L-shaped (3 m)</td>
<td>3.5</td>
<td>5.0</td>
<td>0.0</td>
<td>3.97</td>
<td>0.600</td>
<td>0.0</td>
<td>2.66</td>
<td>0.7</td>
<td>0.02–20</td>
</tr>
<tr>
<td>L-shaped (5 m)</td>
<td>1.0</td>
<td>5.0</td>
<td>0.0</td>
<td>1.14</td>
<td>0.414</td>
<td>3.66</td>
<td>1.4</td>
<td>0.08–34</td>
<td></td>
</tr>
<tr>
<td>Standard branch-type</td>
<td>3.7</td>
<td>3.0</td>
<td>2.1</td>
<td>1.82</td>
<td>0.414</td>
<td>1.65</td>
<td>0.1</td>
<td>0.0003–11</td>
<td></td>
</tr>
<tr>
<td>L-shaped (3 m)</td>
<td>2.5</td>
<td>4.5</td>
<td>0.0</td>
<td>2.84</td>
<td>0.600</td>
<td>2.30</td>
<td>1.2</td>
<td>0.02–20</td>
<td></td>
</tr>
<tr>
<td>L-shaped (5 m)</td>
<td>1.0</td>
<td>3.5</td>
<td>0.0</td>
<td>1.14</td>
<td>0.414</td>
<td>3.02</td>
<td>1.7</td>
<td>0.08–34</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. R3.3** Framework of diffraction coefficient around an edge-modified barrier.

**Fig. R3.4** Efficiency determination of an edge-modified barrier.
in level between them is defined as \( \Delta L_{\text{edge}}(f, \theta_s, \theta_p) \) [dB], a function of the frequency \( f \), \( \theta_s \) and \( \theta_p \). \( \Delta L_{\text{edge}}(f, \theta_s, \theta_p) \) is negative when the edge-modified barrier produces a greater reduction of diffracted sound than the equivalent thick barrier.

The measured \( \Delta L_{\text{edge}}(f, \theta_s, \theta_p) \) is converted to \( D_{\text{edge},m} \) as

\[
D_{\text{edge},m} = 10^{\Delta L_{\text{edge}}(f, \theta_s, \theta_p)/10},
\]

where \( \theta_{s,m} \) and \( \theta_{p,m} \) denotes the angles for the positions of the traffic lane and the prediction point in the \( m \)th path, respectively; see Fig. R3.5 for definitions. Note that these angles are not defined for a point source moving on the traffic lane. \( D_{\text{edge},m} \) is then substituted into Eq. (R3.5) to calculate the propagation. For interference-type devices in which the inner cavities are not partitioned in the lengthwise direction, as shown in Fig. R3.6(b), \( D_{\text{emb},m} \) is defined as

\[
D_{\text{emb},m} = 10^{\Delta L_{\text{emb}}(f \cos \theta_{\text{cross}}, \theta_{s,m}, \theta_{p,m})/20},
\]

whereas Eq. (R3.7) is applied to devices with partitioned cavities such as that shown in Fig. R3.6(a) [128]. Note that \( \theta_{\text{cross}} \) denotes the angle between the horizontal projection of the propagation path and the normal to the vertical surface of the barrier, as shown in Fig. R3.5.

The transfer function measurement described above is usually carried out for the discrete angles \( \theta_s \) and \( \theta_p \); \( D_{\text{emb},m} \) for the arbitrary angles \( \theta_{s,m} \) and \( \theta_{p,m} \) is obtained by the interpolation of the discrete values of \( \Delta L_{\text{edge}}(f, \theta_s, \theta_p) \). \( \Delta L_{\text{edge}}(f, \theta_s, \theta_p) \) is measured in the ranges \( \theta_s \leq 90 \) [deg] and \( \theta_p \leq 90 \) [deg], and \( \Delta L_{\text{edge}}(f, \theta_s, \theta_p) \) for angles outside of the measurement range is estimated by extrapolation [127].

**Reference R4** EXPRESSIONS FOR \( L_{\text{Aeq}} \) UNDER SIMPLE ROAD CONDITIONS

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 by an analytical solution [129]. In this reference, a simple method of estimating \( L_{\text{Aeq}} \) with a calculator is provided.

**R4.1. Relational Expressions for \( L_{\text{Aeq},T}, L_{\text{AE}} \) and \( L_{\text{WA}} \)**

As mentioned in Subsection 1.3.1 of the main body, \( L_{\text{Aeq}} \) can be calculated using the following formula involving the single-event sound exposure level \( L_{\text{AE}} \) [dB] and the traffic volume \( N_T \) [number of vehicles] passing a prediction point during the time \( T \) [s]:

\[
L_{\text{Aeq},T} = L_{\text{AE}} + 10 \log \left( \frac{N_T}{T} \right). \tag{R4.1}\]

When an omni-directional point source with the A-weighted sound power level \( L_{\text{WA}} \) [dB] moves along a straight road of infinite length at the constant speed \( V \) [km/h], \( L_{\text{AE}} \) at the distance \( l \) [m] from the lane can be analytically derived from the following formula obtained by applying the inverse-square law in a hemi-free field and integrating over time up to infinity:

\[
L_{\text{AE}} = L_{\text{WA}} + 10 \log \left( \frac{3.6}{2V} \right). \tag{R4.2}\]

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

\[
L_{\text{Aeq},T} = L_{\text{WA}} - 10 \log l - 10 \log V + 10 \log N_T + 10 \log \frac{3.6}{2T}. \tag{R4.3}\]

Upon substituting the formula for the sound power level of running vehicles proposed in Chapter 2 of the main body (with a dense asphalt pavement) into Eq. (R4.3), \( L_{\text{Aeq},T} \) is expressed as follows.

**R4.2. Case of Single Type of Vehicles**

(1) For steady traffic flow \( (L_{\text{WA}} = a + 30 \log V) \)

\[
L_{\text{Aeq},T} = a - 10 \log l + 20 \log V + 10 \log N_T + 10 \log \frac{3.6}{2T}. \tag{R4.4}\]

(2) For non-steady traffic flow \( (L_{\text{WA}} = a + 10 \log V) \)

\[
L_{\text{Aeq},T} = a - 10 \log l + 10 \log N_T + 10 \log \frac{3.6}{2T}. \tag{R4.5}\]
### R4.3. Case of Component Ratio \( q \) of Heavy Vehicles

When the mean speed \( V \) is the same for heavy and light vehicles in the two-category classification, the mean power level \( L_{WA} \) can be expressed in terms of a component ratio of heavy vehicles \( q \) (\( \leq 1.0 \)), and \( L_{Aeq,T} \) can be obtained more easily.

1. **For steady traffic flow**
   \[
   L_{WA} = 46.7 + 30 \log V + 10 \log(1 + 3.47q) \\
   L_{Aeq,T} = 46.7 + 10 \log(1 + 3.47q) - 10 \log l \\
   + 20 \log V + 10 \log N_T + 10 \log \frac{3.6}{2T} \tag{R4.6}
   \]

2. **For non-steady traffic flow**
   \[
   L_{WA} = 82.3 + 10 \log V + 10 \log(1 + 3.47q) \\
   L_{Aeq,T} = 82.3 + 10 \log(1 + 3.47q) - 10 \log l \\
   + 10 \log N_T + 10 \log \frac{3.6}{2T} \tag{R4.7}
   \]

**Note:** Similarly, \( L_{Aeq,T} \) for drainage asphalt pavement and the structure-borne noise of a viaduct can be calculated by using Eq. (R4.3).

### Table R5.1 Number of data by type of road structure considered in the examination.

<table>
<thead>
<tr>
<th>Road structure</th>
<th>Expressway</th>
<th>General road</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of measurement points</td>
<td>Number of data</td>
<td>Number of measurement points</td>
</tr>
<tr>
<td>Flat</td>
<td>5</td>
<td>100</td>
<td>540</td>
</tr>
<tr>
<td>Bank</td>
<td>18</td>
<td>389</td>
<td>28</td>
</tr>
<tr>
<td>Cut</td>
<td>19</td>
<td>454</td>
<td>8</td>
</tr>
<tr>
<td>Viaduct</td>
<td>18</td>
<td>394</td>
<td>4</td>
</tr>
</tbody>
</table>

### R5.1. Correspondence between Values Predicted Using ASJ RTN-Model 2008 and Actual Measurement Values at General Road Section

#### R5.1.1. Actual measurement data used in this examination

The actual measurement data were obtained at straight sections of general roads and expressways in fiscal years 2001 and 2002. The measurement conditions of these data are as follows.

1. **Noise levels considered**
   \( L_{Aeq} \) and \( L_{AN} \)\( (L_{A5}, L_{A10}, L_{A50}, L_{A90}, L_{A95}) \)

2. **Measurement method**
   In accordance with JIS Z 8731:1999 (almost identical to ISO 1996-1:2003)

3. **Measurement point**
   1.2 m above the ground on a public/private boundary

4. **Measurement duration**
   Generally 10 minutes (although the measurement duration was extended until approximately 200 vehicles had passed by), and multiple measurements were performed over 24 hours at each location

5. **Traffic volume**
   Generally, four-category vehicle classification or two-category vehicle classification (by attended measurement or using an unattended traffic counter)

6. **Running speed**
   Obtained for both directions (by attended measurement or using an unattended traffic counter)

The actual measurement values used in the examination are shown in detail in Table R5.1. The data were obtained at points away from juxtaposed roads or road intersections, and the variations in the patterns of traffic volume and the actually measured values of \( L_{Aeq} \) mostly coincided with each other. The predicted values were obtained using the calculation procedures described in Subsection 1.3.2 under the actual measurement conditions. To simplify the calculations, multiple lanes of traffic traveling in the same...
direction were combined into a hypothetical single lane at the center of the traffic stream.

**R5.1.2. Comparison of values predicted using ASJ RTN-Model 2008 and actual measurement values**

The correspondence between predicted values and actual measurement values is shown in scatter diagrams and statistics indicating their difference (actual measurement values minus predicted values), which were classified for each type of road structure and whether the correction for drainage asphalt pavement was carried out. In the scatter diagrams, the \(X\)-axis indicates the values predicted using ASJ RTN-Model 2008, the \(Y\)-axis indicates the actual measurement values and \(N\) indicates the number of data. \(a\) is the mean difference between the two sets of data, \(S\) is the standard deviation of the difference and \(R\) is the correlation coefficient. The statistics indicating these differences are shown in Table R5.2. To make the comparison without the influence of background noise, which is considered a cause of uncertainty in the actual measurement, we also compared values of \(L_{A95}\) that were corrected using the actually measured \(L_{A95}\) (the lower limit of the 90% percentile range), which is assumed to be equivalent to the background noise level, with the actual measurement values in Table R5.3 as a reference.

**Table R5.2** Statistics indicating differences between values predicted using ASJ RTN-Model 2008 and actual measurement values (without correction of background noise).

<table>
<thead>
<tr>
<th>Road condition</th>
<th>(a)</th>
<th>(S)</th>
<th>(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat road</td>
<td>1.4</td>
<td>2.5</td>
<td>0.85</td>
</tr>
<tr>
<td>Bank road</td>
<td>1.7</td>
<td>2.8</td>
<td>0.85</td>
</tr>
<tr>
<td>Cut road</td>
<td>0.2</td>
<td>2.9</td>
<td>0.92</td>
</tr>
<tr>
<td>Viaduct (5-type classification)</td>
<td>0.7</td>
<td>2.8</td>
<td>0.90</td>
</tr>
<tr>
<td>Viaduct (3-type classification)</td>
<td>0.9</td>
<td>2.8</td>
<td>0.89</td>
</tr>
<tr>
<td>Drainage asphalt pavement (with correction)</td>
<td>1.3</td>
<td>2.6</td>
<td>0.88</td>
</tr>
<tr>
<td>Drainage asphalt pavement (without correction)</td>
<td>--2.1</td>
<td>2.8</td>
<td>0.84</td>
</tr>
</tbody>
</table>

**Table R5.3** Statistics indicating differences between values predicted using ASJ RTN-Model 2008 and actual measurement values (with correction of background noise).

<table>
<thead>
<tr>
<th>Road condition</th>
<th>(a)</th>
<th>(S)</th>
<th>(R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat road</td>
<td>1.2</td>
<td>2.6</td>
<td>0.84</td>
</tr>
<tr>
<td>Bank road</td>
<td>1.1</td>
<td>3.0</td>
<td>0.83</td>
</tr>
<tr>
<td>Cut road</td>
<td>--0.6</td>
<td>2.9</td>
<td>0.92</td>
</tr>
<tr>
<td>Viaduct (5-type classification)</td>
<td>--0.2</td>
<td>2.9</td>
<td>0.89</td>
</tr>
<tr>
<td>Viaduct (3-type classification)</td>
<td>0.1</td>
<td>3.0</td>
<td>0.88</td>
</tr>
<tr>
<td>Drainage asphalt pavement (with correction)</td>
<td>1.2</td>
<td>2.6</td>
<td>0.87</td>
</tr>
<tr>
<td>Drainage asphalt pavement (without correction)</td>
<td>--2.2</td>
<td>2.8</td>
<td>0.84</td>
</tr>
</tbody>
</table>

**R5.2. Comparison between Values Predicted Using ASJ RTN-Model 2008 and Actual Measurement Values at Special Road Sections**

**R5.2.1. Actual measurement data used in this examination**

The actual measurement data used in this examination were obtained near signalized intersections of general roads (10 points), semi-underground expressways (3 points) and flat roads with overhead viaducts (2 points). Measurement points at the signalized intersections were set 1.2 m above the ground surface on a public/private boundary approximately 50 m before or after the intersections. Measurements at the semi-underground expressways and flat roads with overhead viaducts were made at points 1.2 to 7 m above the ground surface at a horizontal distance of less than 20 m from a public/private boundary at each measurement site.

The actual measurement data used in this examination were obtained by three different methods, namely, the method in which the sound power levels are calculated using a non-steady traffic flow section at the intersection described in Sect. 4.3, and the practicable and simplified methods described in Appendix A3. The predicted values for semi-underground roads were obtained by the two-dimensional FDTD method described in Appendix A4.
R5.2.2. Comparison between values predicted using ASJ RTN-Model 2008 and actual measurement values

The correspondence between predicted values and actual measurement values is shown in scatter diagrams and statistics indicating their differences (actual measurement values minus predicted values).

(1) Signalized intersections

Figure R5.2 shows the predicted values and the actual measurement values at signalized intersections. While the predicted values obtained by the method using the non-steady traffic flow section are, on average, 0.9 dB larger than the actual measurement values, the standard deviation was 1.9 dB, and thus, good agreement with the actual measurement values was obtained. The values predicted by the practicable method and the simplified method differ from the actual measurement values by, on average, 0.1 and 0.4 dB, respectively, indicating excellent agreement with the actual measurement values.

(2) Semi-underground roads

Figure R5.3 shows the predicted values and the actual measurement values at semi-underground roads. The average difference between the two sets of results is 0.4 dB, and the standard deviation is 2.7 dB. This indicates that the two sets of values were in good agreement.

(3) Flat roads with overhead viaduct

Figure R5.4 shows the predicted values and the actual measurement values at flat roads with overhead viaducts and a noise barrier installed. Although the predicted values are, on average, 1.5 dB smaller than the actual measurement values, the standard deviation is 1.9 dB, which is relatively small; thus, the two sets of values are in good agreement.

R5.3. Causes of Errors in ASJ RTN-Model 2013

R5.3.1. Setting of hypothetical traffic lanes

In ASJ RTN-Model 2013, the combination of two or more lanes into a hypothetical single lane for convenience of calculation is allowed. According to the results described in Ref. 133, the error is 1 dB or less, and no significant error is observed, even in the case of a road with eight lanes, if the distance from the center of the nearest lane to the receiver is 5 m or more. However, the error increases drastically 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 desirable to increase the number of hypothetical lanes.

R5.3.2. Road traffic conditions

(1) Variations of vehicle running speed and sound power level

In ASJ RTN-Model 2013, 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 [134], 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 2013, two types of vehicle classification are applied: the four-category classification (passenger cars, 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 four-category classification are 1 dB or less if the ratio of medium-sized vehicles to large-sized vehicles ranges from 10 to 80% [133].

R5.3.3. Range of unit pattern calculation

In the basic scheme of ASJ RTN-Model 2013, 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 [133], 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

Fig. R5.2 Comparisons between values predicted using ASJ-RTN-Model 2008 and actual measurement values at signalized intersections.

Fig. 5.3 Comparison between values predicted using ASJ-RTN-Model 2008 and actual measurement values at semi-underground roads.

Fig. R5.4 Comparison between values predicted using ASJ-RTN-Model 2008 and actual measurement values at flat roads with overhead viaducts.
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.

**R5.3.4. 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. **Influences of meteorological factors**

   When sounds propagate outdoors, the influences 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 influences, the wind and temperature profiles are extremely complicated phenomena, and it is still difficult to take these influences into account in practical noise prediction. Thus, only the variation of road traffic noise as influenced by wind, which is based on actual measurement results, is introduced in ASJ RTN-Model 2013, as described in Sect. 3.6. Sound propagation may also be influenced by the temperature gradient. However, its influence 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 Sect. 3.4.

2. **Influence of background noise**

   In the measurement of road traffic noise, other types of noise (background noise) always influence the measurement results to some extent. In particular, the influence 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. **Influence 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 drainage asphalt pavement, although the noise reduction effect and its change with time after the installation are taken into account in ASJ RTN-Model 2013, 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 2013, but also noise from the expansion joints of the road may often be included in actual measurement values.

**REFERENCES**


K. Takagi, Y. Park, R. Hotta and K. Yamamoto, "Calculation method for sound attenuation by multi-barriers, "


