Sādhanā (2020)45:170
https://doi.org/10.1007/s12046-020-01400-7

Research on optimal values of contrast revealing coefficient in road tunnel lighting

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MS received 28 March 2019; revised 30 March 2020; accepted 20 May 2020

Abstract. Based on the perceived contrast method in road tunnel lighting, Commission Internationale de l´Eclairage (CIE) defined the contrast revealing coefficient q_c. The research report CIE 189-2010 recommended that contrast revealing coefficient q_c was one of the indicators of tunnel lighting quality evaluation system. Many studies suggested that the value of q_c was 0.6 under counter-beam lighting in tunnel lighting threshold zone. The value of contrast revealing coefficient was 0.2 under symmetric lighting. However, no studies have recommended the optimal value of contrast revealing coefficient under different lighting systems. The optimal value of contrast revealing coefficient was closely related to visual efficacy and driving safety in road tunnel lighting. Based on the range values of contrast revealing coefficient and visual efficacy experiment, this paper aimed to study the optimal values of contrast revealing coefficient under different lighting systems. The research results were as follows: the optimal value of contrast revealing coefficient q_c was 0.20 under symmetric lighting and the optimal value of q_c was 0.85 under counter-beam lighting. The optimal value of contrast revealing coefficient was 0.17 under pro-beam lighting.

Keywords. Tunnel lighting; contrast revealing coefficient; optimal value; visual efficacy; reaction time.

1. Introduction

Narisada and Yoshikawa [1] defined the ratio between road surface luminance L_b and vertical illuminance of a small target E_v as the contrast revealing factor (CRF). CRF can evaluate luminance contrast and artificial lighting systems. Commission Internationale de l´Eclairage (CIE) [2] recommended that the ratio L_b/E_v can be used as an index for measuring lighting systems. Research report CIE 88-1990 [3] indicated that the value of L_b/E_v was rare between 0.2 and 0.6. There was corresponding relationship between lighting system and L_b/E_v. The value of L_b/E_v was not greater than 0.2 under symmetrical lighting. Meanwhile, L_b/E_v was not less than 0.6 under counter-beam lighting. According to Dijon's [4] research, the value of L_b/E_v was from 0.1 to 0.2 under symmetrical lighting and was from 0.1 to 0.45 under counter-beam lighting. L_b/E_v was from 0.05 to 0.1 under pro-beam lighting.

Research report CIE 88-2004 [5] defined the L_b/E_v ratio as contrast revealing coefficient with the symbol q_c. It pointed out that the value of q_c was 0.2 under symmetrical lighting in tunnel lighting threshold zone and q_c was 0.6 under counter-beam lighting. Research report CIE 189-2010 [6] recommended that contrast revealing coefficient was one of the index of road tunnel lighting quality evaluation system. The lighting quality evaluation system also included average luminance of road surface, overall uniformity on the road, longitudinal uniformity on the road, wall luminance (up to a height of 2 m), contrast revealing coefficient and the glare control. British road tunnel lighting standards, BS 5489-2:2003+A1:2008 [7], indicated that contrast revealing coefficient was not less than 0.6 under counter-beam lighting. The EU road tunnel lighting standard, CR 14380-2003[8], showed that the road tunnel lighting quality was measured by contrast revealing coefficient q_c. The value of contrast revealing coefficient should be higher than 0.6 under counter-beam lighting and q_c was about 0.15 under symmetrical lighting. Bommel [9] pointed out that tunnel lighting system can be defined by contrast revealing coefficient q_c. He thought that if the influence of indirect reflection was not considered, the value of contrast revealing coefficient would be smaller.

On the basis of tunnel field measurements, Weng *et al* [10] found that contrast revealing coefficient q_c was affected by influencing factors, including lighting system, light source power, lamp installation distance, lamp installation height, lamp light distribution curve and multiple reflection effects of light in tunnels. Yin [11] obtained the value of contrast revealing coefficient q_c in tunnel lighting threshold zone under different lighting systems.

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The value of the contrast revealing coefficient was 0.562 under counter-beam lighting and q_c was 0.33 under pro-beam lighting. The value of the contrast revealing coefficient was 0.199 under symmetrical lighting.

Based on contrast revealing coefficient calculation software, Lin [12] got the relationship between contrast revealing coefficient and influencing factors including road surface reflection coefficient, wall reflection coefficient, and among others. It is shown that the relationship between road surface reflection coefficient and contrast revealing coefficient was almost linear. In other words, the contrast revealing coefficient increased when road surface reflection coefficient was increased [13].

In summary, the contrast revealing coefficient corresponded to different lighting systems through literature analysis. However, no studies have recommended the optimal values of contrast revealing coefficient under different lighting systems. The optimal value of contrast revealing coefficient was related to visual efficacy and driving safety in road tunnel lighting. Thus, the purpose of this paper was to study the optimal values of contrast revealing coefficient under different lighting systems based on the range values of contrast revealing coefficient and visual efficacy experiment. If the optimal value of contrast revealing coefficient was studied intensively, the perceived contrast method can be improved in road tunnel lighting design.

2. Visual efficacy experiment

2.1 *Experimental idea*

Visual efficacy was related to the response of human visual system. It means measuring the time required by human eye to detect a target that appears randomly under certain ambient luminance level. According to the visual efficacy theory, the shorter the reaction time was, the better the visual efficacy would be. Weng *et al* [14] determined the threshold values of contrast revealing coefficient q_{c0} under different viewing angles and luminance contrasts. q_{c0} ensured that the small target can be just perceived in different tunnel lighting environments. Based on the threshold values of contrast revealing coefficient q_{c0}, we got the range values of contrast revealing coefficient q_c under different lighting systems. Based on visual efficacy measuring system, we can create tunnel lighting environment and developed the range values of contrast revealing coefficient q_c under different lighting systems. The range value of q_c is shown in table 1.

Based on visual efficacy experiment, we can get subjects' reaction time under different tunnel lighting environments. The tunnel lighting environments corresponded to the contrast revealing coefficient. Thus, the optimal values of contrast revealing coefficient under different lighting systems can be determined based on reaction time. There was a relationship between luminance contrast and lighting systems which included symmetric lighting, counter-beam lighting and pro-beam lighting. Counter-beam lighting enhanced negative luminance contrast and pro-beam lighting enhanced positive luminance contrast. So we created negative and positive luminance contrast in the visual efficacy measuring system.

2.2 *Visual efficacy measuring system*

The visual efficacy measuring system was developed based on reaction time and the principle of visual efficacy measurement. The visual efficacy measuring system can measure reaction time of subject perceiving the target in observation box under different lighting conditions (such as background luminance, target luminance, etc.). This visual efficacy measuring system included light box, observation box, optical system, reaction time measuring device and luminance meter. The detail about visual efficacy measuring system is shown in figure 1.

As shown in figure 1, negative luminance contrast is simulated by the weak light box and positive luminance contrast is created by the intense light box. The visual efficacy measuring system relied on luminance meter to determine the exact luminance value in the observation box. The measuring range of LM–3 luminance meter was from 0.001 to 5000000 cd/m^2 and the measuring accuracy was from − 5% to 5%. The LM–3 luminance meter had four viewing angles: 0.03°, 0.1°, 0.3° and 1°. The precise device of LM–3 luminance meter and extremely small viewing angles can meet the needs of road tunnel lighting measurement.

2.3 *Experimental parameter setting*

2.3a Background luminance: According to research reports and specifications in road tunnel lighting [5, 15–17], background luminance under different driving speeds is shown in table 2. The driving speed of 80 km/h was

Table 1. Range values of contrast revealing coefficient under different lighting systems.

Lighting system	Symmetric lighting	Counter-beam lighting	Pro-beam lighting
Range values of q_c	0.15–0.20	0.60–0.85	0.09–0.17

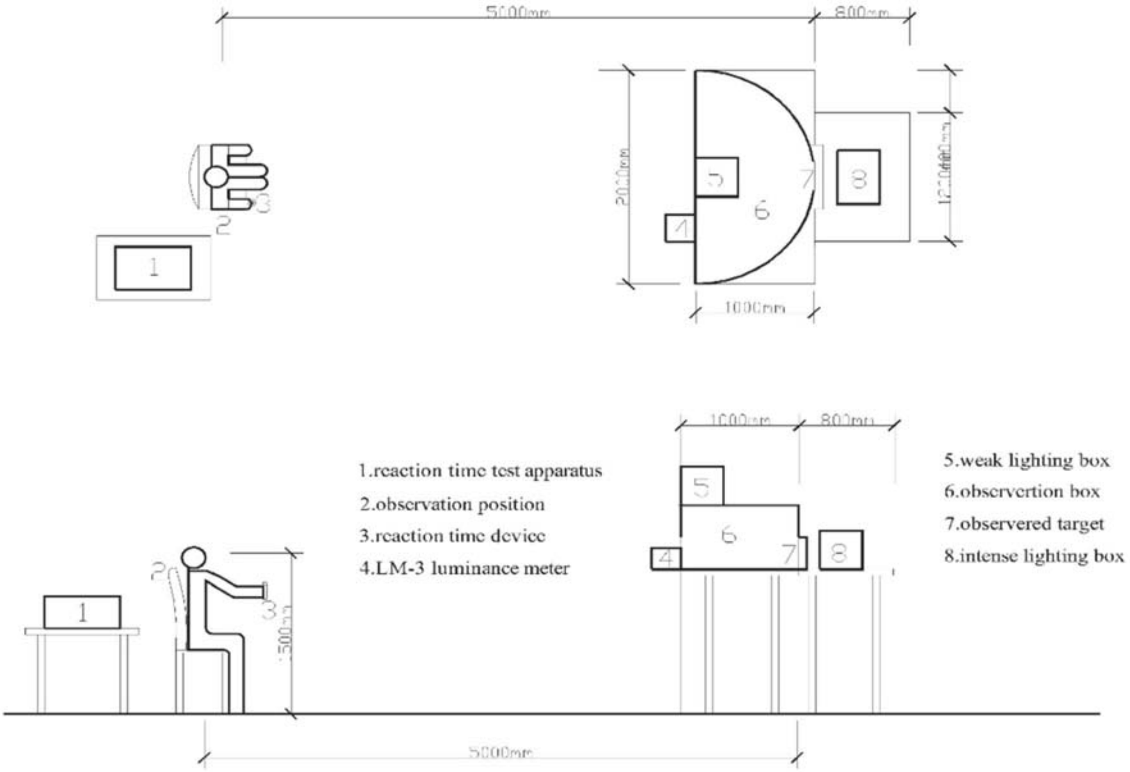


Figure 1. Visual efficacy measuring system.

Table 2. Background luminance① in different lighting zones under different driving speed.

	Threshold zone (cd/m^2)		Transition zone (cd/m^2)			Interior zone (cd/m^2)		Exit zone (cd/m^2)	
Driving speed (km/h)	L_{th1}	L_{th2}	L_{tr1}	L_{tr2}	L_{tr3}	L_{in1}	L_{in2}	L_{ex1}	L_{ex2}
80	175	87.5	26.25	8.75	3.5	3.5	1.75	10.5	17.5
100	247.5	123.75	37.125	12.375	4.95	6.5	3.25	19.5	32.5
120	420	210	63	21	8.4	10	5	30	50

① The traffic flow was 1200 vehicles/ (h·ln) in one-way traffic tunnel. The sky area accounted for 25% of the environment outside the tunnel portals.

selected in this paper. So the value of experimental background luminance was from 1.75 cd/m^2 to 175.0 cd/m^2. Based on research reports and specifications, the road surface luminance must not be less than 1.5 cd/m^2 [5, 15–17]. Thus, the final value of experimental background luminance was from 1.5 cd/m^2 to 175.0 cd/m^2.

2.3b Observed target: According to Eq. (1), the contrast revealing coefficient under different lighting systems can be converted into the corresponding luminance contrast. Based on the range values of contrast revealing coefficient under different lighting systems, range values of luminance contrast between observed target and background luminance can be determined.

$$\mathrm{C} = \frac{\rho}{\pi \cdot q_c} - 1 \tag{1}$$

In Eq. (1), C is the luminance contrast between target luminance and background luminance. ρ is the reflection coefficient of small target. q_c is the contrast revealing coefficient.

Based on driver's visual characteristics, three observed targets under negative luminance contrast were placed at an angle of − 10°, 0° and 10° between the center line of observation box and targets. Three observed targets can be replaced at any time during the experiment. Observed target under negative luminance contrast is shown in figure 2.

2.3c Experimental observation distance: The observation distance was determined based on the security stopping distance. The security stopping distance under different driving speeds is shown in table 3. The visual efficacy measuring system included the observed targets, observation hole, and among others. The main parts of the visual efficacy measuring system were made at a ratio of 1:20 in

Figure 2. Luminance negative contrast targets.

this experiment. Thus, the observation distance was reduced to 1/20 of the security stopping distance (table 3). Considering that the distance between observed target and observation hole was 1 meter in observation box, the observation distance between subjects and observation hole was 4.0 m when driving speed was 80 km/h.

2.3d Experimental error and time precision control: There were differences between the reaction time of human and different feeling types. The reaction time measured by single stimulation was significantly different from the reaction time measured by complex stimulation [18]. Table 4 shows the reaction time under different feeling types and stimulation types. The observed target in the visual efficacy measuring system would produce a loud noise during the pop-up process. So sound can interfere with the subjects' reaction time. To ensure rigorous of experiment and accuracy of the results, subjects must wear soundproofing equipment before the experiment [19].

2.4 *Experimental procedures*

Based on Miao's vision acuity recording method, National Health Commission of the People's Republic of China [20] recommended the standard for logarithmic visual acuity charts (GB 11533-2011). The vision acuity charts set the normal vision at 5 points. In contrast, no light perception was specified as 0. The vision acuity can be expressed by Eq. (2). All vision acuity levels form a numerical system. Table 5 showed the relationship between 5-mark record and decimal record.

Table 3. The security stopping distance under different driving speeds.

Driving speed (km/h)	60	80	100	120
Stopping distance* (m)	56	100	158	210

*The road longitudinal slope was 0.

$$L = 5 - \lg \alpha \tag{2}$$

In Eq. (2), L is vision acuity level. α is visual angle, and the unit of α is minute ($'$).

Kuntz and Sleight [21] pointed out that persons were considered subnormal vision who demonstrated a visual acuity below 1.0 in decimal record. In contrast, persons were considered normal who had a visual acuity above 1.0. Wang *et al* [22] indicated that once the amblyopic patients who had been successfully treated (visual acuity$\geq$5.0), they had almost normal contrast sensitivity and normal vision. Nielsen and Hjortdal [23] pointed out that after the DSAEK surgery, patients with normal visual acuity above 5.0 had an increased ability to discern contrast. It should be noted that the visual efficacy was related to visual acuity and visual psychology. Thus, we selected ten subjects who had normal vision and visual acuity (visual acuity $\geq$5.0). The subject team consisted of 5 men and 5 women, with an average age of 25.5 years.

The subjects entered the laboratory to adapt to lighting environment 30 minutes in advance. Subjects went through many exercises to familiarize themselves with the entire experimental process before experiments. Thus, subjects can follow the entire experimental process (figure 3) to complete the visual efficacy experiment. The explanations of the entire experimental process are as follows:

Step 1: Subjects adapted to the laboratory lighting environment before the visual efficacy experiments. Subjects went through many exercises to familiarize themselves with the entire experimental processes. *Step 2*: Subjects spent 30 minutes adapting to the laboratory lighting environment based on the step 1. Meanwhile, researchers did all the preparations before the experiment, such as debugging the experimental equipment. *Step 3*: According to table 2, researchers adjusted the background luminance and the luminance contrast. The luminance contrast corresponded to reflection coefficient of small target, and the luminance contrast can be converted into contrast revealing coefficient based on Lambert's law. For instance, researchers adjusted the viewing angle to $12.29'$ and set the background luminance to 1.75 cd/m^2. *Step 4*: Once the subject perceived the target in the observation box, he/she pressed the button of the device to test the reaction time. *Step 5*: Researchers recorded the reaction time of the subjects. Meanwhile, subjects closed their eyes and had a break. *Step 6*: Keep the background luminance and the luminance contrast in the same conditions. Researchers changed the viewing angle to continue the experiment. The viewing angles were respectively $12.29'$, $6.88'$, $4.35'$, $3.28'$. *Step 7*: After the experiment was completed under all the viewing angles, researchers changed the luminance contrast to continue the visual efficacy experiment. (Repeat step 3–6) *Step 8*: After the experiment was completed under all the luminance contrast, researchers changed the background luminance to continue the visual efficacy experiment. Repeat step 3–7.

Table 4. Reaction time under different feeling types and stimulation types.

Feeling type	Reaction time (ms)	Stimulus type	Reaction time (ms)
Hearing sense	120–182	Light	168
Sense of sight	150–225	Light & sound	133

Table 5. The relationship between 5-mark record and decimal record.

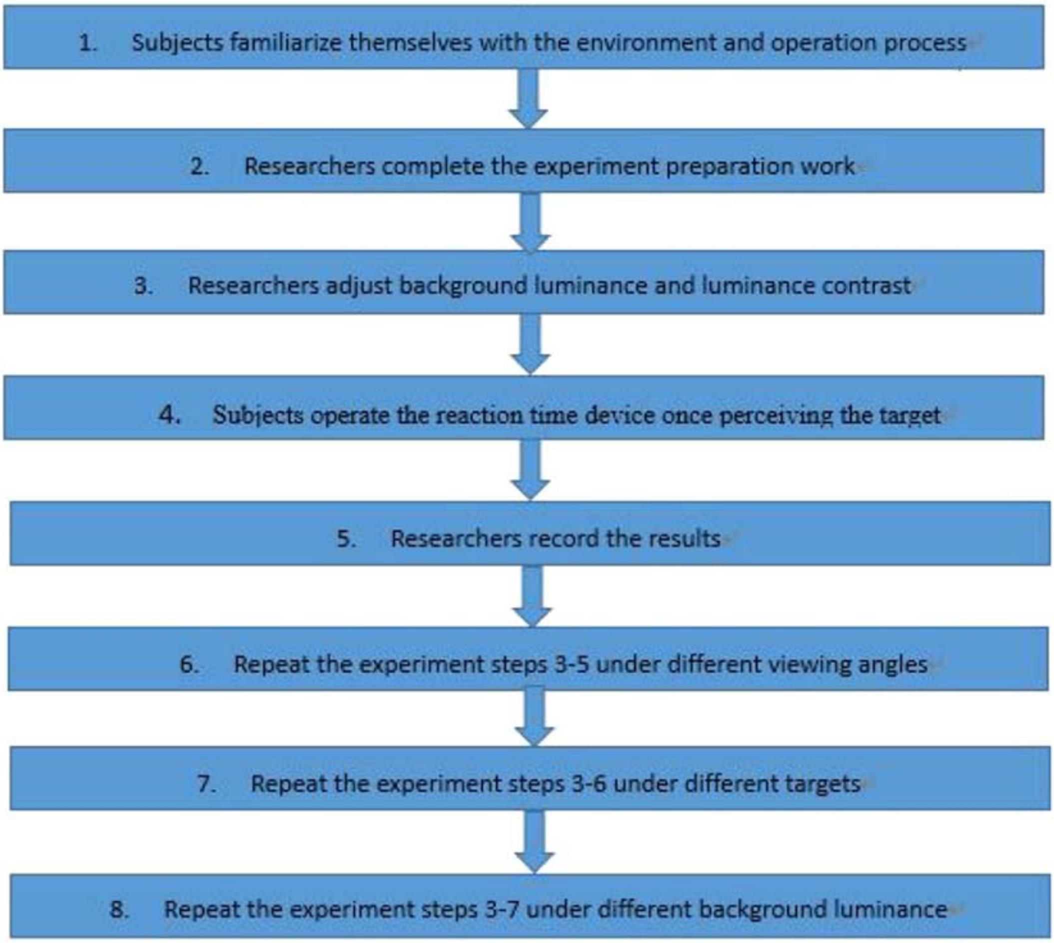
5-mark record	0	4.0	4.7	5.0	5.1	5.2	5.3
decimal record	0	0.1	0.5	1.0	1.2	1.5	2.0

No light perception was specified as 0.

3. Experimental results

The contrast revealing coefficient definition equation, $q_c=L_b/E_v$, indicated the relationship between road surface luminance and vertical surface illuminance of small target. In other words, larger the ratio of contrast revealing coefficient was, the larger the ratio between road surface luminance and small target vertical surface illuminance would be. Based on the Lambert's law $L_t=\rho E_v/\pi$, luminance of small target with uniform diffuse reflection was obtained by vertical surface illuminance of small target. According to Eq. (3), the larger the contrast revealing coefficient was, the larger the luminance contrast between road surface and small target would be.

$$\begin{cases} q_c = {}^{L_b}\!/_{E_v} = {}^{\rho \cdot L_b}\!/_{(\pi \cdot L_b)} \\ C = {}^{(L_t - L_b)}\!/_{L_b} \end{cases} \tag{3}$$



1. Subjects familiarize themselves with the environment and operation process
2. Researchers complete the experiment preparation work
3. Researchers adjust background luminance and luminance contrast
4. Subjects operate the reaction time device once perceiving the target
5. Researchers record the results
6. Repeat the experiment steps 3-5 under different viewing angles
7. Repeat the experiment steps 3-6 under different targets
8. Repeat the experiment steps 3-7 under different background luminance

Figure 3. The entire experimental processes.

Many scholars researched the relationship between reaction time and luminance contrasts of small target. Some researchers studied the effect of luminance contrast between small target and background luminance on reaction time under the same light source condition. Results showed that the reaction time decreased when the luminance contrast was increased [24–26]. Thus, based on the relationship between luminance contrast and reaction time, we can analyze qualitatively the relationship between the contrast revealing coefficient and reaction time. In other words, the reaction time decreased when the contrast revealing coefficient was increased.

We processed the experimental data under the same background luminance. Then we set the contrast revealing coefficient as the independent variable and reaction time as the dependent variable. So we can establish the relationship between the contrast revealing coefficient and the reaction time under a certain background luminance. Finally, we determined the functional relationship between the contrast revealing coefficient and reaction time.

3.1 *The results under negative luminance contrast*

Based on visual efficacy experiment, we got 10 subjects' reaction time under different background luminance and contrast revealing coefficient. Then we got different subjects' reaction time under the same background luminance and negative luminance contrast. Thus, we can get the average reaction time of ten subjects under the same background luminance. Figure 4(a) showed the relationship between contrast revealing coefficient and reaction time under background luminance L_b=1.0 cd/m^2.

As shown in figure 4(a), the reaction time decreased when the contrast revealing coefficient is increased. The reaction time varied greatly when the values of contrast revealing coefficient are from 0.6 to 0.95. If the contrast revealing coefficient is greater than 0.8, the variation range of reaction time becomes small. And the relationship curve between contrast revealing coefficient and reaction time tends to be gentle. It is well known that the range value of contrast revealing coefficient is from 0.6 to 0.85 under negative luminance contrast (counter-beam lighting). Although the reaction time is shorter when contrast revealing coefficient is greater than 0.85, they exceed the range value of contrast revealing coefficient under negative luminance contrast in road tunnel lighting. Thus, the optimal value of contrast revealing coefficient is 0.85 under negative luminance contrast and the background luminance L_b=1.0 cd/m^2. The Eq. (4) shows the function relationship between contrast revealing coefficient and reaction time under the background luminance L_b=1.0 cd/m^2.

$$\mathrm{T} = 326.5 \times q_c^{-0.7824} (0.6 \le \mathrm{q_c} \le 0.95) \quad (4)$$

Reaction time is represented by the letter T in Eq. (4). R-Square is 0.9204 and residual sum of squares is 1316.07 in Eq. (4). Reduced chi-square is 219.35. It means the data fitting works well. There was an error between the fitting result and the experimental data. The relative error between the calculated reaction time and measured reaction time is shown in table 6.

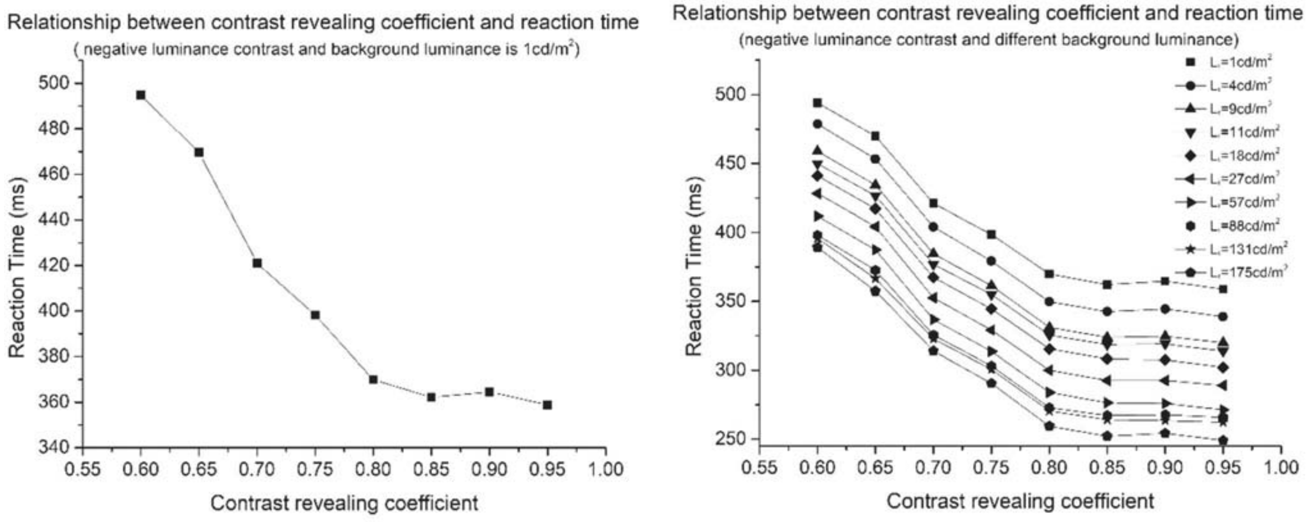
It is shown in table 6 that relative error between calculated reaction time and measured reaction time is from − 5.27% to 5.11%. It means that it can meet the basic requirements of experiment. Similarly, the relationship between contrast revealing coefficient and reaction time can be obtained under different background luminance. The result is shown in figure 4(b).

As shown in figure 4(b), if the background luminance is under the same condition, the larger the contrast revealing coefficient is, the shorter the reaction time will be. So drivers can spend less time perceiving small target. Research results showed that the reaction time decreased when the luminance contrast is increased. In other words, the larger the contrast revealing coefficient is, the shorter the reaction time will be. The reaction time varies greatly when the values of the contrast revealing coefficient are from 0.6 to 0.8. When the contrast revealing coefficient is greater than 0.8, the variation range of reaction time becomes small. The relationship curve between contrast revealing coefficient and reaction time tends to be gentle. It is well known that the range value of contrast revealing coefficient is from 0.6 to 0.85 under the negative luminance contrast (counter-beam lighting). Although the reaction time is shorter when the contrast revealing coefficient is greater than 0.85, they exceed the range value of contrast revealing coefficient under negative luminance contrast in road tunnel lighting. So, the optimal value of contrast revealing coefficient is 0.85 under negative luminance contrast.

3.2 *The results under positive luminance contrast*

According to the method of processing experimental data under negative luminance contrast, we got 10 subjects' reaction time under different background luminance and contrast revealing coefficient by visual efficacy experiment. Then we obtained different subjects' reaction time under the same background luminance and positive luminance contrast. Thus, we can get the average reaction time of ten subjects under the same background luminance. The relationship between contrast revealing coefficient and reaction time is shown in figure 5(a) under the background luminance L_b=1.0 cd/m^2.

As shown in figure 5(a), the reaction time decreased when contrast revealing coefficient is increased. The reaction time varies greatly when the values of contrast revealing coefficient are from 0.09 to 0.19. It is well known



(a) background luminance L_b=1cd/m^2 **(b)** different background luminance

Figure 4. The relationship between contrast revealing coefficient and reaction time (negative luminance contrast).

Table 6. Relative errors between calculated and measured reaction time (negative luminance contrast).

Contrast revealing coefficient q_c	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95
Calculated reaction time (ms)	486.9	457.4	431.6	408.9	388.8	370.8	354.5	339.9
Measured reaction time (ms)	494.2	469.9	421.1	398.6	369.9	362.2	364.6	358.8
Relative error (%)	− 1.48	− 2.67	2.49	2.58	5.11	2.37	− 2.77	− 5.27

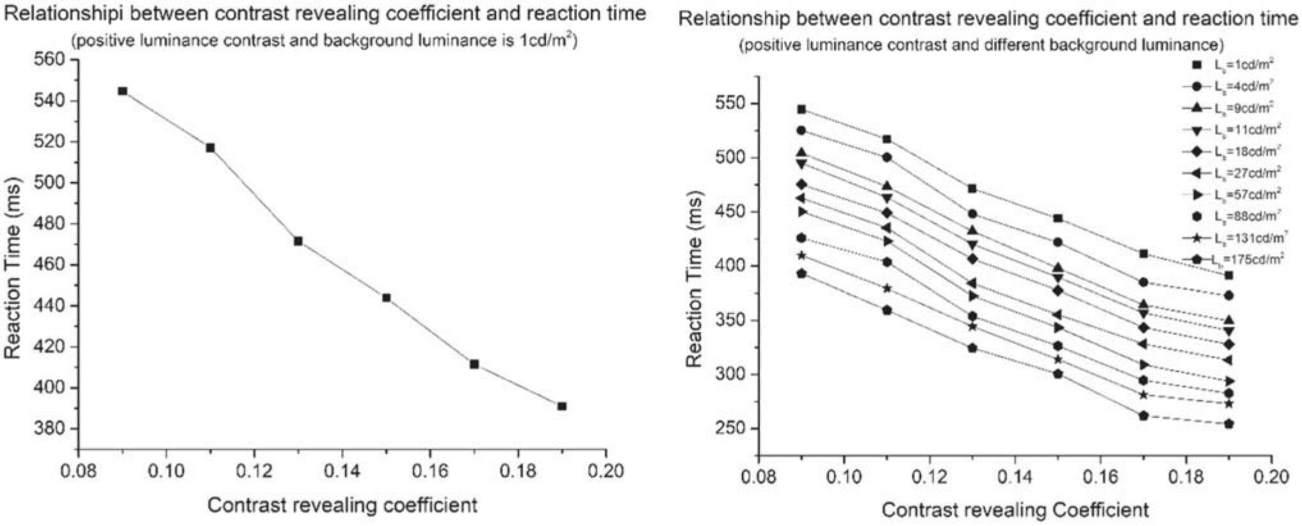
that the range value of contrast revealing coefficient is from 0.09 to 0.17 under positive luminance contrast (pro-beam lighting). Although the reaction time is shorter when contrast revealing coefficient is greater than 0.17, it exceed the range value of contrast revealing coefficient under positive luminance contrast in road tunnel lighting. Thus, the optimal value of contrast revealing coefficient is 0.17 under positive luminance contrast and the background luminance L_b= 1.0 cd/m^2. The Eq. (5) shows the function relationship between contrast revealing coefficient and reaction time under the background luminance L_b=1.0 cd/m^2.

$$T = 187.17 * q_c^{-0.4504} (0.09 \leqq q_c \leqq 0.19) \tag{5}$$

R-Square is 0.9810 and residual sum of squares is 271.349 in Eq. (5). Reduced chi-square is 67.837. It means the data fitting works well. There is an error between the fitting result and the experimental data. The relative error is shown in table 7.

It is shown in table 7 that the relative error between calculated reaction time and measured reaction time is from − 2.20% to 1.67%. It means that it can meet the basic requirements of experiment. Similarly, the relationship between contrast revealing coefficient and reaction time can be obtained under different background luminance. The result is shown in figure 5(b).

As shown in figure 5(b), if the background luminance is under the same condition, the reaction time decreased when the contrast revealing coefficient is increased. So drivers can spend less time perceiving the small target. Research results showed that the greater the luminance contrast is, the shorter the reaction time would be. In other words, the larger the contrast revealing coefficient is, the shorter the reaction time would be. The reaction time varies greatly when the values of contrast revealing coefficient are from 0.09 to 0.19. It is well known that the range value of contrast revealing coefficient is from 0.09 to 0.17 under positive luminance contrast (pro-beam lighting). Although the reaction time is shorter when contrast revealing coefficient is greater than 0.17, it exceed the range value of contrast revealing coefficient under positive luminance contrast in road tunnel lighting. Thus, the optimal value of contrast revealing coefficient is 0.17 under positive luminance contrast.



(**a**) background luminance L_b=1cd/m^2 (**b**) different background luminance

Figure 5. The relationship between contrast revealing coefficient and reaction time (positive luminance contrast).

Table 7. Relative errors between calculated and measured reaction time (positive luminance contrast).

Contrast revealing coefficient q_c	0.09	0.11	0.13	0.15	0.17	0.09
Calculated reaction time (ms)	553.7	505.8	469.2	439.9	415.8	553.7
Measured reaction time (ms)	544.6	517.2	471.5	443.9	411.5	544.6
Relative error (%)	1.67	– 2.2	– 0.49	– 0.90	1.04	1.67

4. Discussion

4.1 *Comparison of optimal values of contrast revealing coefficient under different luminance contrast*

According to figures 4(b) and figure 5(b), there are relative errors between calculated reaction time and measured reaction time under negative luminance contrast and positive luminance contrast. The relative error under different luminance contrast and background luminance is shown in tables 8 and 9.

It is shown in table 8 that relative errors between calculated reaction time and measured reaction time are from – 5.19% to 5.33% under negative luminance contrast. As shown in table 9, relative errors between calculated reaction time and measured reaction time are from – 5.27% to 5.11% under positive luminance contrast. It means that it can meet the basic requirements of experiment. Similarly, the relationship between contrast revealing coefficient and reaction time can be determined under different background luminance. The optimal values of the contrast revealing coefficient are shown respectively in figures 6(a) and 6(b).

It is shown in figure 6(a) that the optimal value of contrast revealing coefficient is a straight line under negative luminance contrast and different background luminance. It means that the optimal value of contrast revealing coefficient is 0.85 under negative luminance contrast in road tunnel lighting. As shown in figure 6(b), the optimal value of contrast revealing coefficient is also a straight line under positive luminance contrast and different background luminance. It means that the optimal value of contrast revealing coefficient is 0.17 under positive luminance contrast in road tunnel lighting.

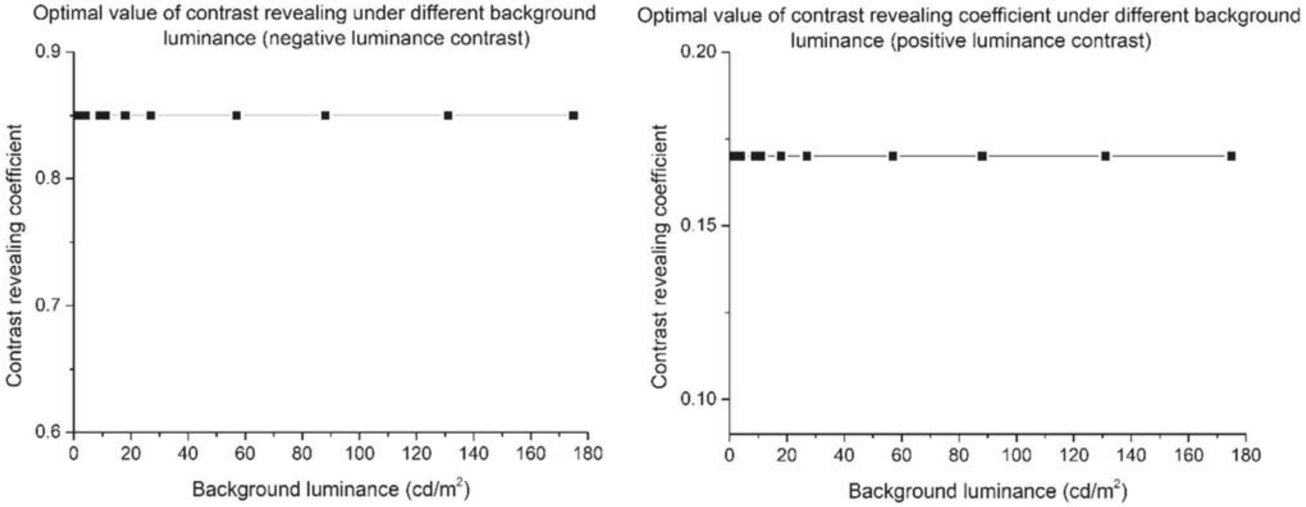
Symmetric lighting generated both negative luminance contrast and positive luminance contrast in road tunnel lighting. So it is difficult to get the optimal value of contrast revealing coefficient by visual efficacy measuring system. On the basis of the method to get the optimal value of contrast revealing coefficient under negative luminance contrast and positive luminance contrast and the range value of contrast revealing coefficient under symmetric lighting, we can draw a conclusion that the optimal value of contrast revealing coefficient was 0.2 under symmetric lighting. It is obvious that the maximum value of the range

Table 8. Relative errors between calculated and measured reaction time for different L_b (negative luminance contrast).

Background luminance	1 cd/m^2	4 cd/m^2	9 cd/m^2	11 cd/m^2	18 cd/m^2	27 cd/m^2	57 cd/m^2	88 cd/m^2	131 cd/m^2	175 cd/m^2
Error range %	− 4.85 to 5.11	− 4.93 to 5.19	− 5.18 to 5.4	− 5.03 to 4.90	− 5.14 to 5.33	− 5.03 to 4.90	− 5.19 to 4.85	− 5.07 to 4.76	− 4.92 to 5.09	− 5.01 to 4.83

Table 9. Relative errors between calculated and measured reaction time for different L_b (positive luminance contrast).

Background luminance	1 cd/m^2	4 cd/m^2	9 cd/m^2	11 cd/m^2	18 cd/m^2	27 cd/m^2	57 cd/m^2	88 cd/m^2	131 cd/m^2	175 cd/m^2
Error range %	− 5.27 to 5.11	− 2.92 to 2.27	− 2.08 to 2.08	− 2.08 to 1.69	− 2.54 to 2.06	− 3.14 to 1.7	− 3.37 to 2.33	− 3.78 to 2.59	− 1.96 to 3.28	− 2.28 to 4.01



(a) negative luminance contrast **(b)** positive luminance contrast

Figure 6. The optimal values of contrast revealing coefficient for different background luminance.

Table 10. The optimal values of contrast revealing coefficient under different tunnel lighting systems.

Tunnel lighting system	Counter-beam lighting	Symmetric lighting	Pro-beam lighting
The optimal values of contrast revealing coefficient	0.85	0.20	0.17

values of contrast revealing coefficient was the optimal value under different lighting system.

4.2 *Research evaluation and improvement*

It is well known that the contrast revealing coefficient q_c was one of the parameters in calculation equation of the threshold zone luminance. Meanwhile, the contrast revealing coefficient q_c was one of the indicators of tunnel lighting quality evaluation system. Thus, based on the visual efficacy theory, the optimal value of contrast revealing coefficient determined the best lighting environment under different lighting systems in road tunnel lighting. According to the optimal value of contrast revealing coefficient, we can determine the appropriate lighting installation method in different tunnel lighting zones. Thus, we can improve tunnel lighting design method and optimize the tunnel lighting quality evaluation system.

It is obvious that we did not consider the effect of color temperature on experimental results in this research. Only LED light of the same color temperature (color temperature was 5257 K) was selected in the visual efficacy experiment. However, research results indicated that different light sources had different visual efficacy [27]. Meanwhile, light source with different color temperatures also had different visual efficacy [28]. Thus, we should consider the effects of different light sources and different color temperatures. Besides, we only considered the subjects between the ages of 20 and 30 in visual efficacy experiment under different luminance contrasts. However, subjects between the ages of 20 and 75 years can be chosen in visual efficacy experiments [29, 30]. Therefore, to expand the scope of research results, we should take different light sources, light sources with different color temperatures and subjects of all ages into account. Thus, the visual efficacy experiment can be optimized in further researches.

5. Conclusions

(1) Based on the visual efficacy experiment, we got the relationship between the contrast revealing coefficient and reaction time. The experiment results showed that the reaction time decreased when the contrast revealing coefficient was increased. The experimental results were consistent with the results of qualitative analysis.
(2) On the basis of the visual efficacy measuring system, we got the optimal values of the contrast revealing coefficient under different luminance contrasts and background luminance. The results are shown in table 10. The optimal value of the contrast revealing

coefficient is 0.85 under negative luminance contrast (counter-beam lighting). The optimal value of the contrast revealing coefficient is 0.17 under positive luminance contrast (pro-beam lighting). The optimal value of the contrast revealing coefficient is 0.20 under symmetric lighting.

According to optimal value of the contrast revealing coefficient, we can determine the appropriate lighting installation method in different tunnel lighting zones. Besides, we can improve tunnel lighting design method and optimize the tunnel lighting quality evaluation system.

Acknowledgement

This work was supported by the National Natural Science Foundation of China through grants (Fund No. 51278507) and the Natural Science Foundation of Fujian Science and Technology Department (Fund No. 2019J01787).

List of symbols

q_c	Contrast revealing coefficient
q_{c0}	Threshold values of contrast revealing coefficient
E_v	Vertical illuminance of a small target (lx)
ρ	The reflection coefficient of small target
C	The luminance contrast
L	Vision acuity level
α	Visual angle ($'$)
T	Reaction time (ms)
L_b	Background luminance (cd/m^2)

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