Study of Calculation of road surface luminance for new pavement in Japan

Contents

1. Overview of Japanese highways

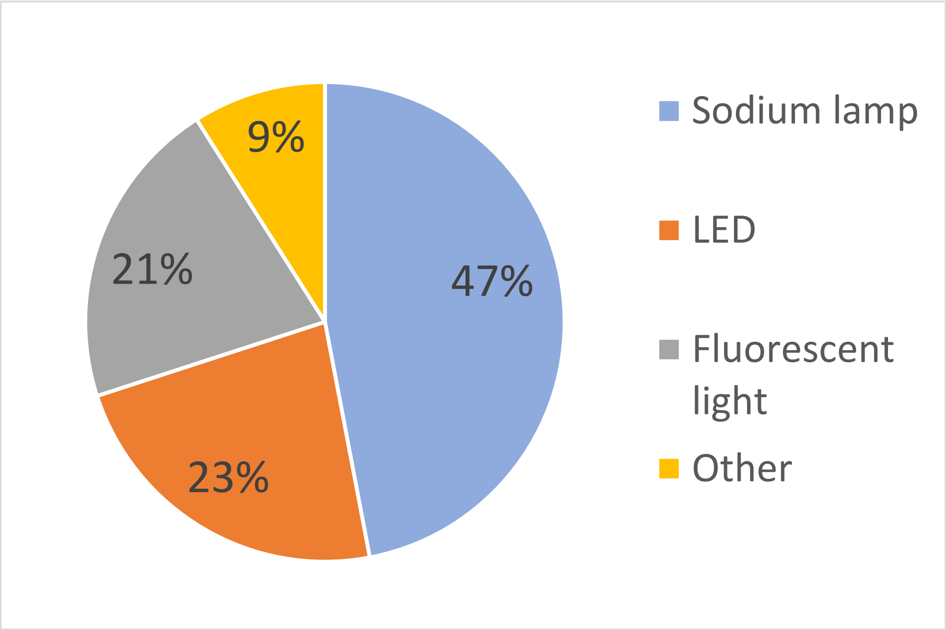
- Total length of roads managed by NEXCO
⇒ 9,608 km

- Number of tunnels ⇒ 1,941 tubes

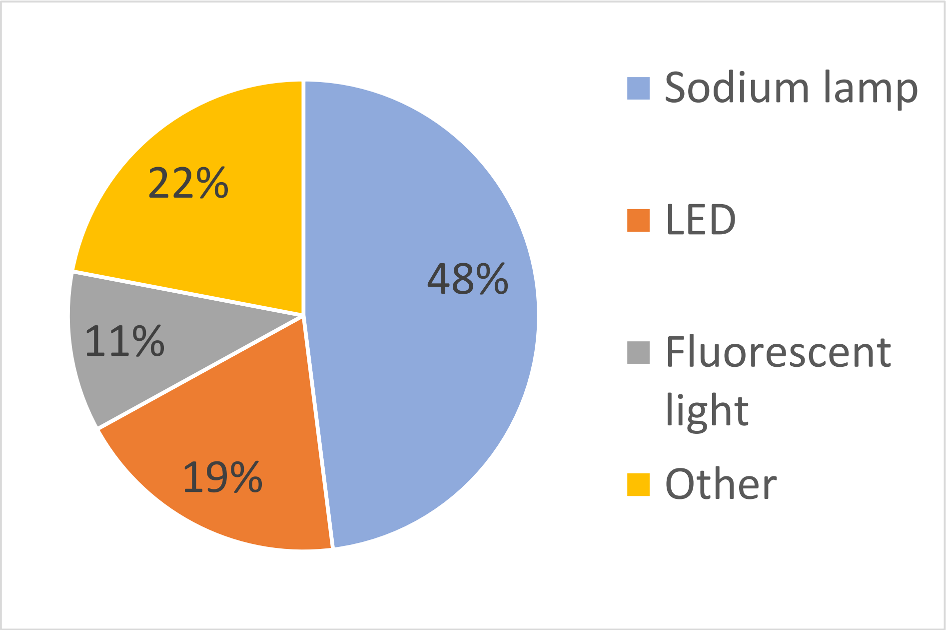
- Total tunnel length ⇒ 1,852km

• Ratio of LED luminaires

⇒ Tunnel lighting : 23% Road lighting : 19%

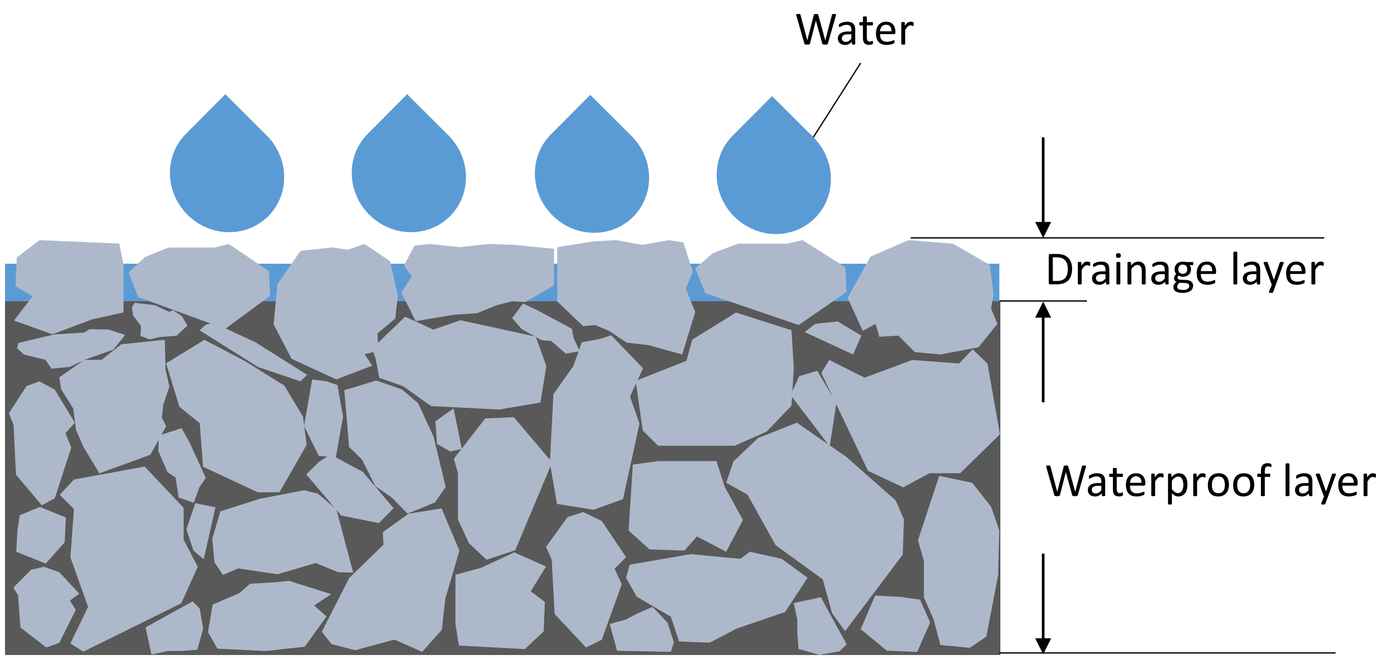


Tunnel lighting



Road lighting

Ratio of drainage pavement to total expressway length
⇒ About 80%



New drainage pavement

Left : Dense-Graded Asphalt

Right: Drainage Asphalt

2. Problems of tunnels with LED luminaire and drainage asphalt pavement

Uniformity of road surface luminance

- With conventional light sources (High frequency electric ballast fluorescent lamps, etc.), there was no problem with the road surface luminance distribution even when tunnel lighting installation was designed using CIE's r-table "C2".

Example of tunnel lighting using high frequency electric ballast fluorescent lamp

Uniformity of road surface luminance for tunnels with LED luminaire and drainage pavement

- In the field where LED luminaire are used, "low uniformity of road surface luminance " may become noticeable.

Example of tunnel lighting using LED

Problems of tunnels with LED luminaire and drainage pavement

- Since the LED luminaire has a luminous intensity distribution with strong directivity, low uniformity of road surface luminance is remarkable.
- Drainage pavement has a relatively high specularity and is considered to have different reflection characteristics from conventional dense graded asphalt pavement.
- Since the r-table for drainage pavement has not been revealed, the calculation accuracy of road surface luminance is low.

It is necessary to make efforts to improve calculation accuracy of road surface luminance in order to ensure proper uniformity of road surface luminance in tunnel.

Examination

① Evaluate the consistency between the measured value on site and the calculated value of the road surface luminance.

② Evaluate the correlation between the calculated Maximum Luminance Slope (de Boer et al, 1963) and the subjective appraisal value of comfort regarding uniformity of road surface luminance on site.

3. Tunnel lighting design method in Japan

Tunnel lighting design method in Japan

- "lumen method" and "point-by-point method" are used as calculation method for tunnel lighting design in Japan.

・Lumen method：

Average road surface luminance , Wall surface luminance

・Point-by-point method：

Luminance uniformity, Relative threshold increase

Lumen method

- This is a method of calculating the average illuminance of a surface based on the luminous flux on a surface from the luminaire.

$$E_{\mathrm{r}} = \frac{F \cdot U \cdot M \cdot N}{S \cdot W \cdot P}$$

$$K = \frac{E_{\mathrm{r}}}{L_{\mathrm{r}}}$$

$$L_{\mathrm{r}} = \frac{F \cdot U \cdot M \cdot N}{S \cdot W \cdot K \cdot P}$$

E_r ： Illuminance (lx)
L_r ： Luminance (cd/m^2)
F ：Light source luminous flux (lm)
U ：Utilization factor
M ： Maintenance rate
N ：Array Luminaire arrangement coefficient
 ・Staggered, Unilateral, Central N=1
 ・Opposite N＝2
S ：Luminaire spacing (m)
W：Road width (m)
P ：Lighting system
 ・Pro-beam lighting system P = 1.3
 ・Symmetrical lighting system P = 1.0
K ：Average illuminance conversion coefficient (lx/cd/m^2)
 ・Cement concrete pavement K = 13
 ・Asphalt concrete pavement K = 18

An example of how to calculate the utilization factor

○Full width utilization factor

$U_4 = A_{41} \cdot U_{10} + A_{42} \cdot U_{20} + A_{43} \cdot U_{30} + A_{44} \cdot U_{40}$ ･･･ Equation 1

○ utilization factor of road width

$U = U_{40}' + (W / W_0) \cdot (U_4 - U_{40})$ ･･･ Equation 2

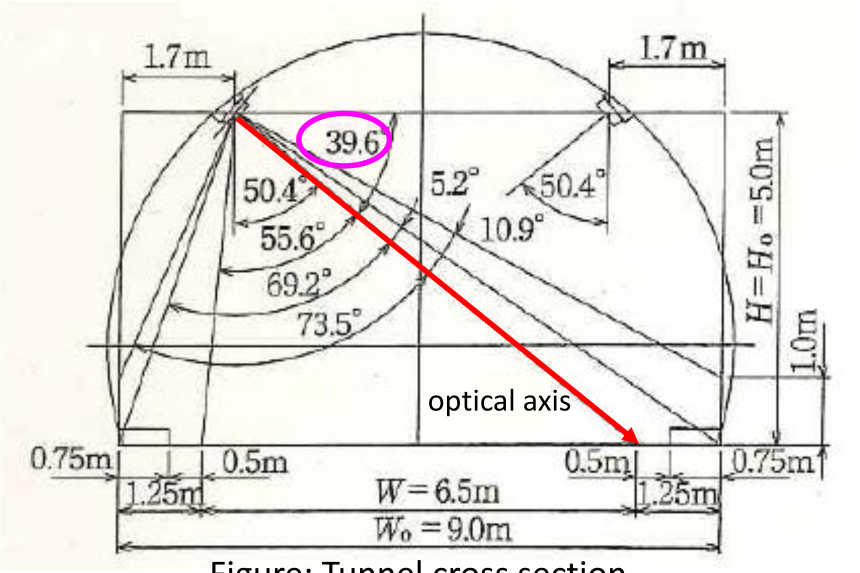


Figure: Tunnel cross section

(1) Basic lighting

Calculation of direct lighting rate of each part

U_{10}: Direct lighting rate for the ceiling surface

$= (90.0°) - (39.6°) = 0.274 - 0.232 = 0.042$

U_{20}: Direct illumination rate on the wall surface near the lamp

$= (-90.0°) - (69.2°) = 0.326 - 0.322 = 0.004$

U_{30}: Direct illumination rate for walls far from the lamp

$= (39.6°) - (5.2°) = 0.232 - 0.049 = 0.183$

U_{40}: Direct lighting rate for full width

$= (-69.2°) + (55.6°) = 0.322 + 0.049 = 0.371$

U_{40}': Direct lighting rate for road width

$= (-69.2°) + (55.6°) = 0.322 + 0.049 = 0.371$

$W_0 / H_0 = 9/5 = 1.8$

ρ1: Reflectance on the ceiling = 25%

ρ2、ρ3: Reflectance on the wall = 25%

ρ4: Road surface reflectance = 10%

A_{41}: Coefficient (ceiling surface) = 0.161

A_{42}、A_{43}: Coefficient (wall surface) = 0.116

A_{44}: Coefficient (road surface) = 1.014

From Equation 1 $U_4 = 0.405$

$U = 0.339$

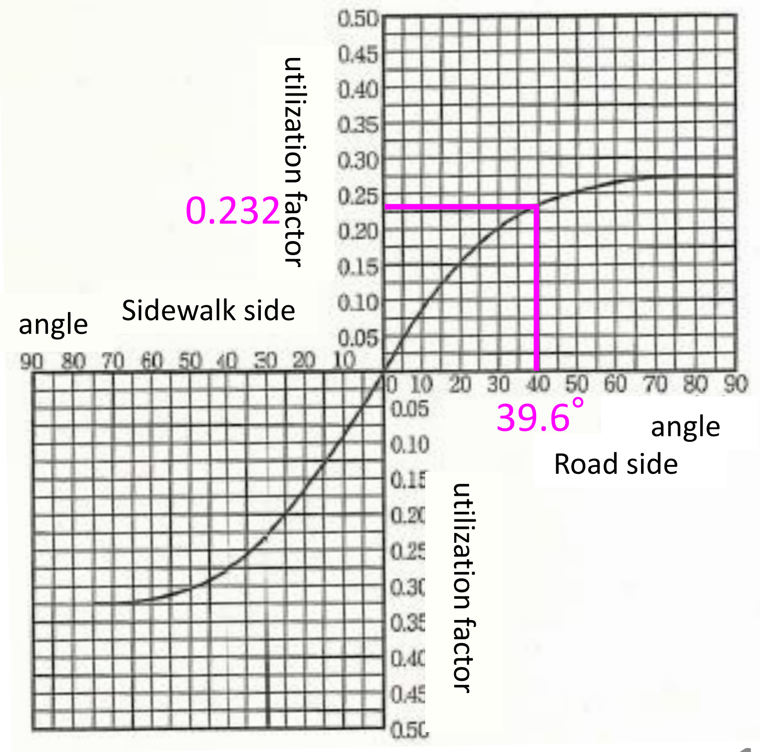


Figure: Illumination curve

Point-by-point method

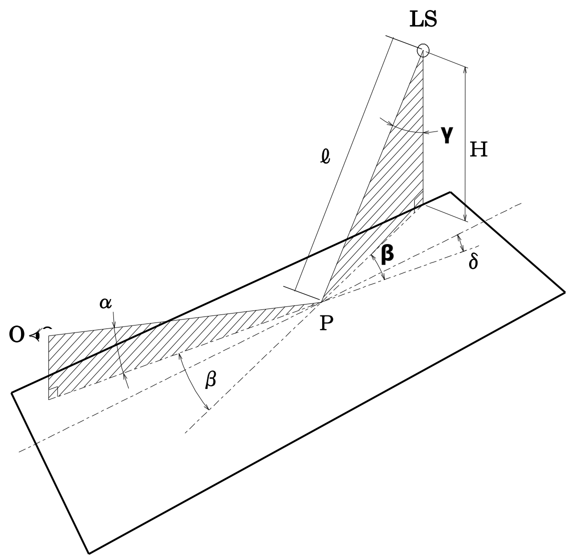
The luminance calculation is obtained by multiplying the illuminance of the road surface by the luminance coefficient q at the calculation point seen from the driver's point of view.

The luminance coefficient q is expressed by Equation 1.

$$q = \frac{L}{E}$$

・・・ Equation 1　L：Luminance (cd/㎡)、E：Illuminance(lx)

The illuminance at the calculation point P shown in the figure is expressed by Equation 2.



LS ：Luminous intensity
α ：Observation angle
γ ：Incident angle of light
O ：Observer
β ：The angle between the incident angle and the observation surface
δ ：The angle between the road axis and the observation surface

$$E = \frac{I}{\ell^2}\cos\gamma$$

・・・ Equation 2　I：Luminous intensity(cd)、ℓ：Distance from light source LS to point P(m)、γ：The angle between the normal and the perpendicular from point P to the light source(°)

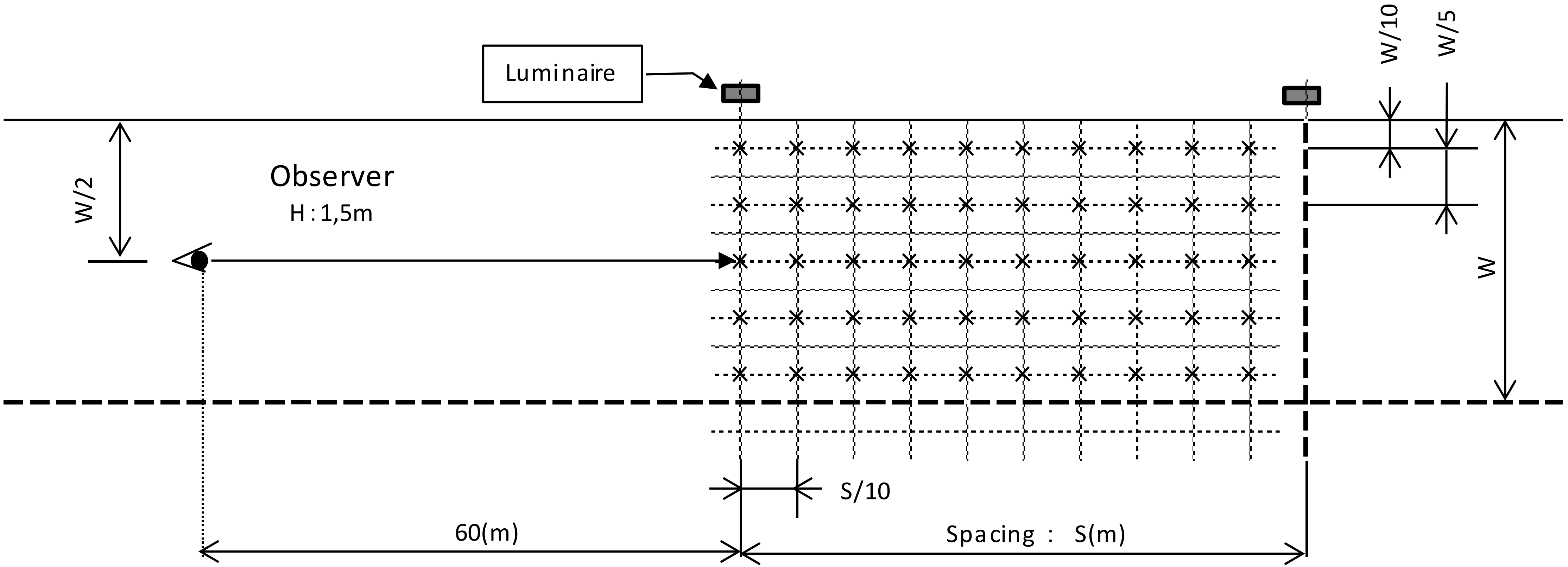
The luminance L at the calculation point P is expressed by Equation 3.

$$L = q \cdot \frac{I}{H^2 / \cos^2\gamma} \cdot \cos\gamma = \frac{I \cdot q \cdot \cos^3\gamma}{H^2} = \frac{I \cdot r}{H^2}$$

（cd/m²）・・・ Equation 3

H：The height of the lamp　(m), r：reduced luminance coefficient (q・cos3γ)

Calculation point of point-by-point luminance(CIE Pub.No.30.2)



r-table used in Japan

C1 : Cement Concrete pavement

C2 : Dense grain asphalt pavement(dry)

4. Luminance measurement on site

Tunnel lighting Installation

	Tunnel A	Tunnel B	Tunnel C
Luminaire arrangement	Staggered	Opposite	Staggered
Luminaire spacing	12,2m	4,4m	11,5m
Height of lighting installation	4,8m	4,9m	4,8m
Elapsed years	Immediately after laying		Two years
Light source	LED		

Tunnel lighting Installation

staggered, *S*=12,2m

opposite, *S*=4,4m

opposite, *S*=8,8m

opposite, *S*=13,2m

staggered, *S*=11,5m

staggered, *S*=4,4m

staggered, *S*=13,2m

Measuring method

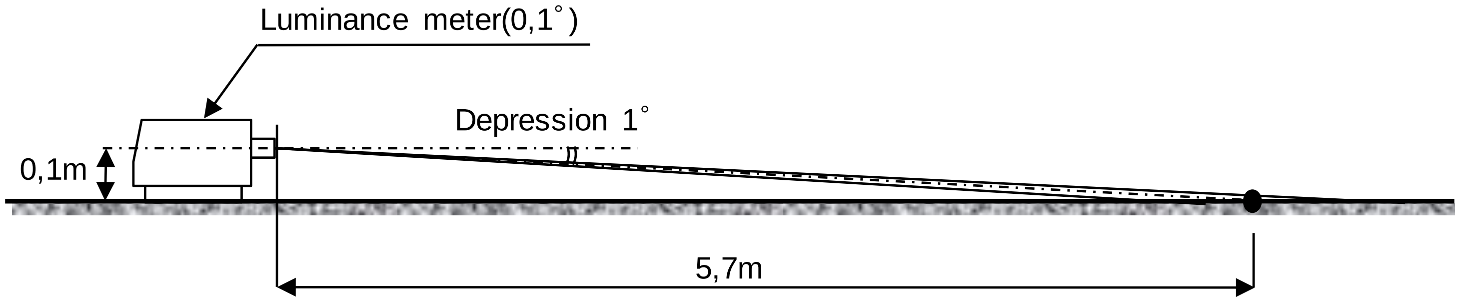
Measure the road surface luminance using a luminance meter (viewing angle dimension 0.1°)

【Measurement points】

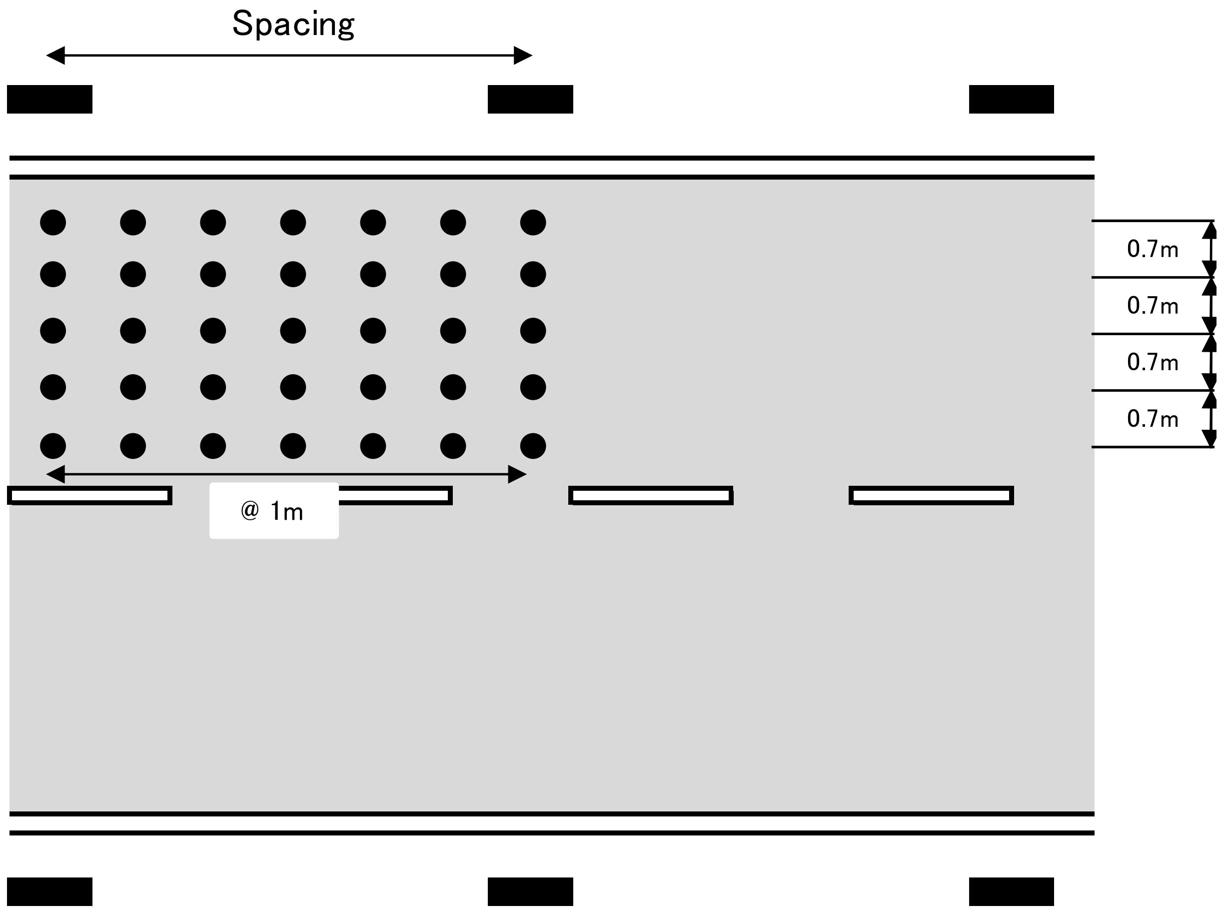
Road longitudinal direction : 1 span at 1 m intervals (Opposite luminaire arrangement)

2 spans at 1 m intervals (Staggered luminaire arrangement)

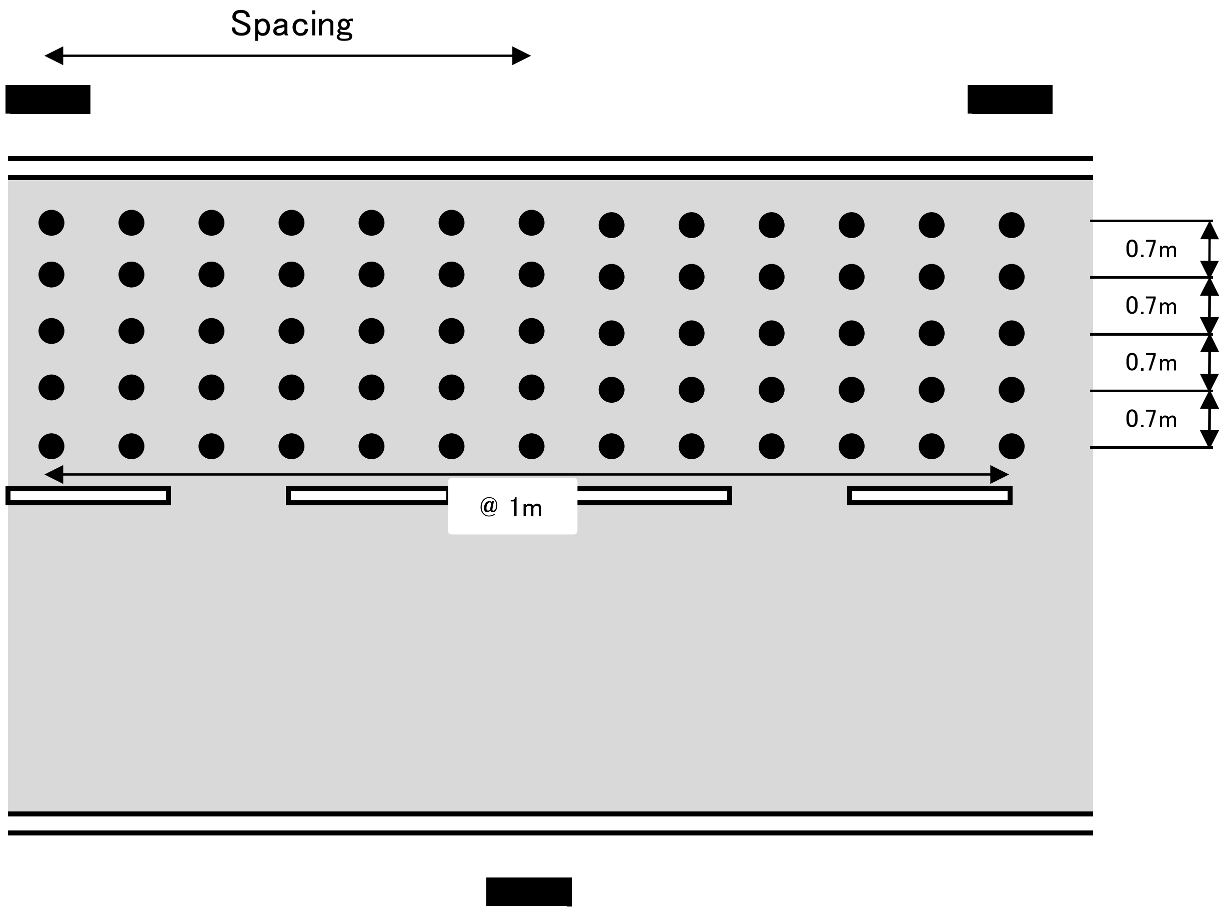
Road crossing direction : 5 points／ Lane



Measuring points



(a) Opposite luminaire arrangement



(b) Staggered luminaire arrangement

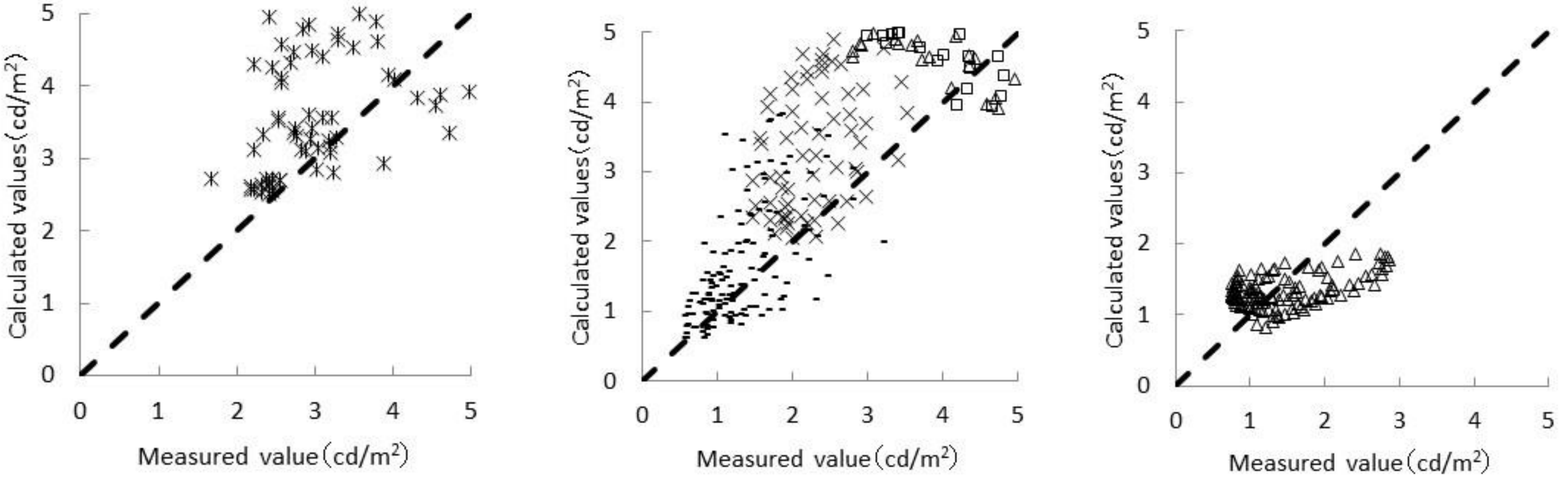
●: Measured points, ■: Luminaire

5.　Results

① Evaluation of consistency between measured and calculated values

Comparison of measured and calculated values

【 Conditions of the tunnel to be measured】



（a） tunnel A　　（b） tunnel B　　（c） tunnel C

Figure: Relationship between measured value and calculated value (reflection characteristic: C2)

- In all tunnels, the difference between the measured value and the calculated value was remarkable.
- It is considered that the difference between the measured value and the calculated value was caused by the fact that the site was drainage pavement and did not have standard reflection characteristics (C2: asphalt road surface).

Comparison of measured and calculated values for each reflection characteristic

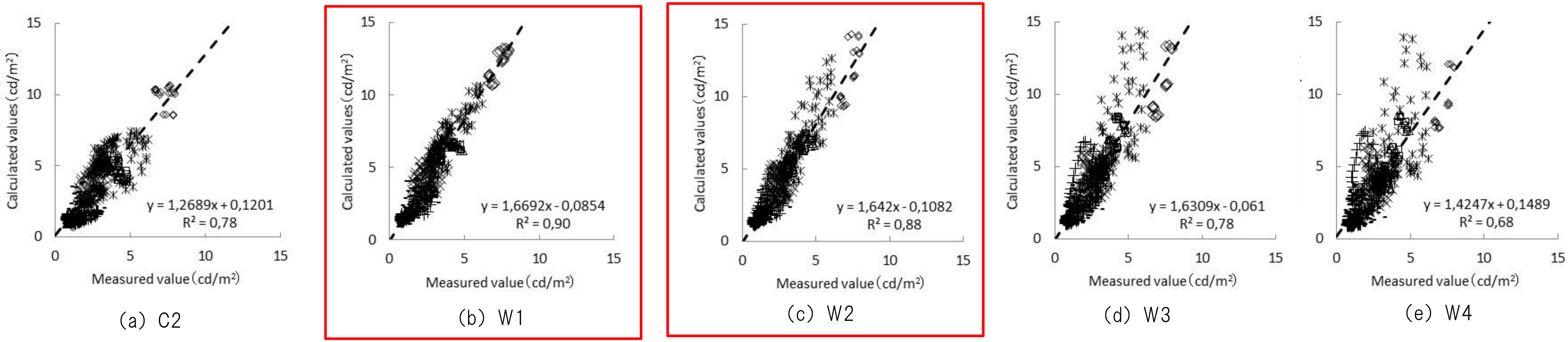


Figure: Relationship of road surface luminance by reflection characteristics
(Data for tunnel A, tunnel B and tunnel C)

The coefficient of determination R2 of the reflection characteristics W1 and W2 is W1 (0.90) and W2 (0.88), and it was found that they have a very strong correlation.

5. Results

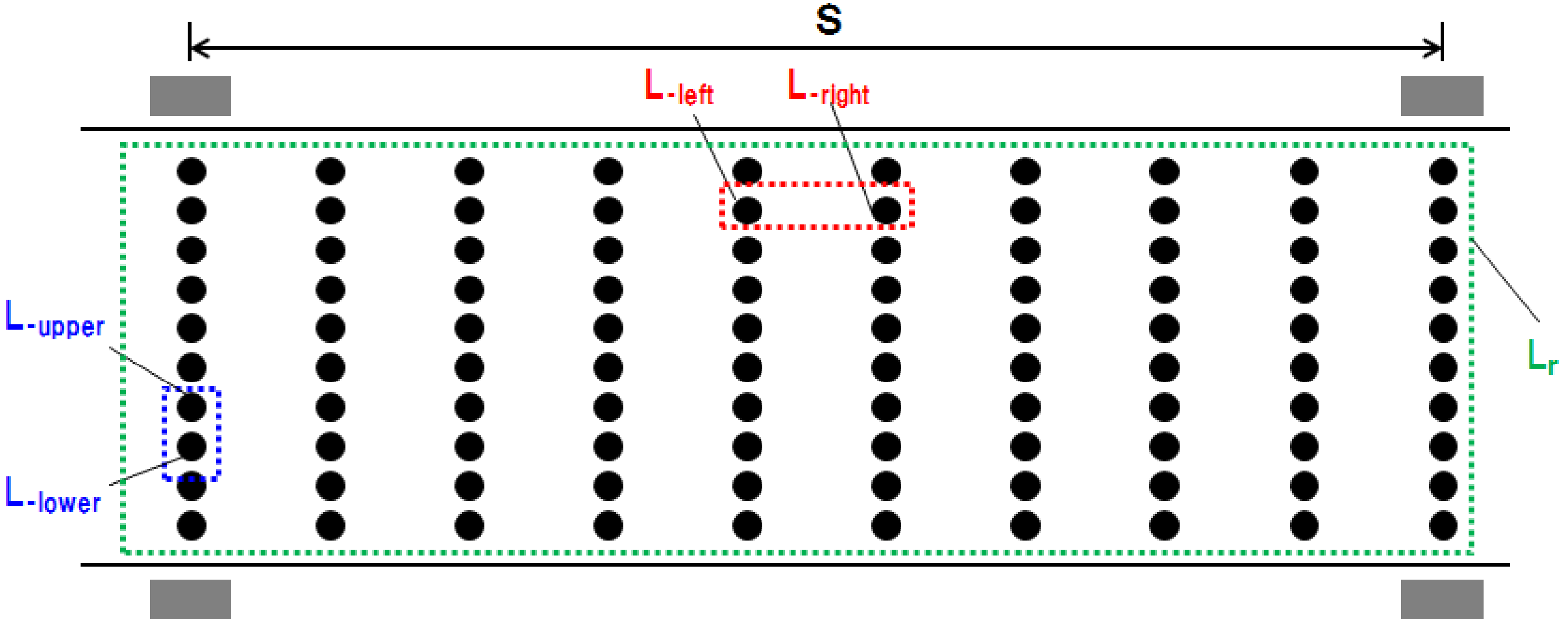
②Correlation evaluation of luminance gradient and subjective evaluation value

Comparison of luminance gradient and subjective evaluation value

The relationship between the Maximum Luminance Slope（LS_{max}） calculated by W1 and W2 and the subjective evaluation value was confirmed.

Maximum Luminance Slope LS_{max}（De Boer、1963）

$$|L_{\text{-upper}} - L_{\text{-lower}}| / L_r \ , \ |L_{\text{-left}} - L_{\text{-right}}| / L_r$$



Concept of LS_{max}

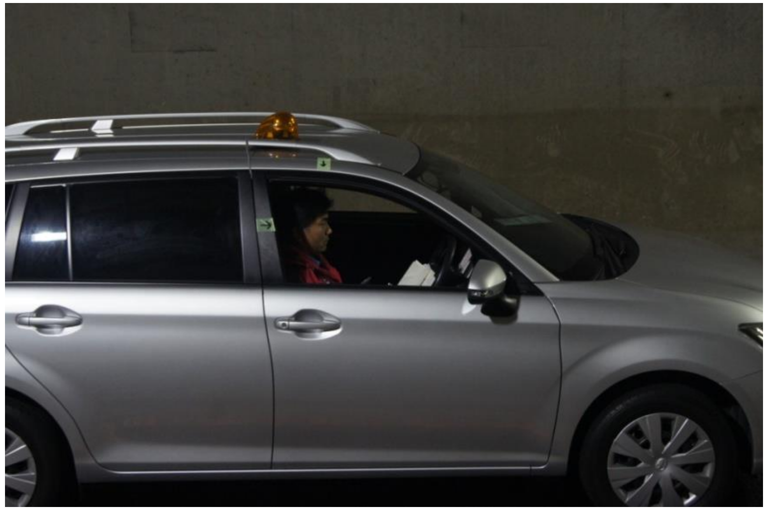
Comparison of luminance gradient and subjective evaluation value

【Observation and evaluation experiment of discomfort due to uneven luminance of road surface】

Subject : 9 lighting engineers with driver's licenses aged between 30s and 50s

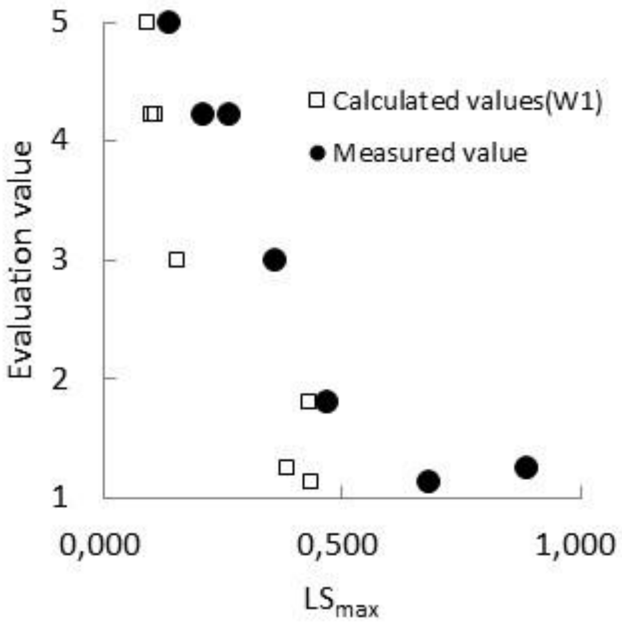
Evaluation scale : 5-grade evaluation scale

1	2	3	4	5
Noticeable	Slightly noticeable	Just permissible	Slightly good	Good

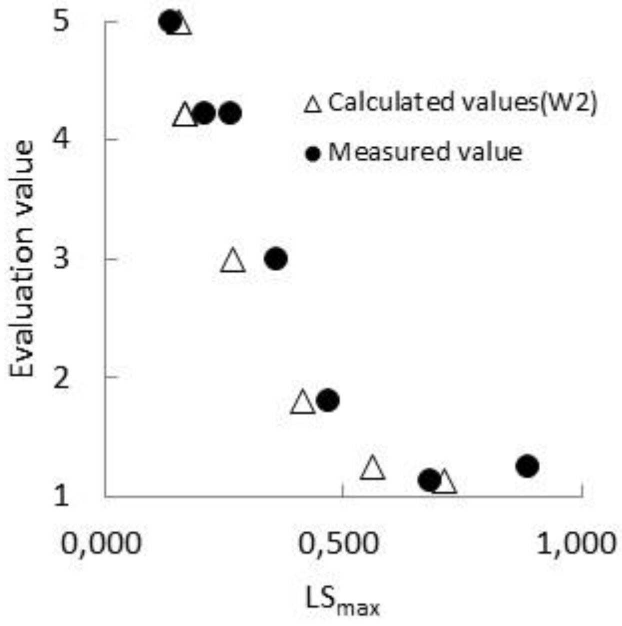


Comparison of luminance gradient and subjective evaluation value

【 Relationship between the luminance gradient (LSmax) of W1 and W2 and the evaluation value】



(A) Relationship between LSmax and evaluation value
(Road crossing direction, reflection characteristic W1)



(B) Relationship between LSmax and evaluation value
(Road crossing direction, reflection characteristic W2)

Figure: Relationship between LSmax and evaluation value of reflection characteristics W1 and W2

- For drainage pavement, it was decided to calculate the luminance distribution using "reflection characteristic W2".

6. Suggestion of new indicators for assessing discomfort due to uniformity

Suggestion of new index of road surface luminance uniformity

In tunnels with LED luminaire and drainage pavement, dark areas occur near the roadside zone, so an index that can be evaluated comprehensively is desirable.

Example of tunnel lighting for lighting fixtures using LED

Suggestion of new index of road surface luminance uniformity

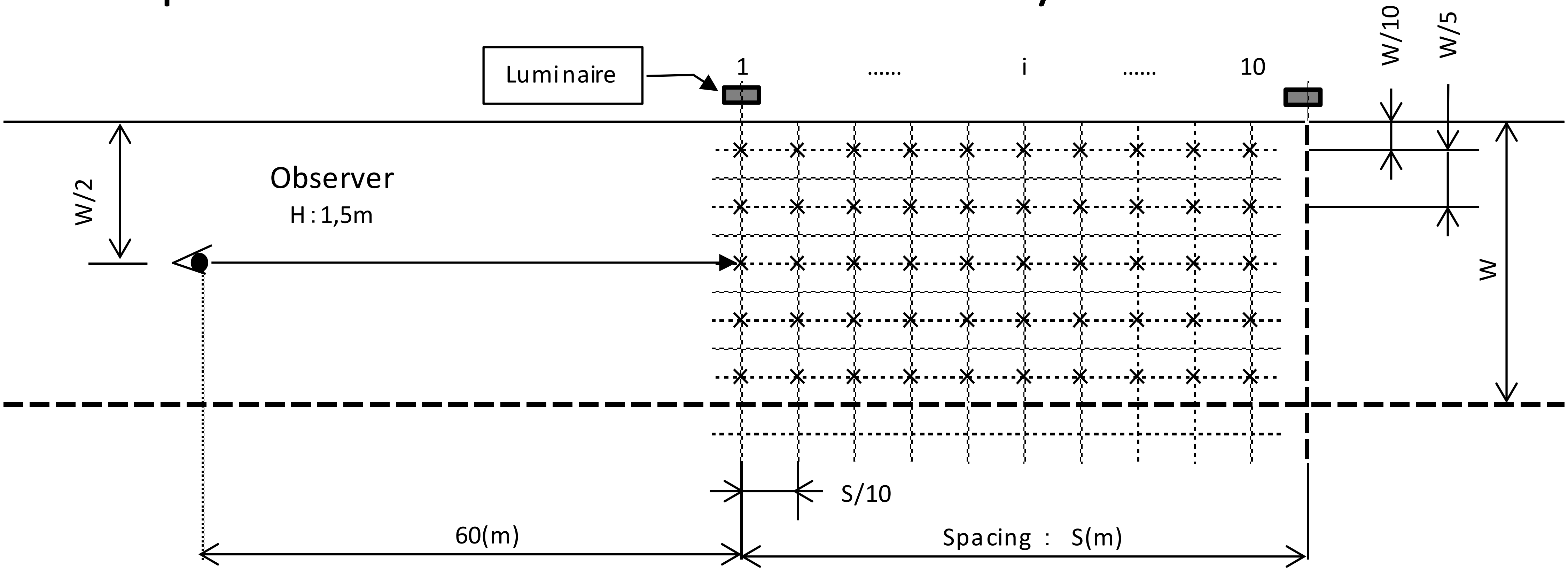
The minimum value within one span of “minimum road surface luminance / maximum road surface luminance” in the road crossing direction (U_w: Transverse uniformity) was investigated.

$$U_w = L_{min(w)} / L_{max(w)}$$

$L_{min(w)}$: Minimum luminance in column (cd/m^2)

$L_{max(w)}$: Maximum luminance in column (cd/m^2)

Concept of transverse uniformity



$$U_w = L_{min(w)} / L_{max(w)}$$

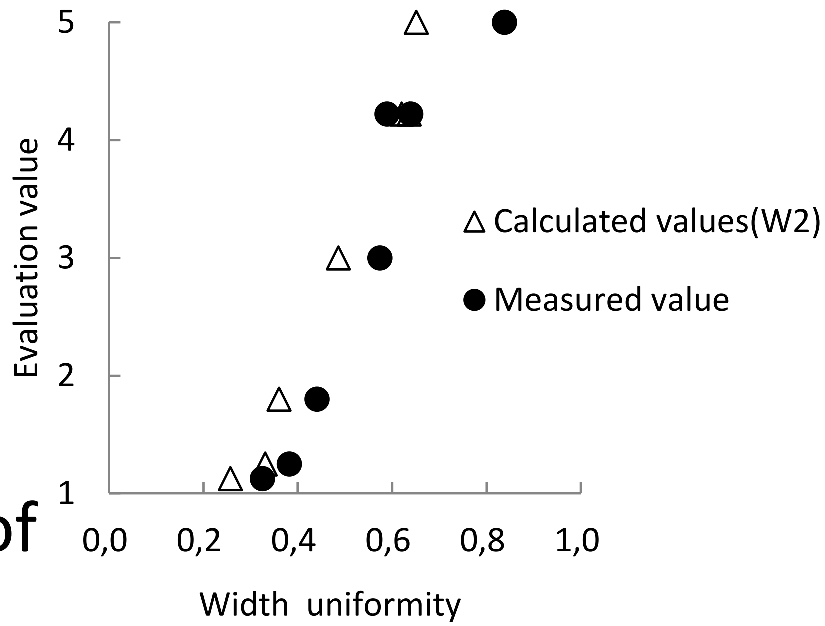
U_{wi} : transverse uniformity in column i
$L_{min(wi)}$: minimum luminance in column i (cd/m²)
$L_{max(wi)}$: maximum luminance in column i (cd/m²)
Uw : minimum value of transvers uniformity in column 1 to 10

Suggestion of new index of road surface luminance uniformity

【Relationship between Uw and evaluation value in measured value and calculated value (W2)】

The measured value and the calculated value in the measurement range showed the same tendency.

NEXCO have decided to specify "Transverse uniformity (Uw)" as an index for evaluating the uneven brightness of the road surface.



Relationship between lateral uniformity and evaluation value (Reflection characteristics: W2)

$$U_{w} = L_{min(w)} / L_{max(w)}$$

$U_{(w)}$: Transverse uniformity

$L_{min(w)}$: Minimum luminance in column (cd/m^2)

$L_{max(w)}$: Maximum luminance in column (cd/m^2)

Convenient method for calculating road surface luminance distribution in tunnel lighting

- NEXCO use the existing r-table "W2" for convenience when calculating lighting design for drainage pavement.
- By defining “Transverse uniformity (Uw)" as an index for evaluating the luminance unevenness of the road surface, "road surface luminance unevenness" is suppressed.

The situation where there is still a difference in the road surface luminance distribution

It is necessary to formulate an r-table for drainage pavement peculiar to Japan

7. The next deployment

The next deployment

In order to develop an r-table for drainage pavement in Japan, the following research will be carried out…

- Collection and measurement of drainage pavement in Japan
  - Japanese drainage pavement (more than 2 years old)

- Validation of the calculated r-table
  - Compare the road surface brightness distribution simulated using r-table with the results measured in the field.

- Standardization of an r-table
  - We will standardize an r-table for drainage pavement in Japan.
  - To report an r-table for drainage pavement in Japan to CIE for international standardization.

Thank you for your attention.