Evaluation Index of Visibility in Tunnel Lighting

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ABSTRACT
The revealing power was proposed as an index to evaluate visibility in road lighting. However, applicability in tunnel lighting has not been studied. We evaluate the tunnel lighting visibility on the basis of the revealing power in this paper. Our simulation and field experiment, made clear the relationship between the brightness and overall uniformity of the road surface and revealing power. This result confirms tunnel lighting can reduce the road surface luminance while maintaining visibility and can also save energy.

KEYWORDS: tunnel lighting, revealing power, visibility, overall uniformity

1. Introduction
The purpose of road lighting and tunnel lighting (road/tunnel lighting, hereinafter) is to provide a visual environment that enables drivers to travel safely and with a sense of security. Traditionally, the degree of overall uniformity of road surface luminance (overall uniformity, hereinafter) and the average road surface luminance have been the most important performance indicators relating to the visibility of road lighting. Accordingly, the average road surface luminance, degree of overall uniformity, disability glare and the like have been established as criteria for road and tunnel lighting1).

On the other hand, revealing power (RP, hereinafter) is used as a criterion for evaluating visibility, and it expresses the number of objects visible with a road lighting installation as a percentage of objects that may exist on the road surface2). For road lighting, the distribution of RP on the road surface has been studied13). For tunnel lighting, however, no studies have yet been conducted on evaluating visibility in consideration of the road surface RP distribution.

Thus, the authors have examined the application of RP, in consideration of its distribution, to tunnel lighting. First, ①, we compared the RP distributions of road lighting and tunnel lighting, and examined the application of the RP of tunnel lighting having a high degree of overall uniformity as a criterion for evaluating visibility. Next, ②, for the purpose of applying this evaluation index to lighting design, we examined the relation between RP and average road surface luminance and degree of overall uniformity. Additionally, ③, in an actual tunnel, we conducted subjective visibility evaluation tests of visual targets having 20 to 40% reflectance, and examined the consistency between the visibility level (VL, hereinafter), calculated from onsite optical measurements, and visibility. Then, ④, from the reflection factor threshold obtained from the VL value, we calculated the RP and examined visibility evaluations that use RP as a parameter.

In this paper, from ①, ②, ③ and ④, we use the aforementioned RP as a parameter to obtain the relation between the overall degree of overall uniformity and average road surface luminance for tunnel lighting, and based upon that relationship, examine the possibility of increasing the degree of overall uniformity to reduce the average road surface luminance while maintaining a constant degree of visibility.

2. Characteristics of road and tunnel lighting, and an index for evaluating visibility
A tunnel is a closed space having environmental conditions that differ from those of a road, and therefore the criteria used to evaluate visibility, such as the average road surface luminance, are also different. For example, road surface luminance, which is a criterion for road lighting, is 0.5 to 1 cd/m², regardless of the design speed, while in the case of tunnel lighting, the road surface luminance ranges from 1.5 to 9.0 cd/m² according to the design speed (60 to 100 km/h)3).

In addition, although the roadway width in a tunnel is the essentially the same as that of a road (7 m in the case of one-way two-lane traffic), the luminaire height, which is about 10 m or higher for road lighting, is restricted to approximately 5 m for tunnel lighting. Accordingly, the ratio (W/H) of roadway width (W) to luminaire height (H) is about 0.7 for roads but is about 1.4 for tunnels. For this reason, a broader luminous in-
tensity distribution in the cross-road direction is required for tunnel lighting than for road lighting.

2.1 Differences between road lighting and tunnel lighting

For road lighting, the use of VL values to evaluate visibility have been studied. VL is an index that expresses the ease of visualizing objects having a certain luminance difference, and as shown in Eq. (1), is defined as the ratio of the luminous difference between a visual target and its background (ΔL) to the luminance difference threshold (ΔLmin) for human vision.

\[ VL = \frac{\Delta L}{\Delta L_{\text{min}}} \]

\[ \Delta L = |L_b - L_o| \]

\[ L_b: \text{background luminance (cd/m}^2) \]

\[ L_o: \text{visual target luminance (cd/m}^2) \]

In addition to VL, RP is used as an index for evaluating visibility by considering the existence probability of an object, and is a concept that was proposed in 1935 by Waldram of the British Ministry of Transport’s Street Lighting Panel. RP is represented by a percentage (%) expressing the ratio of “visible” objects to objects that “probably exist” on the road. Moreover, the sum of the RP value for “silhouette vision” where the luminance of the object is lower than that of the background road surface and the RP value for “reverse silhouette vision” where the luminance of the object is higher than that of the background road surface is known as the total revealing power (TRP, hereinafter) (see Eq. 2).

\[ TRP = P_s(\rho_{S_{\text{threshold}}}) + P_{RS}(\rho_{RS_{\text{threshold}}}) \]

\[ P_s(\rho_{S_{\text{threshold}}}) \]: Cumulative existence probability (%) in the case of silhouette vision of a visual target having a reflection factor of \( \rho_{S_{\text{threshold}}} \) or less

\[ P_{RS}(\rho_{RS_{\text{threshold}}}) \]: Cumulative existence probability (%) in the case of reverse silhouette vision of a visual target having a reflection factor of \( \rho_{RS_{\text{threshold}}} \) or less

\[ \rho_{S_{\text{threshold}}} \]: Threshold reflection factor (%) of a visual target in silhouette vision

\[ \rho_{RS_{\text{threshold}}} \]: Threshold reflection factor (%) of a visual target in reverse silhouette vision

In order to compare the characteristics of road lighting and tunnel lighting, we calculated the road surface luminance and TRP for road lighting and tunnel lighting. The results are shown in Figures 1–4.

The road lighting calculation were carried out for the conditions of two lanes, a single-sided lighting arrangement, road surface reflection factor of CIE C2, luminaire height of 10 m, luminaire spacing of 40 m and average road surface luminance of 1.0 cd/m², while tunnel lighting calculations were carried out for the conditions of two lanes, an opposite lighting arrangement, road surface reflection factor of CIE C2, luminaire height of 5 m, luminaire spacing of 12.5 m and an average road surface luminance of 4.5 cd/m². Additionally, for objects having a size of 20 cm square and a reflection factor given by the cumulative probability of existence proposed by Smith and shown in Figure 5, in consideration of previous research, the field factor was set to 3 for road lighting and to 6 for tunnel lighting (and these same values are used in the subsequent TRP value calculations). The field factor is the ratio between required luminance values, at which an object can be visibly discriminated against its background, in the case
where an object on the road is expected to exist and in the case where it is not expected to exist\(^9\). The field factor is set independently because conditions relating to the driver’s visual environment and to the visibility of objects differ for roads and tunnels\(^{10}\).

Due to the effects of the distribution of luminous intensity and the arrangement of luminaires, the road surface luminance and TRP distributions will differ for road lighting and tunnel lighting.

In looking at the distribution of road surface luminance, it can be seen that illumination with lamps on the road shoulder side at a height of at least 10 m will result in areas of insufficient luminance in the vehicle lane distant from the lamp, as shown in Figure 1. On the other hand, with tunnel lighting in which lamps are arranged on opposing sides of the roads, areas of low luminance can be observed mainly in the vicinity of the road shoulder between lamps. As shown in Figures 1 to 4, a comparison of road lighting and tunnel lighting will reveal differently shaped distributions of both road surface luminance and TRP.

### 2.2 Application and challenges of using the total area ratio (TAR)

As an index for evaluating the visibility of objects in

![Figure 5](image1.png) Relationship between reflectance and cumulative probability of the existence (Smith, 1938)

![Figure 6](image2.png) Distribution of TRP that luminaire spacing is different in case of constant road surface luminance
a complex luminance distribution on a road due to road lighting, Narisada, et al. proposed the “total area ratio” (TAR, hereinafter) as the percentage (%) area of the total road surface in which the TRP is higher than a certain value. TAR is an index that expresses the range of road surface that provides a certain visibility (TRP), and is based on the idea that driver visibility (safety) will be improved by enlarging this range as much as possible. In the TRP distribution of Figure 2, the TAR values when TRP is at least 70%, 80% and 90% are 100%, 83% and 63%, respectively.

Below, the challenges in applying TAR to evaluate visibility in tunnel lighting are described. Figure 6 shows TRP distributions for different luminaire spacings for the example of a standard tunnel in cross-section (two lanes, one-way traffic, 7 m roadway width) having a luminaire luminous intensity distribution of BZ5 (British Zonal lighting classification), an average road surface luminance of 3.2 cd/m² and a constant luminaire height of 5 m.

In Figure 6(a) to (c), the scale of the luminaire spacing is changed and the TRP distribution becomes more uniform as the luminaire spacing becomes narrower. Furthermore, Figure 7 shows the relationship between luminaire spacing and TAR, which was determined based upon Figure 6. This result shows that when TRP≥90%, TAR tends to decrease as the luminaire spacing is narrowed, but that when TRP≥80%, TAR tends to increase as the luminaire spacing is narrowed. In the case where the luminaire spacing is reduced from 12.5 to 5.0 m, TAR increases from about 75 to 95% when TRP≥80%, but that TAR decreases from about 38% to about 17% when TRP≥90%.

In the case where the luminous intensity distribution is constant, the degree of uniformity will typically improve when the luminaire spacing is narrowed, and thus visibility tends to improve, but as described above, in the relationship between the TAR and luminaire spacing, at TRP≥90%, visibility tends to decrease when the luminaire spacing narrows and as a result, TAR is difficult to apply as an evaluation index in tunnel lighting.

### Table 1: Conditions for calculation of TRP

| Units          | Road lighting | Tunnel lighting |
|----------------|---------------|-----------------|
| Number of lanes| 2             |                 |
| Road width     | 7 (3.5×2)     |                 |
| Reflection factor characteristics of road surface | Asphalt (C2) |                 |
| Luminaire arrangement | Single-sided arrangement | Opposite arrangement |
| Installation height (H) (m) | 8, 10, 12 | 5 |
| Installation spacing (S)/Installation height (H) | 3, 4 | 1.1, 1.6, 2.1, 2.7 |
| Road surface luminance (cd/m²) | 0.5, 1.0 | 2.25, 3.2, 4.5 |

3. Investigation of visibility evaluation index

3.1 Proposed visibility evaluation index (TRPave) for use with tunnel lighting

As described in Section 2.2, it is difficult to use TAR to evaluate tunnel lighting visibility. Accordingly, we investigated the treatment of TRP in tunnel lighting.

First, for the existing standard road lighting and tunnel lighting listed in Table 1, we calculated the TRP for the road surface within a single span of luminaire spacing under conditions that satisfy the lighting criteria, and determined the cumulative relative frequency of TRP. Here, for the road surface within a single span of luminaire spacing, the cumulative relative frequency is defined as the sequential accumulation of TRP values, from low to high, for a total of 30 points of intersection within a single lane that has been divided horizontally into thirds and divided longitudinally into tenths.

The cumulative relative frequency of TRP determined under the conditions of Table 1 is shown in Figure 8. An object size of 20 cm square was used, and the cumulative probability of existence proposed by Smith was used as the existence probability for that reflection factor.

From Figure 8(a) and (b), it can be seen that, for road
lighting, TRP is distributed widely, from 10 to 100 (%), with mean and variance ranges of 64 to 95 and 33 to 980, respectively, while for tunnel lighting, TRP is roughly in the range of 70 to 100 (%), with mean and variance ranges of 87 to 92 and 6 to 73, respectively. Thus, it can be seen that within a single span of luminaire spacing, the variance in TRP distribution is less for tunnel lighting than for road lighting.

Therefore, for the visibility evaluation of tunnel lighting installations, we carried out the following investigation using the average TRP value (TRPave, hereinafter) within a single span of luminaire spacing as an index for evaluating visibility.

3.2 Relationship between average value of total revealing power (TRPave) and average road surface luminance/overall uniformity

TRP is an index for evaluating visibility according to the probability that a visually recognizable object exists, but is difficult to use directly as an indicator of performance based on the design, because performance indicators based on the design must directly express such lighting characteristics as the road surface luminance, overall uniformity and so on.

Here, overall uniformity consists of overall uniformity and longitudinal uniformity. Overall uniformity is an index for evaluating the appearance of an object on the road surface.

If the relationship between TRPave and the traditionally performance evaluation indices of average road surface luminance and overall uniformity can be clarified, then average road surface luminance and overall uniformity can be used as design-based performance indices while using TRPave as an index for evaluating visibility. Therefore, we investigated the relationship between TRPave and average road surface luminance and overall uniformity.

Figure 6 is an example of a TRP distribution diagram under the conditions of a BZ5 luminaire luminous intensity distribution and different luminaire spacing, and based upon the results of these calculations, the relationship between average road surface luminance and overall uniformity was determined using equal TRPave as a parameter, and is shown in Figure 9. Figure 9 shows that when the overall uniformity is increased, the average road surface luminance necessary to obtain the same TRPave decreases. For example, when TRPave=90%, it can be said that the conditions of an average road surface luminance of 3.5 cd/m² and overall uniformity of 0.4 will yield equivalent visibility as the conditions of an average road surface luminance of 2 cd/m² and overall uniformity of 0.8 when evaluated with TRPave. Moreover, when the overall uniformity approaches 1, the average road surface luminance necessary to obtain the same TRPave tends to converge. Depending on the number of lanes, the light distribution and the like, the relationship between road surface luminance and overall uniformity may differ from that shown in Figure 9, however.

In regards to the relationship between the average road surface luminance and overall uniformity at equal TRPave, in order to evaluate the visibility of two light-
ing environments of different degrees of average road surface luminance and overall uniformity as shown in Figure 10 in an actual tunnel, we calculated the TRP while varying the lighting conditions. As a result, in the two lighting conditions of high overall uniformity and low overall uniformity shown in Table 2, the average road surface luminance and overall uniformity differed, and we set a lighting environment of equal TRPave (90.2%). The results of the TRP calculation are shown in Figure 11.

4. Visibility evaluation experiment

To confirm the validity of the investigation results of the relationship, discussed in section 3 above, between average road surface luminance and overall uniformity at equal TRPave, we conducted visibility experiments with on-road objects in a local tunnel.

4.1 Overview of the experiments

4.1.1 Test equipment

In the Shiratori Tunnel (694 m extension) of the Takamatsu Expressway, we established the lighting environments of Table 2, and conducted experiments concerning the appearance of on-road objects having different reflection factors. Figure 12 shows the conditions at the time of the experiments in the region of low overall uniformity (fluorescent lamps) and in the region of high overall uniformity (LEDs). Figure 13 and 14 show the luminaires with fluorescent lamp and LED light sources that were used in the experiments.
4.1.2 Test method

Figure 15 shows the layout of the test equipment.

1) Evaluation method: The appearance of a visual target (size: 20 cm square, reflection factor: 20%, 30%, 40%) from a stationary vehicle was evaluated in five stages, from “clearly visible” to “not visible at all.” The evaluation points were weighted as follows: 1 point for “not visible at all,” 3 points for “visible” and 5 points for “clearly visible.”

2) Installation location of visual target: The fluorescent lamp region was divided into four equal parts over a single span beginning from directly underneath a luminaire in the road axis direction (the visual target location directly underneath the luminaire of Figure 14 is denoted as “I,” and subsequent locations of “II,” “III” and “IV” are spaced apart by 2.85 m), while for the LED region, a luminaire spacing of 2.7 m was adopted and because there was almost no unevenness in brightness in the road axis direction, the visual target was located directly underneath a luminaire. In the cross-road direction, three visual targets, spaced apart by 1.17 m, were arranged in each lane.

3) Observers: 11 people (ranging in age from their twenties through fifties)

In order to eliminate errors due to preconceptions and biases, the testing was conducted without providing the observers any advance explanation of such conditions as the location of the visual targets, the presentation sequence of target reflectivity, and so on.

4.2 Test results

4.2.1 Subjective visibility evaluation results

Figure 16 shows the percentage of subjective visibility evaluation responses for each observer and Figure 17 shows the average subjective visibility evaluation value for each visual target location (in the cross-road direction).

In the region of low overall uniformity, in the case of 20% reflection factor of the visual target, at the location directly underneath a luminaire (0 m point; I in Figure 14) there were many responses of “not visible at all” and “poorly visible,” but at the 5.7 m point (III in Figure 14), there was a high percentage of “highly visible” and “visible” responses. On the other hand, in the case of
40% reflectance of the visual target, at the location of the 0 m point, there were many responses of “highly visible,” but at the 5.7 m point, there was a high percentage of “not visible at all” and “poorly visible,” responses. In the case of 30% reflectance of the visual target, no significant tendency depending upon the point could be observed. We found that, in a region of low overall uniformity, the evaluation value depended greatly on the installation location and reflectance of the visual target. In the region of high overall uniformity, in the case of 20% reflectance of the visual target, the majority of responses were “visible,” while in the cases of 30% and 40% reflectance, “poorly visible” and “not visible at all” were the responses.

Below, Table 3 lists average values of the target visibility subjective evaluation results in lighting environments having different degrees of overall uniformity. The results of a t-test conducted at a 5% significance level for each observer’s evaluation values in the regions of low overall uniformity and high overall uniformity yielded a two-sided $P$ value ($T<0.17$, and since $P>0.1$, no significant difference in average values of the two populations was found.

### 4.2.2 Calculation of reflection factor threshold

From the road luminance measured onsite and from the equivalent veiling luminance and the vertical plane luminance of the visual target, we computed the visible limit of reflectance (reflection factor threshold, hencein-
The results are listed in Table 4. In the table, values of the reflection factor threshold have been computed under the assumption that VL=1. The silhouette vision upper limit means that, according to the definition of VL, the target will be visible in silhouette vision at reflectance below this value, and the reverse silhouette vision lower limit means that the target will be visible in reverse silhouette vision at reflectance above this value.

For example, at visual target location ② in the region of high overall uniformity, given the reflection factor threshold values calculated from onsite optical measurements of a silhouette vision upper limit of 13% and a reverse silhouette vision lower limit of 36%, if the reflectance of the presented visual target is 20%, the result will be "not visible," or if the visual target has a reflectance of 40%, the result will be "visible" in accordance with the definition of VL.

### Table 4 Reflection factor threshold at various locations of the visual target (left lane)

| Configuration of installation | Location of visual target | Vertical plane luminance (lx) | Background luminance (cd/m²) | Luminance difference threshold (cd/m²) | Equivalent veiling luminance (cd/m²) | Reflection factor threshold (%) |
|------------------------------|---------------------------|-------------------------------|-----------------------------|---------------------------------------|-----------------------------------|------------------------------|
| High overall uniformity (LED) | ①                         | 11.6                          | 1.05                        | 0.42                                  | 0.26                              | 17.0                         |
|                              | ②                         | 11.6                          | 0.86                        | 0.39                                  | 13.0                              | 36.0                         |
|                              | ③                         | 10.5                          | 0.91                        | 0.40                                  | 15.0                              | 39.0                         |
| Low overall uniformity (fluorescent lamp) | ④                         | 23.2                          | 1.62                        | 0.55                                  | 0.42                              | 14.0                         |
|                              | ⑤                         | 23.2                          | 1.52                        | 0.53                                  | 13.0                              | 28.0                         |
|                              | ⑥                         | 28.6                          | 1.94                        | 0.60                                  | 15.0                              | 28.0                         |
|                              | ⑦                         | 24.7                          | 1.61                        | 0.55                                  | 14.0                              | 27.0                         |
|                              | ⑧                         | 24.7                          | 1.50                        | 0.53                                  | 11.0                              | 24.0                         |
|                              | ⑨                         | 31.3                          | 2.02                        | 0.61                                  | 14.0                              | 27.0                         |
|                              | ⑩                         | 18.5                          | 1.56                        | 0.54                                  | 17.0                              | 36.0                         |
|                              | ⑪                         | 18.5                          | 1.47                        | 0.52                                  | 16.0                              | 35.0                         |
|                              | ⑫                         | 21.4                          | 1.90                        | 0.59                                  | 19.0                              | 37.0                         |
|                              | ⑬                         | 18.8                          | 1.52                        | 0.53                                  | 17.0                              | 34.0                         |
|                              | ⑭                         | 18.8                          | 1.38                        | 0.51                                  | 13.0                              | 29.0                         |
|                              | ⑮                         | 22.0                          | 1.94                        | 0.60                                  | 19.0                              | 36.0                         |

Figure 18  Subjective visibility evaluation and VL

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### 4.3 Analysis of test results

#### 4.3.1 Relationship between VL and subjective visibility evaluation results

The VL calculation values and the appearance evaluation results are shown in Figure 18. From these, the determination coefficient for VL and the questionnaire evaluation value is $R^2=0.66$ in the region of high overall uniformity (LEDs) and is $R^2=0.74$ in the region of low overall uniformity (fluorescent lamps), and a positive correlation was found between VL and the appearance evaluation. Then, the VL value that will result in a visibility evaluation value of "3" was found to be 1.0 in a low overall uniformity region and 0.8 in a high overall uniformity region.

#### 4.3.2 Calculation of average value of total revealing power (TRPave)

TRP values were calculated from the VL values
obtained in the experiment. As described above, VL is expressed as the ratio of \( \Delta L \), the luminous difference between a visual target on the road and its background, and \( \Delta L_{\min} \), the luminance difference threshold. If the light reflectance of the visual target surface is a Lambertian surface, then the visual target luminance becomes \( L_0 = \rho E/\pi \) and VL is expressed by Eq. (3), which has been obtained by converting Eq. (1).

\[
VL = \frac{|L_b - (\rho E/\pi)|}{\Delta L_{\min}}
\]

(3)

\( \rho \): visual target reflection factor (%)

E: vertical plane luminance of the target surface (lx).

If the VL threshold for visually recognizing the target is known, the reflection factor thresholds for silhouette vision and reverse silhouette vision (\( \rho_{S\_\text{threshold}}, \rho_{RS\_\text{threshold}} \)) can be obtained from Eq. (3), and TRP can be derived using Eq. (2).

With the method described above, TRP values were calculated at each installation location of the visual target as shown in Figure 15. First, the reflection factor threshold was calculated from the desired VL at each of the overall uniformity conditions obtained in Section 4.3.1, and then TRP was calculated from Eq. (2). Figure 19 shows the computed results of TRP at each visual target location. From Figure 19, it can be seen that the TRPave in the lighting environment of a region of high overall uniformity is 84.7% and the TRPave in the lighting environment of a region of low overall uniformity is 83.8%, and that these two values of TRPave are approximately equal.

4.4 Discussion

In Section 4.3.2 it was found that the values of TRPave in the lighting environments of high overall uniformity and low overall uniformity regions were approximately equal. However, these values were approximately 6% lower than the TRPave=90.2% calculated from the lighting conditions of Table 2 in Section 3.2. This discrepancy is believed to have resulted from the onsite measurement of road luminance being approximately 40% lower than the values of the theoretical investigation (Table 2) in both the high overall uniformity region and the low overall uniformity region. Because the lighting environment, which includes such factors as light distribution, luminaire height and luminaire spacing, was reproduced locally and the horizontal luminance was found to be the same as the result from the theoretical investigation, the difference in road surface luminance is presumed to be due to the difference between the road surface reflectance CIE C2 used in the calculation of road surface luminance in the theoretical investigation and the road surface reflectance in the experimental tunnel. However, for lighting environment factors other than road surface luminance, because the theoretical investigation conditions (Table 1) were reproduced, and based on a comparison and investigation of the value of VL calculated from optical characteristics measured onsite and the subjective visibility evaluation results, it was determined that there would be no problem in comparing the evaluations of two environments of different degrees of overall uniformity.

In the region of low overall uniformity, the reflection factor threshold values from Table 4 differ with the road axis direction (I, II, III and IV in Figure 16), and silhouette vision was found to be predominant in the area of the first half of a single span of luminaire spacing (III, IV), while reverse silhouette vision was found to be predominant in the area of the latter half (I, II). Moreover, regarding the reflection factor threshold values from Table 4, because the maximum value of the silhouette vision lower limit is 19% and the minimum value of the reverse silhouette vision upper limit is 40%, it can be said that the threshold of visibility is approximately 20 to 40%, and that the reflectance of the visible target used in the subjective evaluation was appropriate.

Regarding the two lighting environments of different road surface luminances and overall luminance uniformities shown in Figure 10 and Table 2, since there is no significant difference in average values of the subjective visibility evaluations, and also because the values of TRPave calculated from onsite optical measurement data are also in close agreement, the visibility in both environments can be said to be nearly equal.

5. Summary

For road lighting, TAR based on TRP has traditionally been used as an index for evaluating visibility. For tunnel lighting, however, there had been no investigation into evaluating visibility by considering the TRP distribution. Therefore, applying the average value of TRP (TRPave) as a method for evaluating visibility of tunnel lighting where there is high overall uniformity, a constant relationship was found to exist between the TRPave value and the existing criteria of average road surface luminance and overall uniformity. Additionally, the relationship between VL and visibility was evalu-
ated on the basis of theoretical investigations and experiments involving onsite questionnaire-based subjective evaluations. As a result, it was found that for the same TRPave value, several possible combinations of average road surface luminance and overall uniformity exist, and through using TRPave as a novel index for evaluating visibility, visibility can be ensured while reducing average road surface luminance, and conditions that result in energy savings can be expected.

In the case where visibility is to be evaluated on the basis of revealing power in a lighting environment that satisfies existing lighting criteria (in terms of average road surface luminance and overall uniformity), evaluations based on the average value of the total revealing power (TRPave) are effective for evaluating tunnel lighting.

In this study, a BZ5 luminous intensity distribution pattern was used when investigating TRP, but further study of visibility with luminaires having light distribution patterns other than BZ5 will be necessary in the future. Additionally, in the TRP calculations, the often-used Smith’s cumulative existence probability curve was utilized in determining the cumulative existence probability of an object on the road, but different results have been reported on the basis of recent surveys of objects that have fallen onto highways. Future studies will be needed to determine which data should be used.

In the future, in highway tunnels and the like, by selecting the luminaire light distribution appropriately based upon the TRPave value, the average road surface luminance and the degree of overall uniformity can be combined freely while maintaining visibility to realize facilities that have greater energy efficiency. However, if the road surface luminance is to be reduced, a comprehensive evaluation of the visibility of preceding vehicles and of the visual environment inside the tunnel will be necessary.

References

(1) Japan Road Association: Road Lighting Facilities Installation Standards, The Practical Guide (2007). (in Japanese).
(2) Waldram, J. M.: The revealing power of street lighting installations. Trans. Illum. Eng. Soc. (London), pp. 173–186 (1938).
(3) Adrian, W.: Visibility of targets: Model for calculation. Light. Res. Technol., Vol. 21(4), pp. 181–188 (1989).
(4) ANSI/IESNA RP-8-00, Roadway Lighting (2000).
(5) Harris, A. J. and Christie, M. A.: The revealing power of street lighting installations and its calculation. Trans. Illum. Eng. Soc. (London), Vol. 19, pp. 120–128 (1951).
(6) Smith, F. C.: Reflection factors and revealing power, Trans. Illum. Eng. Soc. (London), Vol. 3, pp. 196–206 (1938).
(7) Roper, V. J. and Howard, E. A.: Seeing with motor car headlamps. Trans. Illum. Eng. Soc., Vol. 33(5), pp. 417–438 (1938).
(8) Sakamoto, M. et al.: Light veiling phenomenon and visibility in automobile tunnel. National Technical Report, Vol. 38, No. 6, Dec. 1992, pp. 87–88 (1992) (in Japanese).
(9) Narisada, K.: Perception under road lighting conditions with complex surroundings. J. Light & Vis. Env., Vol. 19, No. 12 (1995).
(10) Narisada, K.: Perception in complex field under road lighting conditions, Light. Res. Technol., Vol. 21(4), pp. 171–179 (1989).
(11) Karasawa, Y. and Narisada, K.: New Method of Road Lighting Design, Proceeding of CIE Session in Beijing (2007).
(12) Sugawara, T. et al.: A critical object for road lighting design. Proc. 2002 Annual Conf. IEIJ, p. 104 (2002) (in Japanese).
(13) Narisada, K.: A method to balance energy, environment and visual performance. Light Eng., pp. 13–22 (2000).

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