Holistic digital-twin-based framework to improve tunnel lighting environment: From methodology to application

Yi Shen [a,b], Jiaxin Ling [a*], Xiaojun Li [a], Haijiang Li[c], Shouzhong Feng[d], Hehua Zhu [a,b]

[a] *Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China*

[b] *State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China*

[c] *School of Engineering, Cardiff University, Queens Building, The Parade, Cardiff, CF24 3AA, UK*

[d] *Anhui Zhongyi New Material Science and Technology Co., Ltd, Chuzhou 239500, China*

Abstract: The design of the lighting environment inside the tunnel has a profound impact on the long-term operation of the tunnel. The existing field studies, full-scale experiments and simulation methods, mostly focus on the luminance level inside the tunnel, ignoring the effect of the luminaires and decorations from the visual perspective. This paper proposed a novel digital-twin-based integral method, including virtual world design (the virtual reality (VR) experiment and the numerical simulation) and real-world validation (the tunnel mock-up experiment and the field experiment), to improve the design of the luminaires and decorations in the interior zone of the tunnel. The VR experiment and the numerical simulation in lighting software were firstly conducted to determine the lighting parameters. Then the obtained lighting scheme was tested and validated in the real scenarios, where tunnel mock-up experiments and field experiments were conducted respectively. According to the results from the numerical simulations and the virtual reality experiments, the double-side luminance scheme is more conducive to driving safety and once the power of the luminaires is excessive low, the driver attention variation rate is also unsatisfied. Moreover, the use of the anti-collision lower-side luminaires enhances the luminance level of the road surface and the sidewall to a certain level. The obtained lighting scheme was applied in a newly built tunnel in Hangzhou. The statistics of accidents data indicate that the installed luminaires and decorations, which are obtained from virtual simulation, can provide a considerably safe lighting environment. Ten months of accident statistics show that the breakdown rate in this tunnel was only 10% of the similar tunnels, and the accident rate was only 3%, thus the safety and environmental performance have been proved to be significantly improved.

Keywords: Tunnel lighting environment; Virtual reality (VR); Digital twin; Numerical simulation; Experimental validation

1 Introduction

The design of the lighting environment inside the tunnel has a profound impact on the long-term operation of the tunnel, especially ensuring safety (Ministry of Transport of the People’s Republic of China, 2014). According to the study carried out by Pena-Garcia (2018), there are three fundamental groups of problems that affect driving safety inside the tunnel, i.e., psychological factors mainly impairing a safe driving, visual factors directly related with the human visual system and psychophysiological factors linking hormones secretion with drivers’ behavior and performance. All these hindrances are not independent but closely related, creating a negative synergy that imposes risk on driving safety in tunnels. The solutions to the abovementioned singularities include a suitable level of the luminance (the luminous flux emitted per unit of solid angle and surface in one given direction) or the illuminance (the received flux per unit of surface) as these problems have a common connection that they are closely related to tunnel lighting (Pena-Garcia, 2018, 2022).

Generally, three types of luminaires exist in the interior zone of the tunnel, as shown in **Fig.1**. The luminaires on the tunnel roof provide the main luminance inside the tunnel and can be arranged as single-side or double-side. The light-emitting diode (LED) lighting system has been spreading fast as the main light choice due to its low energy consumption and the high durability combined with the low maintenance requirement (Domenichini et al., 2017; Moretti et al., 2016). In general, lower-side luminaires are adopted to provide visual reference for drivers to prevent collisions. Moreover, the installation of lower-side luminaires can also increase the luminance and illuminance level of the road surface. Another important type of luminaire inside the tunnel is the auxiliary luminaires such as the marking lines or warning signs.

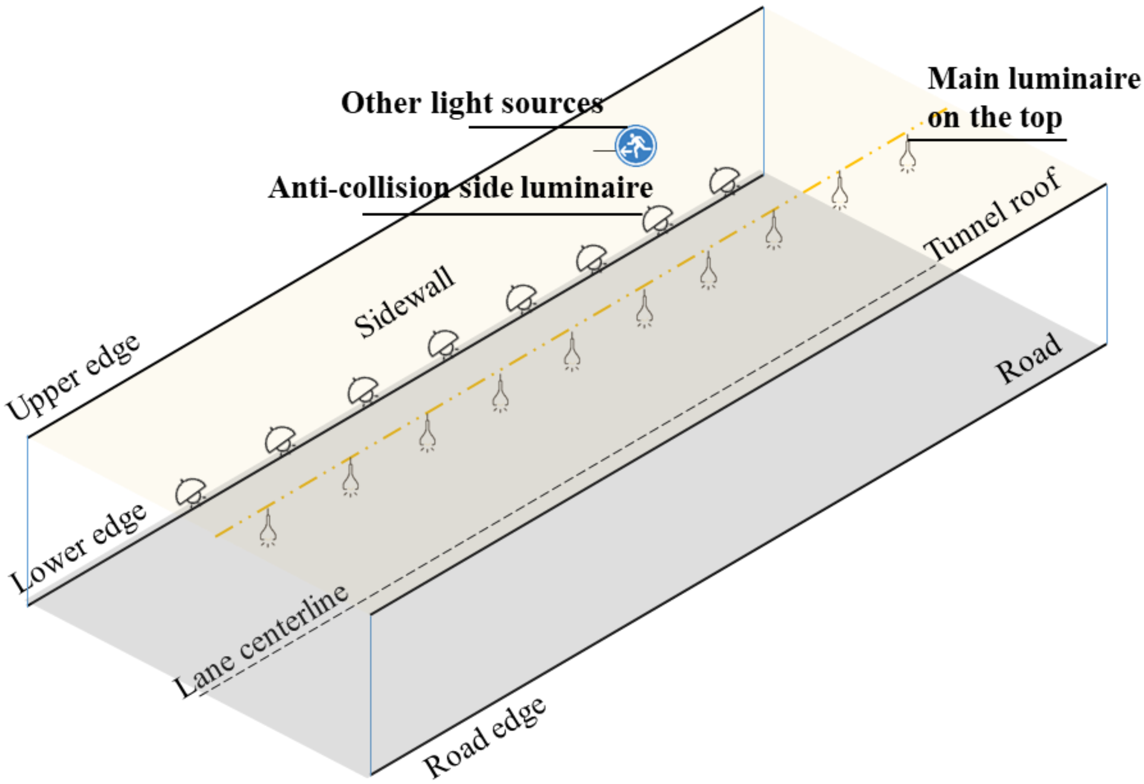


Fig.1 Luminaires in the middle section of the tunnel

Many research endeavors have been allocated to investigate the lighting environment and optimize the lighting scheme. Some researches adopt pre-tunnels as a strategy to reduce lighting consumption, which have been proven to be effective (Cantisani et al., 2018a, b; Gil-Martin et al., 2015). However, the focus of this study is to investigate lighting scheme in the interior zone of the tunnel, so solutions such as pre-tunnels are not considered in this study. Currently,, as suggested by some standards and specifications (Ministry of Transport of the People's Republic of China, 2014), the scale of tunnel lighting facilities is related to the tunnel length, the horizontal curve, the vertical curve and the designed traffic volume. However, such design procedure is a trial-and-error process and the calculated luminance level may be too high with respect to the current designed value (Zhao et al., 2021). Hence, some researchers turn to other methods to obtain a more suitable lighting design method. Generally, field studies, full-scale mock-up (i.e., the prefabricated tunnel used in the model test) experiments and simulation methods are commonly employed in the design of tunnel lighting environment (Bellazzi et al., 2022). However, as a significant amount of experimental input of time and resources is required in the built tunnels, and some specific variables are sometimes impossible to manipulate with the stakeholders' consent, field studies are used relatively infrequently (Heydarian and Becerik-Gerber, 2017). Instead, full-scale mock-up experiments are used as an alternative to field experiments as they allow better control of the lighting scenarios during the experiment (Bellazzi et al., 2022). For instance, Shen et al. (2022) employed the PSO (Particle Swarm Optimization) algorithm to determine the best luminance design scheme and the proposed method was validated by lighting simulation in 1:1 tunnel mock-ups. Though tunnel mock-up experiments can simulate more variables compared with field studies, only limited configurations can be tested, which reduced the complexity of real spaces where multiple stimuli can occur in combination (Bellazzi et al., 2022; Heydarian and Becerik-Gerber, 2017). Therefore, the simulation methods are widely employed in the design of the lighting environment for less cost and a better control of experimental variables. Konstantzos et al. (2015) conducted full-scale experiments in the working place with two glazing systems and an integrated daylighting and glare model. Leitao et al. (2009) and Zhao et al. (2021) used genetic algorithms and deep learning-based approach to calculate luminance level of each lighting section respectively. Cantisani et al. (2018c) used the life cycle assessment method to analyze four scenarios composed of two types of road pavements and two types of lighting systems to be built in a road tunnel and found that the construction and installation of LED lamps imply more consequences than that of HPS lamps.

With the advancement of the VR technology, the immersive VR environment of tunnel lighting environment is used by more and more researchers to determine the lighting scheme. Hong et al. (2019) conducted experiments in the physical and virtual environments to investigate occupant responses with window size. Abd-Alhamid et al. (2020) used a physically-based 360° virtual environment to evaluate the view perception at three different viewing locations. Rodriguez et al. (2021) conducted a VR experiment to analyze subjective responses to lightness changes in outdoor views with respect to three view constructs. Heydarian et al. (2015) implemented available lighting control options in an immersive virtual environment. Mahmoudzadeh et al. (2021) analyzed the impact of having personal control over lighting system on occupants' lighting choices in an immersive virtual environment. Li et al. (2021) proposed a VR-based framework to assess the influence of the color temperature on the visual and non-visual performance of the drivers in both normal driving situation and accident situation. The validation indicates that VR can be used to simulate lighting environment inside the tunnel. Although, there is a growing body of literature that recognizes the importance of VR in lighting design, it should be noted that the abovementioned studies mainly focus on the overall luminance or illuminance level produced by the main luminaires or overall lighting of the building. Thus, the holistic design of tunnel lighting environment cannot be fully considered, e.g. the decorated sidewall, the roof, and the anti-collision luminaires of the tunnel etc. In fact, anti-collision luminaires on the lower side of the tunnel can influence road luminance level and thus influencing driving safety (Lu et al., 2021).

It can also be seen from above that most of the studies on the optimization of the lighting scheme focus on the calculation of the luminance or illuminance level produced by the luminaires. However, the drivers' physiological reaction should be taken into account as the criteria for the selection of the lighting scheme because the lighting inside the tunnel can influence the visual and non-visual performance of the driver (Hu et al., 2013; O'Donell et al., 2011). To investigate the drivers' visual and non-visual performance under different lighting schemes, some researches were conducted using simulated tunnel environment (usually in the form of an observation box) to measure the reaction time of the drivers (He et al., 2020; He et al., 2017; Liang et al., 2012). Such simulation method obviously caused high loss in terms of ecological validation, which referred to the extent to which the simulated environment corresponds to its operational equivalent in the real world (Loomis et al., 1999). However, to the authors' best knowledge, few literatures adopt VR, which can reduce the high loss of ecological validation, to investigate the optimization of the luminaires from the perspective of luminance level and the drivers' physiological reaction.

Hence, to fill these knowledge gaps, this paper proposed a novel digital-twin-based integral method, including virtual world design (the numerical simulation and the VR experiment) and real world validation (tunnel mock-up experiment and field experiment), to improve the design of the luminaires in the interior zone of the tunnel. The lower-side anti-collision luminaires were modelled and simulated in the numerical software, then the immersive virtual tunnel lighting environment was created accordingly, and the virtual experiments were conducted. Moreover, the tunnel mock-ups experiments and field experiments were also carried out to further verify the lighting schemes obtained by numerical simulation and VR experiments. The detailed methodology, the experimental setup, the research findings and validation are given in the remainder of the paper. These findings are expected to provide practical recommendations for the design of the lighting scheme in the interior zone of the tunnel and advance the existing knowledge about the tunnel lighting design from a holistic perspective.

2 Research methodology

The impact of tunnel lighting is especially remarkable in terms of driving safety and energy consumption. According to the statistics carried out by Pervez et al. (2020), crashes are the main accidents in tunnels. The reasons for the high proportion of crashes are the mental and visual impairment induced by some common disturbing effects in tunnels such as slow visual adaptation and flicker effect (Pena-Garcia, 2022). An effective measure to solve this problem is to increase the luminance and illuminance level in the tunnel, however this will simultaneously increase energy consumption. Therefore, how to set the layout of luminaires to ensure the sufficient luminance of the road surface and reduce certain energy consumption was always mentioned in the above research.

Generally, geometrical optics and photobiological effects are usually used in the abovementioned field studies, full-scale mock-up experiments and simulation methods. Geometrical optics method focuses on the geometrical layout of the luminaires and calculates the luminance or illuminance level of road surface or sidewall. For instance, Leitao et al. (2009) and Shen et al. (2022) both used optimization algorithms to optimize the layout of the luminaires with the luminance level as the optimization object. However, geometrical optics method fails to take into account the physiological reactions of drivers as excessive luminance will also have an adverse impact on driving safety and energy consumption. Hence, photobiological effect method is used by different researchers to optimize the design of the tunnel interior lighting environment. The pros and cons of two methods are listed in **Table 1**. Taken these into account, our method considers both the quantification of the luminaire layout parameters and drivers' physiological reactions, and the photobiological effect method is employed in the tunnel mock-up experiments and field experiments to validate the simulation results. On the other hand, the geometrical optics method and photobiological effect method (i.e. VR) are comprehensively employed in simulation to determine the luminaire parameters.

Table1 Pros and cons of geometrical optics method and photobiological effect method.

	Geometrical optics method	Photobiological effect method
Aims	Calculate luminance/illuminance level to optimize luminaires layout	Use drivers' physiological reactions to optimize luminaires layout
Examples	Shen et al. (2022), Leitao et al. (2009)	Li et al. (2021), Dong et al. (2020), Liang et al. (2020)

Applications	Usually in simulation and verified by tunnel mock-up experiments and field experiments	Simulation, tunnel mock-up experiments and field experiments
Advantages	Luminaire parameters are quantified theoretically	Closer to the actual driving conditions
Disadvantages	Fail to consider drivers reactions;	Difficult to quantify the luminaire layout;
	May result in energy waste	Multiple experiments to determine luminaire layout

Specifically, the overall research methodology of this study is presented in **Fig.2**. Firstly, the research objects of this study were determined as the main luminaires on the tunnel roof and the anti-collision luminaires on the lower side of the tunnel. Then, based on the digital twin concept, both numerical simulation and VR experiments were applied in the virtual world to investigate the layout scheme of the luminaires. Specifically, the VR experiments were used to compare the pros and cons of double-side and single-side main luminaires on the tunnel roof. What's more, VR experiments were also conducted to study the impact of the lamp power of the anti-collision lower-side luminaires on driving safety. The DIAlux software, which is a professional lighting software, was also used in this study to calculate the luminance level inside the tunnel created by the luminaires. Thirdly, in the real world, the experiments in tunnel mock-up were performed to evaluate the visual performance (visual distance of small object) of the drivers and validate the lighting parameters from the lighting schemes obtained by the simulation methods. Finally, the obtained lighting scheme was validated in a practical engineering project, of which the accident rate was counted and compared with other counterpart in the same type of the tunnel.

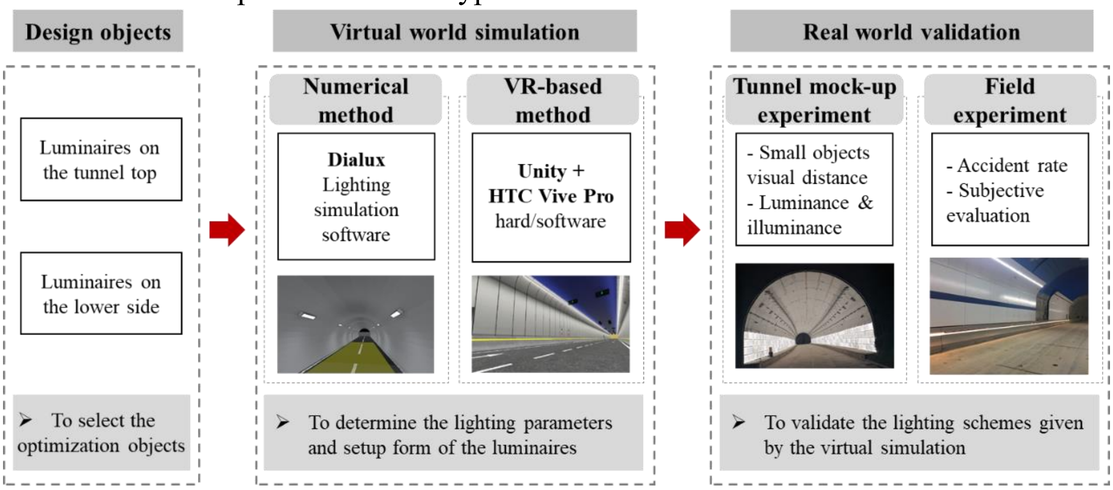


Fig.2 Research methodology of this study.

3 Experimental setup

In this section, the VR experiment approach, the numerical simulation methods and the real-car experiment in tunnel mock-up are discussed in detail.

3.1 VR experiment

3.1.1 Experimental setup

To investigate the physiological reaction of the drivers under different lighting schemes, an immersive virtual tunnel environment was firstly modelled to simulate the lighting in the interior zone of the tunnel. Then, the established model was put into *Unity* for lighting creation and interaction. As for the hardware of the VR experiment, *HTC Vive Pro* was used to display VR environment and *Logitech Momo Driving Force* was used to restore the real driving experience and steer the simulated car in the virtual environment (see **Fig.3**). To measure the physiological reaction of the participants, a brainwave collector was worn by the participants and the collected brainwave signals were transformed to attention data using embedded artificial intelligence (AI) algorithms of the brainwave collector (Kosmyna and Maes, 2019).

Fig.3 Hardware of the VR experiment.

3.1.2 Virtual environment

The immersive virtual environment was built according to the design drawings of one practical engineering projects. As shown in **Fig.4**, the basic modelling included lane marking, enamel steel plate, markers, the waistline and essential ventilation equipment. The main luminaires on the tunnel roof and the lower side were added in the *Unity* where the lighting parameters, such as the luminance level, was comparably modulated.

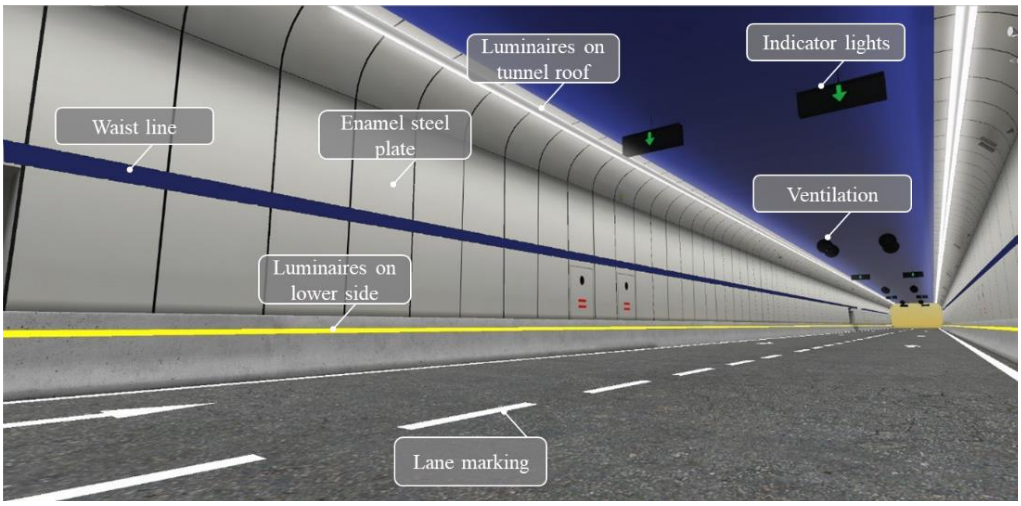


Fig.4 Established virtual tunnel environment in *Unity.*

3.1.3 Visual tasks and participants

In order to optimize the layouts of the luminaires, as shown in **Table 2**, three different layouts of luminaires were set in the virtual environment: i) main luminaires on the tunnel roof were set as double side or single side; ii) the powers of the main luminaires on the tunnel roof were set as 6W, 12W, 18W, 24W and 30W; iii) the powers of the luminaires on the lower side of the tunnel were set as 4W, 6W, 8W, 10W and 12W.

In the experiment, the requirements of the subjects included: i) normal hearing and vision; ii) no nausea and dizziness problems, iii) no wrist and hand injuries; iv) obtaining a motor vehicle driver's license and more than one year driving experience; v) no uncomfortable VR experiences. All the subjects should meet the requirement and consent the test procedure before the VR simulation. A total of 30 subjects from universities and related social groups were recruited in Shanghai, China. 60% were males and 40% were females, and the mean age of them was 28.67 ± 4.47 years, ranging from 23 to 40. It should be noted that before the VR experiment, the participants were asked not to exercise within 1h before the test or drink alcoholic/caffeinated drinks within 12h before the test to ensure the objectivity of the data (Li et al., 2021).

Table 2 Working conditions of the study.

	Variables	Values
Lighting parameters	Layouts of main luminaires	Double-side
		Single-side
	Power of main luminaires	6W
		12W
		18W
		24W
		30W
	Power of lower-side luminaires	4W
		6W
		8W

	10W
	12W

3.1.4 Procedure

As shown in **Fig.5,** the procedures of the VR experiments were as follows:

(1) After arriving at the VR laboratory, the participants were requested to read and sign a form to give consent to take part in the experiments. After signing the consent form, the participants were asked to complete a questionnaire, which contained questions about demographic information, driving years and experience, diseases history and careers.

(2) Before the formal experiment, the participants were firstly given a brief introduction of the VR system and the driving simulator. Then, the participants were suggested to put on the necessary equipment and perform a 3-minute pre-experiment to be familiar with the equipment and ensure that the hardware are in good condition.

(3) After the pre-experiment, the participants were asked to perform the formal experiment. Each participant drove through the tunnel model under different lighting schemes in the virtual environment at the designed speed of 60 km/h. Since there were three different lighting variables to be investigated, the participant took a 10-min break after each experiment.

(4) After all the experiments done, the participants were also asked to fill in a post-experiment questionnaire, which contained questions about to what extent the VR environment corresponded to the real world counterpart, whether the differences in the lighting schemes can be experienced and whether simulation sickness appeared.

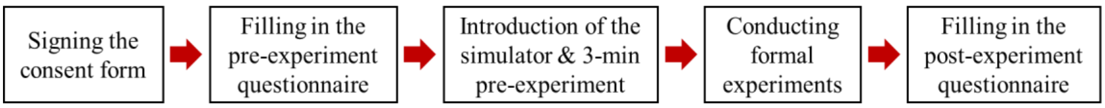


Fig.5 Procedures of the experiments.

3.2 Numerical simulation

The aim of numerical simulation is to investigate the impact of the power of the anti-collision lower-side luminaires on the distribution of the luminance/illuminance inside the tunnel, hence providing evidence for the design of the lighting scheme.

3.2.1 Model design

The length of the numerical model in DIAlux (DIAL, 2020) was set to 120m to fully simulate the lighting environment in the interior zone of the tunnel, which is shown in **Fig.6**. As show in **Fig.6 (a)**, the model was modelled after the practical engineering project which is shield tunnel (Shen et al., 2022). The rendering of the interior environment and the details are shown in **Fig.6 (b)** and **(c)**.

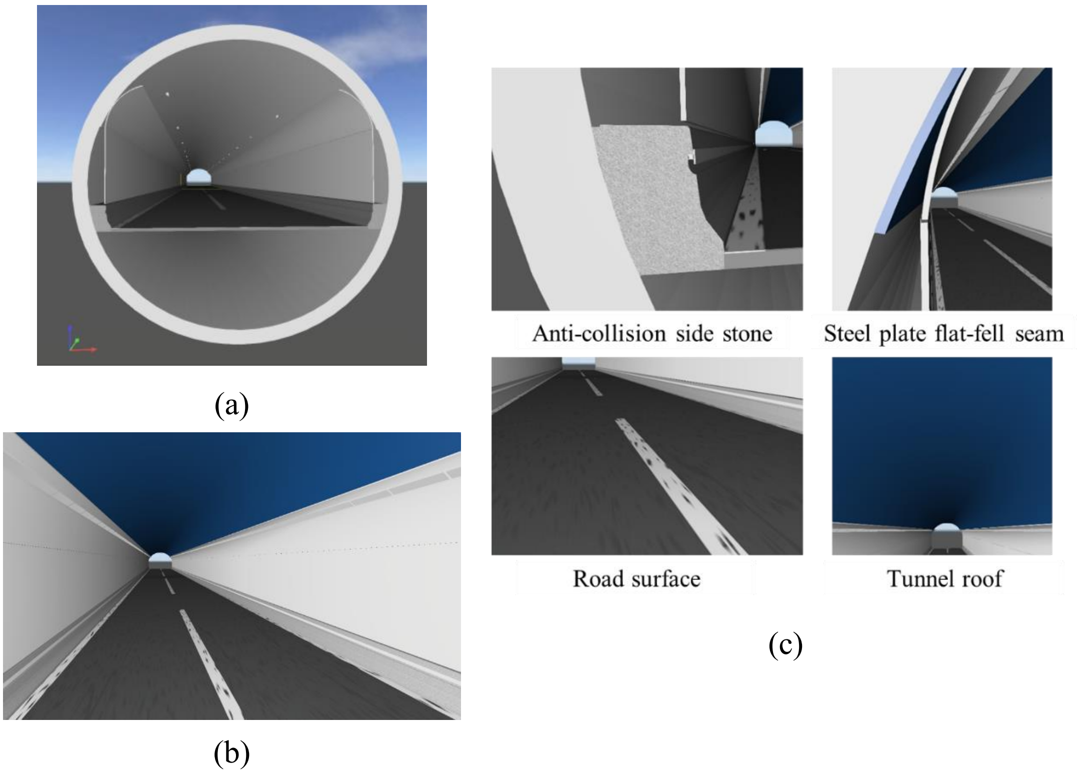


Fig.6 Numerical model in DIAlux: (a) Tunnel cross-sectional view; (b) Interior environment rendering; (c) Model details.

3.2.2 Reflection parameters

Referring to the existing tunnel lighting schemes, the main luminaires on the tunnel roof were set as double-side and arranged as a discontinuous lamp strip to correspond to the lighting effects in the VR scenario. It should be noted that the main aim of the numerical simulation was to compare the impact of luminaires with different power on the luminance level to determine a more suitable lighting scheme from the safe-driving perspective (rather than the energy-saving perspective). Hence, the luminaires were set as double-side discontinuous lamp strip, creating the similar lighting environment to that in the VR environment.

As for the internal surface reflection coefficient of the objects in the interior zone, the test model pavement was set as asphalt pavement, and the reflection coefficient of newly built asphalt pavement was 0.14 according to relevant specifications (Ministry of Transport of the People's Republic of China, 2014). In the tunnels in operation, the roof is generally sprayed with black paint and paint treatment, combined with the tunnel smoke and oil pollution. As a result, the reflection coefficient of the roof is quite low (generally 0.05 or even lower). Hence, the luminaire distributes little lighting to the roof. In this case, the reflection effect of the roof on the light was quite limited, and its reflection coefficient was taken as 0.05. The surface reflectivity of the enamel steel plate was set as 0.7. For anti-collision side stones with concrete surfaces, the surface reflection coefficient was set as 0.31 according to relevant specifications (Ministry of Transport of the People's Republic of China, 2014).

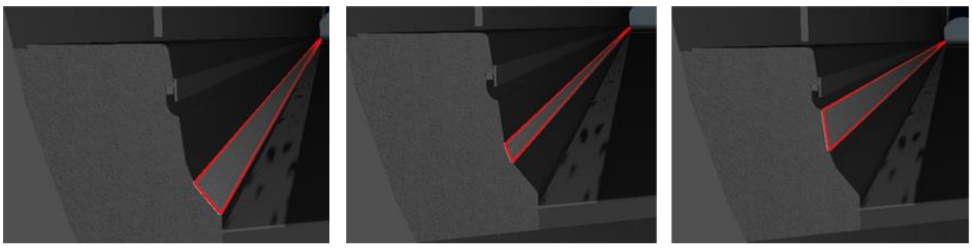
3.2.3 Simulated conditions

The numerical simulation was composed of four different working conditions, i.e., without lower-side anti-collision luminaires and with lower-side anti-collision luminaires (the power of the lower-side anti-collision luminaires are 4W, 6W and 8W, respectively). For the main luminaires, the size of the shell was 1.2m*0.3m*0.16m and the size of the luminous surface was 1.16m*0.21m. For the lower-side anti-collision luminaires, the size of the shell was 1m*0.023m*0.024m and the size of the luminous surface was 0.998m*0.020m.

3.2.4 Analysis indicators

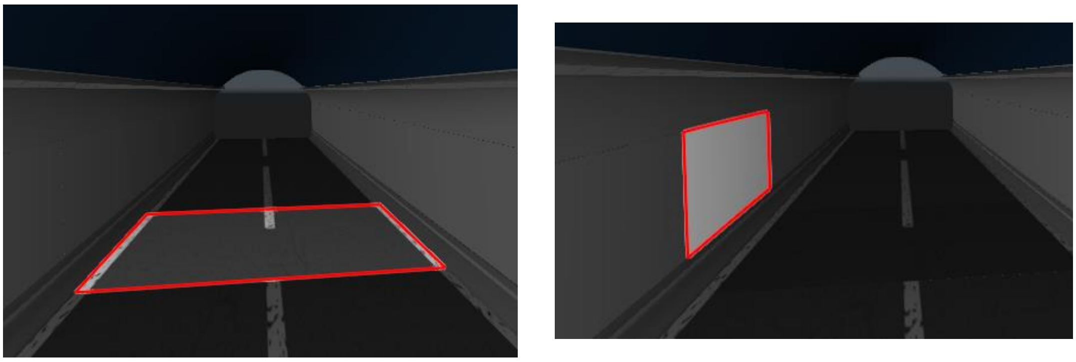
The evaluation of the impact of the lower-side anti-collision can be divided into three types: i) luminance/illuminance level of the surface of the anti-collision side stone, which directly reflected the brightness perception ability of the driver to the anti-collision side stone; ii) luminance/illuminance level of the road surface, which reflected the gain effect of anti-collision lower-side luminaires on the road illumination; iii) luminance/illuminance level of the sidewall, which reflected the gain effect of anti-collision lower-side luminaires on the sidewall illumination.

The calculation areas of the above three types of surfaces are presented in **Fig.7**. In the simulation model, since the wall surface of the anti-collision side was a curved surface, it was divided into three computed surfaces for brightness/illuminance analysis, as shown in **Fig.7 (a)**. The direction of surface 1 was at a certain angle to the direction of the lower-side luminaire light line, which can accept more light flux of lower-side luminaire light. The directions of surface 2 and 3 were approximately parallel to the direction of light, which can accept limited light flux of the lower-side luminaire light. Similar work on illuminance was undertaken by Shen et al. (2022). As for the calculation area of the road surface, in order to eliminate the boundary effect of the model, the calculation area was a rectangle with a length of 12m and a width of 8.75m located in the middle of the tunnel, as shown in **Fig.7 (b)**. Similarly, for the calculation area of the sidewall, the calculation area was also a rectangle with a length of 12m and a width of 2.7m located in the middle of the tunnel, as shown in **Fig.7 (c)**. The length of the calculation area was set as 12m referred to the longitudinal distance between the luminaires in the numerical simulation.



Calculation surface 1 Calculation surface 2 Calculation surface 3

(a)



(b) (c)

Fig.7 Calculation areas of different positions in the interior zone of the tunnel: (a) Anti-collision side stones; (b) Road surface; (c) Sidewall.

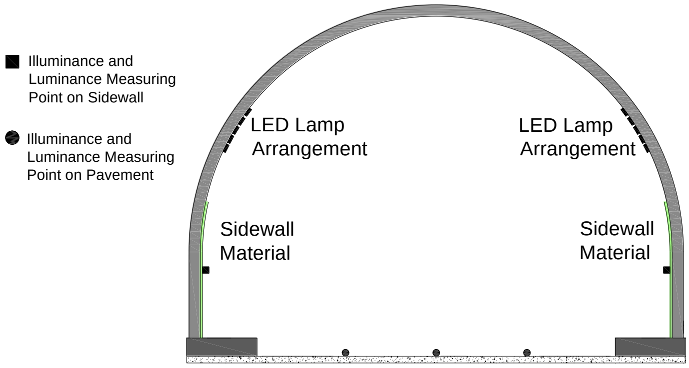
3.3 Real world validation

To investigate the impact of luminance level which was obtained by the simulation methods on the drivers, the real-car experiments were performed to measure the non-visual performance of the drivers under different luminance level.

3.3.1 Setup

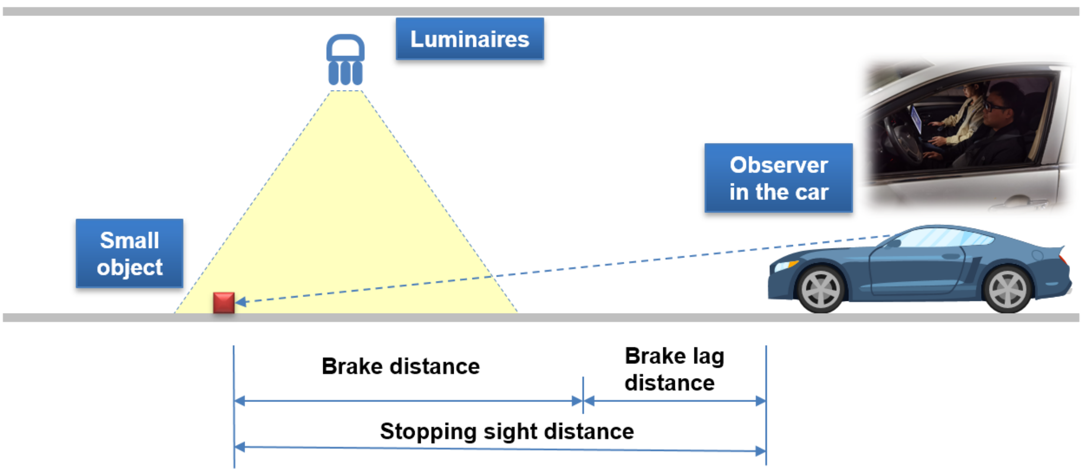
The real-car experiment was carried out in a 1:1 ratio tunnel mock-up whose length is 105m, as shown in **Fig.8**. The mock-up is the prefabricated prototypical tunnel model which is used in the model test. Generally, the installation, control and replacement of the luminaires in the mock-up are easier to implement than that in the real tunnel. For various design schemes, the researchers just need to install the luminaires in the mock-up according to the design scheme and then conduct corresponding experiments. As the interior environment of the mock-up is similar to that of the real tunnel, the results obtained in the mock-up can provide almost identical directions and be an important reference to the design of lighting in the tunnel (Gil-Martin et al., 2015). To simulate the lighting environment in the interior zone of the tunnel, the real-car experiments were all carried out in the night to eliminate the effect of the natural light during the day.

The setup of the luminaires was scattered LED lamps, which corresponded to that in the numerical simulation (see **Fig.6** (a)). One point to clarify is that the luminaires in the VR environment were linear (see **Fig.4**), which was different from that in numerical simulation and in tunnel mock-up experiments. In fact, due to the lighting characteristics in *Unity*, the linear lighting sources can create a more similar lighting environment to that in the physical tunnel (see **Fig.8** (b)) than the scattered lighting sources. Hence, the luminaires in numerical simulation and tunnel mock-up experiments were set as scattered and the luminaires in VR were set as linear to create a similar lighting environment.



(a)

(b)



(c)

Fig.8 Mock-up test: (a) Schematic diagram of the tunnel mock-up and the luminaire layout; (b) The tunnel mock-up in the night with luminaires on; (c) Visual range test of the small object in tunnel mock-up.

3.3.2 Evaluation indicator

The visual task for the drivers was to recognize the grey cube (size: 20cm×20cm×20cm, reflection coefficient: 0.2) from a distance (CIE, 2004), and the farthest distance that the experimenter can recognize the object is called the visual distance, which is used as the evaluation indicator of the lighting environment (see **Fig.8 (c)**). During the experimental process, the illuminance level of the sidewall, the illuminance level of the road surface and the visual distance under each lighting scheme were recorded during each experiment to i) compare the obtained visual distance with the counterpart regulated by the standard and ii) investigate the relationship between luminance level of sidewall and road surface and the visual distance.

Specifically, when testing the visual distance under different lighting schemes, the observer without any eye diseases and with normal sight sit inside the car in the tunnel. With luminaires on, firstly, a black cloth was placed in front of the observer and the aforementioned grey cube was randomly placed on the pavement of the tunnel. Then, the cloth was removed and the observer was asked to recognize the small object for 1 s. After that, three questions were posed to the observer: i) Was there any object recognized? ii) What was the position of the object on the pavement? iii) What was the color and the shape of the object? If the three questions were answered correctly, it was considered that the observer could recognize the object. The distance between the object and the observer was changed every experiment and the experiment was conducted repeatedly until the observer could not recognize the small object anymore. The maximum distance with which the observer could recognize the small object was recorded as the visual distance.

4 Results

4.1 Real world validation results

As shown in **Fig.9**, based on the 105m-long tunnel mock-up, the illuminance level of the road surface, the illuminance level of the sidewall and the visual distance were recorded during each experiment. It is worth noting that the abnormal data (e.g., the visual distance is smaller than the standard-regulated one) is excluded in the analysis.

The fitted formula is given in Eq.(1):

$$d = 50.84 + 54.10x - 21.53x^2 \tag{1}$$

where d denotes the visual distance and x denotes the ratio of the sidewall illuminance and the road surface illuminance. When the ratio of sidewall illuminance and road surface illuminance increases to 1.256, the visual distance also increases to about 85m. However, when the ratio is further increased, the visual distance is decreasing. Hence, according with the luminance and uniformity requirement of the existing tunnel lighting standards and specifications, the ratio of the illuminance of the sidewall to the road surface illuminance should be between 1 and 1.5, which effectively improves the visual distance of small objects and the driving safety.

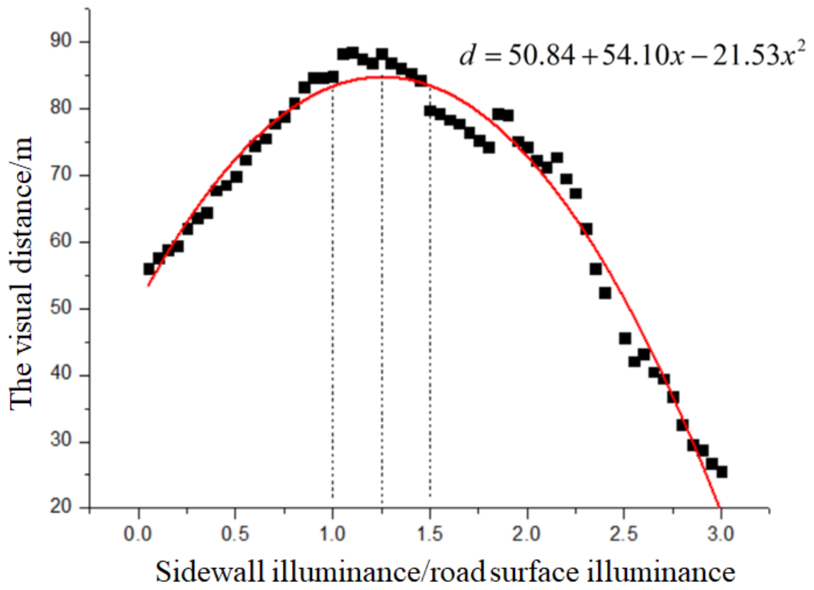


Fig.9 The relationship between the visual distance and the ratio of sidewall illuminance and road surface illuminance

4.2 VR results

4.2.1 Data preprocessing

As mentioned above, the physiological signals collected during the VR experiment are the attention data which are transformed by the embedded AI algorithms in the brainwave collector. As the attention data value of different experimenters differ a lot, to reduce the impact of the individual different, attention change rate p is used in this study to represent attention changes, which is given in Eq.(2):

$$p = \frac{n_2 - n_1}{n_1} \tag{2}$$

where n_1 denotes the attention value of the driver under the calm state and n_2 denotes the attention value during the driving process. The attention change rate p is a value between -1 and 1, and the higher the value, the more focused the driver, the safer driving can be guaranteed, and vice versa.

4.2.2 Layout of main luminaires

According to the previous study (CIE, 2004), the layout of the main luminaires can be divided into two categories: double side or single side. Hence, the two types of layouts of main luminaires were compared in the VR experiment. The data of all subjects were processed to obtain the mean value of the subjects' attention variation rate and the mean square error of the attention rate under the two schemes. For the double-side layout, the mean value of drivers' attention change rate was 8.21% and the mean square error was 39.55%. In comparison, the mean value and mean square error for the single-side layout were 3.11% and 79.30%, respectively. Compared with the single-side layout, the mean value of the drivers' attention change rate under the double-side layout was higher, indicating the drivers' attention was more concentrated. In addition, the mean square error of the attention change rate under the double-side layout was lower, which further verified that the double-side layout was more conducive to driving safety. By evaluating the subjects' intuitive feelings, this may be attributed to that the road surface brightness was uneven under the single-side luminance scheme, which influenced the driving comfort. These findings raise the possibility of intriguing implement regarding the combination of main luminaires.

4.2.3 Power of luminaires

To compare the effects of different powers of the luminaires, a series of cases were designed as arithmetic progression of wattages. The power of the main luminaires was set as 6W, 12W, 18W, 24W and 30W. Under each experiment, the other lighting parameters inside the tunnel were the same such as the lighting parameters of the lower-side anti-collision luminaires. The data of the drivers' attention rate versus the power of luminaries were averaged and the curve of the drivers' attention change rate under different powers is shown in **Fig.10**. When the power increased from 6W to 12W, driving attention was significantly improved. It is probable that unclear lines of the light belt are a result of the low illuminance from the main luminaires. When the power increased further from 12W to 30W, the attention change rate fluctuated and the increase in attention was not significant.

The fitting curve of the drivers' attention change rate and power of main luminaires is given in Eq. (3) where p denotes the attention change rate of the drivers and x_1 denotes the power of main luminaires. The fitting curve shows that the attention change rate rises with the increase of the luminaire power if the luminaire power is less than 22W. However, the attention change rate will decrease if the power of the main luminaires exceeds 22W.

$$p = -0.017x_1^2 + 0.761x_1 - 3.318 \tag{3}$$

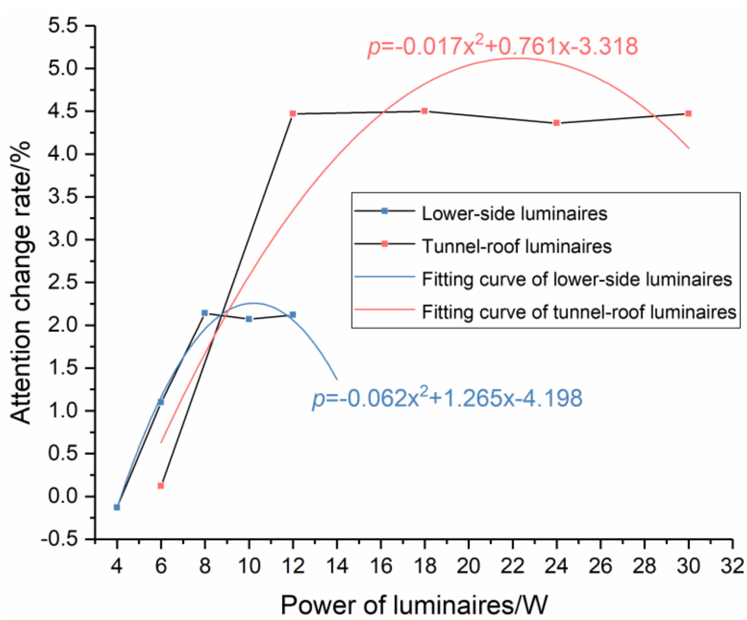


Fig.10 The relationship between the attention change rate of the drivers and the power of the luminaires

The power of lower-side anti-collision luminaires was also investigated in the VR experiment, which was set as 4W, 6W, 8W, 10W and 12W. Similar to that of the main luminaires, under each experiment, the other lighting parameters inside the tunnel were the same such as the lighting parameters of the main luminaires. The data of the drivers under each power were averaged and the curve of the drivers' attention change rate under different powers is also shown in **Fig. 10**. When the power of the lower-side anti-collision luminaire increased from 4W to 8W, driving attention was significantly improved. The reason may be that the low power of the lower-side anti-collision luminaire will lead to unclear lines of the lamp belt. When the power increased further from 8W to 12W, the attention change rate fluctuated but the increase was not obvious.

The fitting curve of the drivers' attention change rate and power of lower-side luminaires is given in Eq. (4) where p denotes the attention change rate of the drivers and x_2 denotes the power of lower-side luminaires. The trend shows similarity to that of the main luminaire. If the power of the luminaires is too low, the driver attention change rate will also be low, indicating that insufficient lighting information is provided.

$$p = -0.062x_2^2 + 1.265x_2 - 4.198 \tag{4}$$

4.3 Numerical simulation results

According to the VR results, the double-side main luminaires outperforms the single-side main luminaires, so in the DIAlux simulation, the layout of the main luminaires was set as double-side. The luminance levels of the calculation area of the anti-collision side stone, the road surface and the sidewall were simulated respectively.

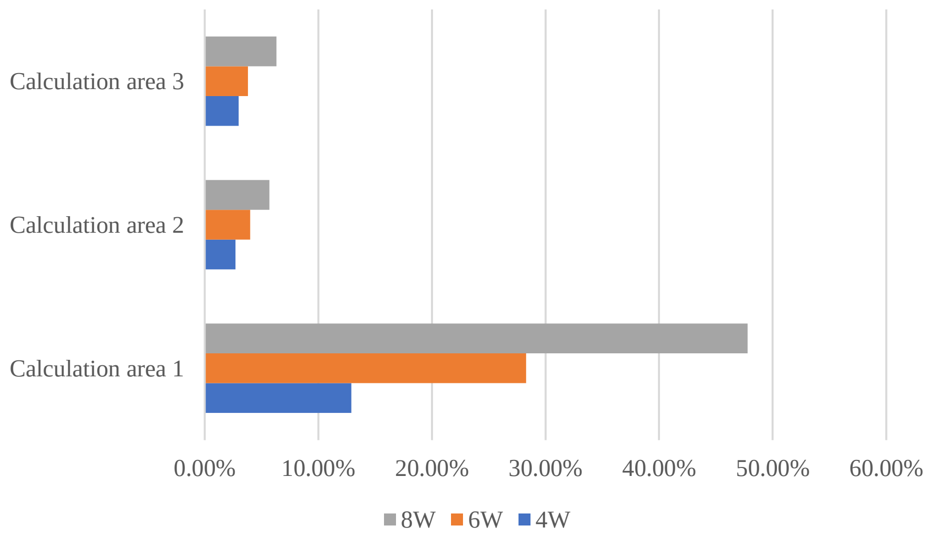
4.3.1 Luminance level of the anti-collision side stone

The luminance and illuminance level and their corresponding uniformity of the anti-collision side stone under different powers of the lower-side luminaires are given in **Table 3**. A one-way analysis of variance (ANOVA) was conducted to test the impact of the luminaire power on the luminance uniformity and illuminance uniformity. Results show that the power of the lower-side luminaires has no significant impact on the luminance uniformity (p = 0.84) and the illuminance uniformity (p = 0.77) in the three calculation areas. However, the increase of the power of lower-side luminaires can increase the luminance and illuminance levels. With the power increases from 0 W (i.e., without lower-side luminaires) to 8 W, the luminance level increases by 47.84% and the illuminance level increases by 47.92% in Calculation area 1.

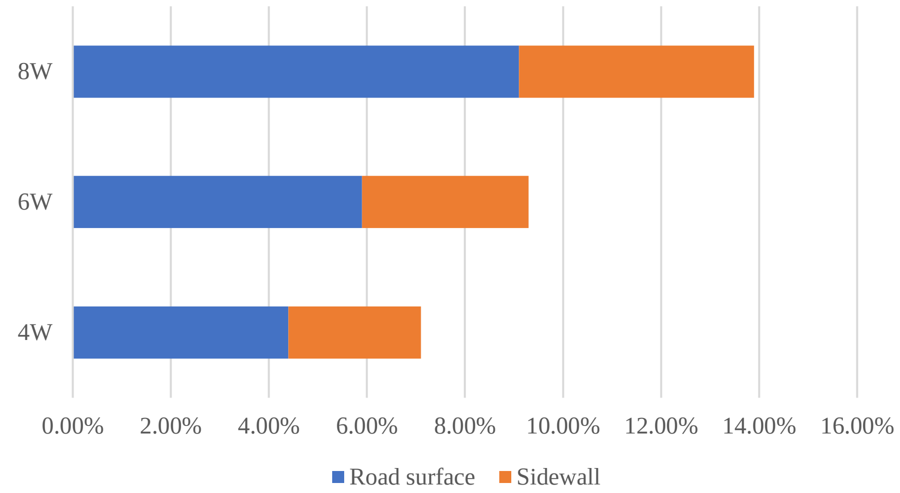
The luminance increments of the three calculation areas under different powers of the lower-side luminaires are shown in **Fig.11 (a)**. As regards the luminance increment of the calculation area 1, as the power increases, the luminance increases significantly in all three types. The luminance increases by 12.9% when 4W luminaires are used, while the increasing rate reaches 47.8% when 8W luminaires are used. Similar trends are also found in the luminance increments of the calculation area 2 and 3 that the luminance increases with power. However, it can also be seen that the luminance increment of the calculation area 2 and 3 by applying different luminaires is quite limited. The luminance increment of calculation area 2 is between 2.7% and 6.2%, which is much lower than that of calculation area 1.

Table 3 Luminance and illuminance level of the three calculation areas

		Without lower-side luminaires	4W	6W	8W
Calculation area 1	Luminance(cd/m^2)	9.74	11	12.5	14.4
	Luminance uniformity	0.99	0.95	0.94	0.92
	Illuminance(lx)	98.7	112	126	146
	Illuminance uniformity	0.99	0.95	0.95	0.92
Calculation area 2	Luminance(cd/m^2)	8.19	8.41	8.52	8.66
	Luminance uniformity	0.99	0.99	0.99	0.99
	Illuminance(lx)	83	85.3	86.4	87.8
	Illuminance uniformity	0.99	0.99	0.99	0.99
Calculation area 3	Luminance(cd/m^2)	7.10	7.31	7.37	7.55
	Luminance uniformity	0.99	0.99	0.99	1
	Illuminance(lx)	71.9	74	74.7	76.6
	Illuminance uniformity	0.99	1	0.99	0.99



(a)



(b)

Fig.11 Luminance increments (a) of the three calculation areas under different lower-side luminaire powers; (b) of the road surface and sidewall under different lower-side luminaire powers

4.3.2 Luminance level of the road surface and sidewall

The luminance and illuminance level and their corresponding uniformity of the road surface and sidewall under different powers of the lower-side luminaires are given in **Table 4**. Analysis of the data shows that after the lower-side luminaires were applied, the luminance of the road surface was enhanced to a certain extent, the uniformity of the road surface was also improved to a certain extent, and the improvement of the uniformity of the road surface by different luminaires is similar. ANOVA test was also conducted and the results show that the power of the lower-side luminaires has no significant impact on the luminance uniformity (p = 0.99) and illuminance uniformity (p = 0.98). However, the ANOVA test also indicates that the power of the lower-side luminaires does not have a significant impact on the luminance (p = 0.99) and illuminance level (p = 0.99), though after the lower-side luminaires were applied, the luminance and illuminance level of both the road surface and sidewall have been enhanced to a certain extent.

As for the luminance increments, similar trends of the change of the luminance increments can be seen in both road surface and sidewall that the luminance increments increase as the power of the luminaires increases (see **Fig.11 (b)**). However, it should also be noted that the luminance increment under different lower-side luminaire power is all below 10%, indicating that the luminance gain of road surface and sidewall by applying different luminaires is not large.

Table 4 Luminance and illuminance level of the three calculation areas

		Without lower-side luminaires	4W	6W	8W
Road	Luminance(cd/m^2)	5.91	6.17	6.26	6.45

surface	Luminance uniformity	0.72	0.78	0.79	0.78
	Illuminance(lx)	133	138	141	145
	Illuminance uniformity	0.71	0.78	0.79	0.79
Sidewall	Luminance(cd/m^2)	14.7	15.1	15.2	15.4
	Luminance uniformity	0.95	0.95	0.95	0.95
	Illuminance(lx)	66.2	67.7	68.1	69
	Illuminance uniformity	0.95	0.95	0.95	0.95

5 Case study

5.1 Project background

The obtained results of the VR experiment and numerical simulation were applied in a practical tunnel engineering project, Boao Tunnel, which is located in Hangzhou city, Zhejiang Province, China. Boao Tunnel is an important river-crossing tunnel and the total length is more than 2.7 km. The designed speed of the two-way four-lane urban tunnel is 60 km/h. According to the holistic digital-twin-based framework, the lighting environment design of the Boao Tunnel corresponds with the established tunnel model in the virtual environment.

5.2 Lighting arrangement scheme

After the construction of the main structure, the luminaires were installed inside of the tunnel and the lighting scheme took into consideration the simulation results. The final lighting scheme was set as the 12W main luminaires on the tunnel roof which acted as the main light and the 8W luminaires on the lower-side of the tunnel which were used for anti-collision purpose. From **Fig.12**, it can be seen on the construction site, main luminaires and anti-collision lower-side luminaires were all installed in the same way as they were in the virtual world (see **Fig.4**). Moreover, the waistline and the enamel steel plate and other facilities in the tunnel were also constructed in line with what they were in the virtual model.

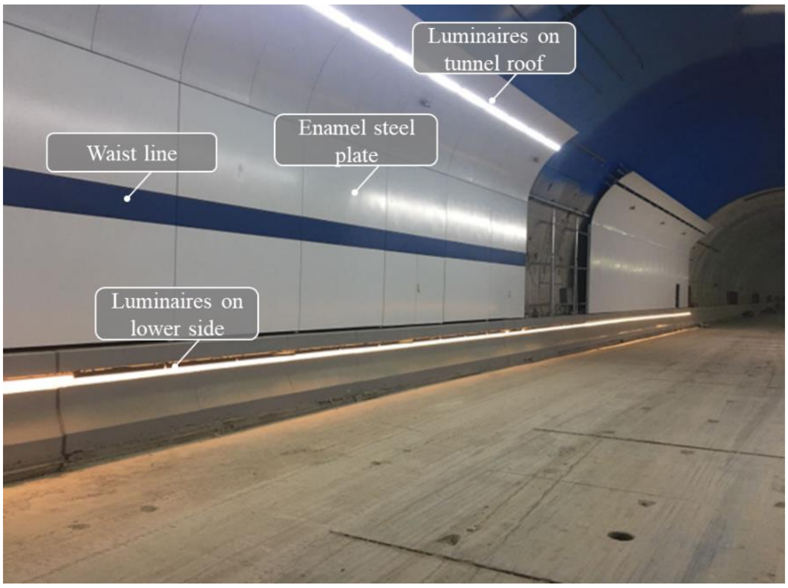
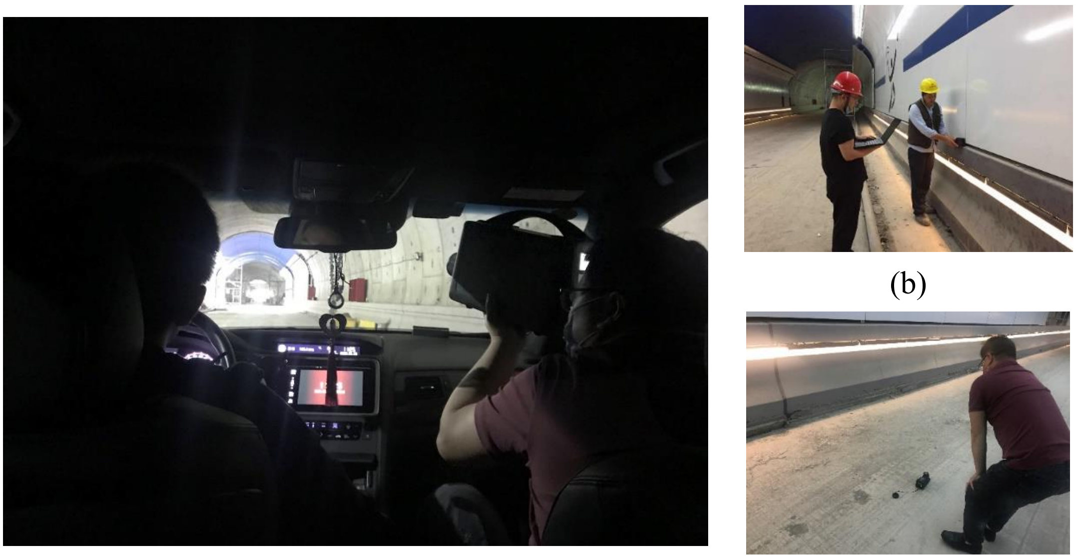


Fig.12 Installed luminaires and other facilities during construction

Field measurements were conducted after the installation of the luminaires, as shown in **Fig.13**. The illuminance level of the road surface and the sidewall were measured using the illuminometer. According to a large number of published studies (Gil-Martin et al., 2015; Cantisani et al., 2018a;b; Liang et al., 2020), due to the inappropriate luminance distribution of the light environment, it may induce discomfort to the human eye and consequently reduce the ability to observe important objects. In urban tunnel lighting, the angle between the position of the luminaires and the viewpoint can induce the light source with extremely high luminance to be reflected to produce extremely bright light or a strong contrast of luminance, resulting in glare. Therefore, the glare phenomena were also measured to ensure that the installed luminaires can improve driving safety (see **Fig.13 (a)**).



(b)

(a) (c)

Fig.13 Field measurement of the lighting distribution in the tunnel: (a) Measurement of glare phenomena; (b) Measurement of sidewall illuminance; (c) Measurement of road surface illuminance

The measured lighting parameters are presented in **Table 5**. The longitudinal and horizontal uniformity and the overall uniformity all meet the requirement of the relevant standard (Ministry of Transport of the People’s Republic of China, 2014). The ratio of sidewall illuminance and the road illuminance was 1.36 (between 1 and 1.5), thus is conducive to the visual distance. Moreover, according to the measurement results, glare phenomena did not exist in the tunnel. Hence, it can be concluded that the lighting scheme obtained by the VR and numerical simulation is effective and safety-conducive.

Table 5 Measured lighting parameters in Boao Tunnel

Road overall uniformity	Longitudinal uniformity of midline	Horizontal uniformity of midline	Sidewall illuminance/road illumination
0.75	0.95	0.80	1.36

Based on the results of the measurement and the calculation, the installed luminaires can meet the requirement of safety and the proposed lighting scheme, including the decoration scheme, was adopted and installed in the Boao Tunnel. Corresponding with the VR model, the final interior environment is shown in **Fig.14**. The luminaires, the enamel steel plate, the waste line, the indicator lights and other facilities in the tunnel were all set in the same or similar way as they were in the VR model.

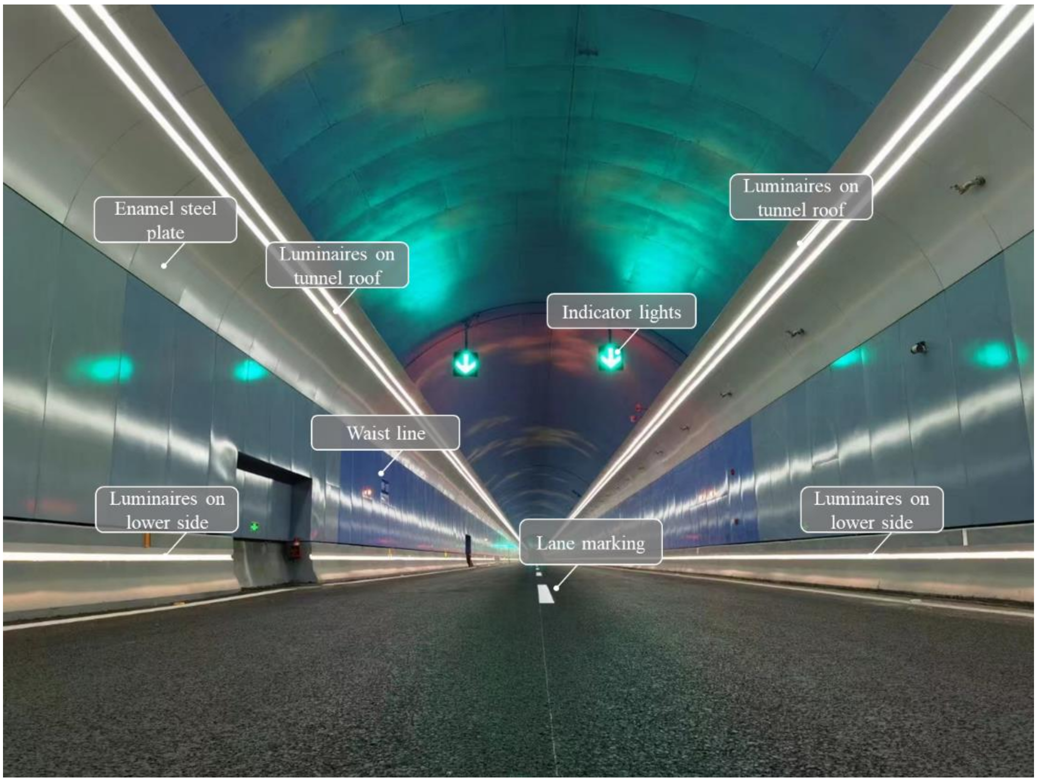


Fig.14 The view of the interior environment in Boao Tunnel under operation

5.3 Accident rate analysis

The Boao Tunnel was open to traffic on September 2021. To further validate the effectiveness of the obtained lighting scheme by the simulation methods, the statistical analysis of accidents occurred in this tunnel and other same type tunnels during the concurrent time period from September 2021 to July 2022 was performed. According to the data obtained from the local road management department, there were 75 vehicle breakdowns and 28 accidents in the Qingchun Tunnel; 27 vehicles breakdowns and 73 accidents in the Wangjiang Tunnel. In the Boao Tunnel, there were only 10 vehicle breakdowns and 3 accidents. As shown in **Fig.15**, breakdown rate was merely 10% of the similar tunnels, and the accident rate was only 3%, which indicates that the lighting environment has greatly improved the safety performance.

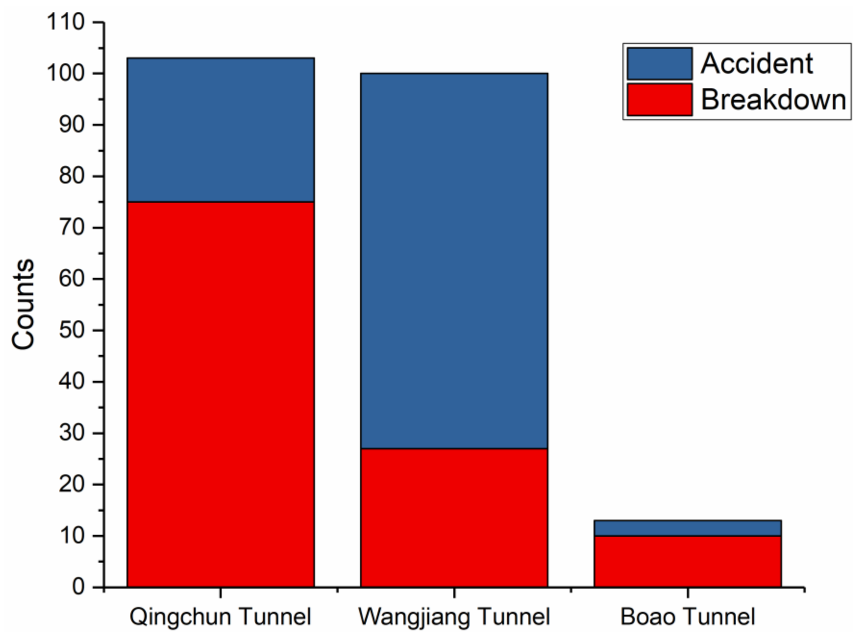


Fig.15 Counts of breakdowns and accidents in Boao Tunnel and other tunnels of the same type

Although there is no exclusion in overall accident rate analysis, these results should also be interpreted with caution as the evaluation of the correlation between the real statistics and the proposed method based on the mock-ups and VR environments. Increased activation of drivers in the lighting environment in this study corroborates these earlier findings. According to the study conducted by Du et al. (2018) and Zhao et al. (2022), the improvement of all the drivers' accurate perception of the speed, the distance, the direction and position, as well as the improvement of visual distance, reduce the accidents and ensure driving safety. The obtained lighting scheme was proved to increase the small object visual distance in the tunnel mock-up experiment as aforementioned analysis in Section 4. Moreover, with the adoption of anti-collision lower-side luminaires, the driving safety was effectively improved from the perspective of driving guidance and side wall spatial recognition. Consistent with the literatures, this research finds that the spatial lighting in tunnel maximizes the visual distance in accordance with the present results.

6 Conclusions

The present study proposed a novel digital-twin-based integral method, including virtual world design and real-world validation in the tunnel lighting environment. The aim of this study was to investigate the effects of the luminaires and decorations in the interior zone of the tunnel. The results showed that this method was effective and considerably aided the design of the city tunnel lighting environment. The main conclusions can be drawn as follows:

(1) As far as the digital twin view was concerned, the numerical simulation and VR experiments were firstly conducted to determine the lighting parameters. Then, the obtained lighting scheme was tested and validated in the real world, where tunnel mock-up experiments and field experiments were conducted respectively. This method provides the first comprehensive investigation of holistic digital-twin-based framework on the tunnel lighting environment. The investigation of the tunnel lighting environment has shown that the layout of luminaires and decorations in the real tunnel can be simulated and designed in the virtual environment to realize more elaborated schemes with the reduction of costs required by real settings.

(2) According to the results from numerical simulation and VR experiments, the double-side luminance layout is more conducive to driving safety. As regards the driver's response, once the power of the luminaires is relatively low, the attention change rate will also be not satisfied. With respect to the identified visual concentration, the power of the lower-side luminaires and main luminaires was selected at least 8W and 12W, respectively. Moreover, the use of the anti-collision lower-side luminaires effectively enhance the luminance level of the road surface and the sidewall to a certain level. This finding suggests a role for aided lower position lighting in promoting the entire tunnel lighting effect.

(3) The tunnel mock-up experiments show that the ratio of the sidewall illuminance to the road surface illuminance needs to be between 1 and 1.5 to meet the requirement of the small objects visual distance. Based the framework of the research methodology, the lighting schemes were implemented in the field experiments in the Boao Tunnel to compare and confirm the installed plan of luminaires and decorations in the tunnel lighting environment. Thus far, ten months of accident statistics show that the breakdown rate in Boao Tunnel was only 10% of the similar tunnels, and the accident rate was only 3%. The safety and environmental performance have been observably improved. Regarding the holistic digital-twin-based framework, this new understanding should help to improve predictions of the impact of the tunnel lighting condition on the road tunnel safety.

Notwithstanding the relatively limited experiment conditions and costs, this work offers valuable insights into the tunnel lighting and photobiological effect. The most important limitation lies in the fact that the evaluation method of the study is based on the attention data of the subjects. For instance, other types of physiological data can also be used to evaluate the lighting schemes more comprehensively such as the heart rate (Muhlberger et al., 2007) and the eye movement data (Wang et al., 2016). Further research could be conducted to determine the coupled effects of the illuminance, the light source typology and correlate color temperature in the virtual environments established by more detailed users' perception.

CRediT authorship contribution statement

Yi Shen: Writing review - editing, conceptualization. **Jiaxin Ling:** Methodology, Writing - original draft. **Xiaojun Li:** Data curation, validation. **Haijiang Li:** Investigation, formal analysis. **Shouzhong Feng:** Resources. **Hehua Zhu:** Funding acquisition, supervision.

Acknowledgements

This study was supported by the Shanghai Sailing Program (20YF1451400) and the Research Fund of State Key Laboratory of Disaster Reduction in Civil Engineering (SLDRCE19-A-14). The support from the Hangzhou Qianjiang New City Construction Management Committee during the in-situ tests is highly appreciated.

References

Abd-Alhamid, F., Kent, M., Calautit, J., Wu, Y., 2020. Evaluating the impact of viewing location on view perception using a virtual environment. Building and Environment 180, 106932.

Bellazzi, A., Bellia, L., Chinazzo, G., Corbisiero, F., D'Agostino, P., Devitofrancesco, A., Fragliasso, F., Ghellere, M., Megale, V., Salamone, F., 2022. Virtual reality for assessing visual quality and lighting perception: A systematic review. Building and Environment 209.

Cantisani, G., D'Andrea, A., Moretti, L., 2018a. Natural lighting of road pre-tunnels: A methodology to assess the luminance on the pavement - Part I. Tunnelling and Underground Space Technology 73, 37-47.

Cantisani, G., D'Andrea, A., Moretti, L., 2018b. Natural lighting of road pre-tunnels: A methodology to assess the luminance on the pavement - Part II. Tunnelling and Underground Space Technology 73, 170-178.

Cantisani, G., Di Mascio, P., Moretti, L., 2018c. Comparative Life Cycle Assessment of Lighting Systems and Road Pavements in an Italian Twin-Tube Road Tunnel. Sustainability 10.

CIE (Commission Internationale de l’Eclairage), 2004. Guide for the lighting of road tunnels and underpasses, CIE Publication, Vienna, Austria.

DIAL, 2020. DIALux evo software (Version 9.2) [Computer Software]. https://www.dialux.com/en-GB/download

Domenichini, L., La Torre, F., Vangi, D., Virga, A., Branzi, V., 2017. Influence of the lighting system on the driver's behavior in road tunnels: A driving simulator study. Journal of Transportation Safety & Security 9, 216-238.

Dong, L.L., Qin, G., Chen, Y., Shang, X.F., Xu, W.H., 2020. Impact of the Spectra of LED Sources on the Light Adaptation in Tunnel Exit. Spectroscopy and Spectral Analysis 40, 1044-1050.

Du, Z.G., Yu, X.Y., Xiang, Y.M., Xu, W.W., 2018. Research on Light Environment Optimization of Highway Tunnel Based on Traffic Accident Prevention. Journal of Wuhan University of Technology(Transportation Science & Engineering) 42, 715-719.

Gil-Martin, L.M., Gomez-Guzman, A., Pena-Garcia, A., 2015. Use of diffusers materials to improve the homogeneity of sunlight under pergolas installed in road tunnels portals for energy savings. Tunnelling and Underground Space Technology 48, 123-128.

He, S.Y., Liang, B., Tahkamo, L., Maksimainen, M., Halonen, L., 2020. The influences of tunnel lighting environment on drivers' peripheral visual performance during transient adaptation. Displays 64.

He, S.Y., Tahkamo, L., Maksimainen, M., Liang, B., Pan, G.B., Halonen, L., 2017. Effects of transient adaptation on drivers' visual performance in road tunnel lighting. Tunnelling and Underground Space Technology 70, 42-54.

Heydarian, A., Becerik-Gerber, B., 2017. Use of immersive virtual environments for occupant behaviour monitoring and data collection. Journal of Building Performance Simulation 10, 484-498.

Hu, J.B., Guo, D., Zhang, X.Q., 2013. Research on Tunnel Interior Zone Luminance Evaluation Method and its Application, in: Kao, J.C.M., Sung, W.P., Chen, R. (Eds.), Materials, Transportation and Environmental Engineering, Pts 1 and 2, pp. 929-934.

Kosmyna, N., Maes, P., 2019. AttentivU: An EEG-Based Closed-Loop Biofeedback System for Real-Time Monitoring and Improvement of Engagement for Personalized Learning. Sensors 19.

Leitao, S., Pires, E.S., de Moura Oliveira, P., 2009. Road tunnels lighting using genetic algorithms, 2009 15th International Conference on Intelligent System Applications to Power Systems. IEEE, pp. 1-6.

Li, X.J., Ling, J.X., Shen, Y., Lu, T., Feng, S.Z., Zhu, H.H., 2021. The impact of CCT on driving safety in the normal and accident situation: A VR-based experimental study. Advanced Engineering Informatics 50.

Liang, B., He, S., Tahkamo, L., Tetri, E., Cui, L., Dangol, R., Halonen, L., 2020. Lighting for road tunnels: The influence of CCT of light sources on reaction time. Displays 61.

Liang, B., Pan, G.B., Pi, Y.H., Li, W.Y., 2012. Energy-saving experimental study on reflective material auxiliary tunnel lighting based on visual effect, Global Conference on Civil, Structural and Environmental Engineering / 3rd International Symp on Multi-field Coupling Theory of Rock and Soil Media and its Applications, China Three Gorges Univ, Yichang, PEOPLES R CHINA, pp. 1193-+.

Loomis, J.M., Blascovich, J.J., Beall, A.C., 1999. Immersive virtual environment technology as a basic research tool in psychology. Behavior Research Methods Instruments & Computers 31, 557-564.

Lu, T., Wu, W., Li, T.C., Shen, Y., 2021. Effect of Continuous anti-glare guiding light band along curbs on light environment in urban tunnels. Modern Tunnelling Technology 58, 81-88. (in Chinese)

Ministry of Transport of the People’s Republic of China, 2014. Guidelines for Design of Lighting of Highway Tunnels, JTG/T D70/2-01-2014. China Communications

Press Co., Ltd., Beijing.

Moretti, L., Cantisani, G., Di Mascio, P., 2016. Management of road tunnels: Construction, maintenance and lighting costs. Tunnelling and Underground Space Technology 51, 84-89.

Muhlberger, A., Bulthoff, H.H., Wiedemann, G., Pauli, P., 2007. Virtual reality for the psychophysiological assessment of phobic fear: responses during virtual tunnel driving. Psychological Assessment 19, 340-346.

O'Donell, B.M., Colombo, E.M., Boyce, P.R., 2011. Colour information improves relative visual performance. Lighting Research & Technology 43, 423-438.

Pena-Garcia, A., 2018. The impact of lighting on drivers well-being and safety in very long underground roads: New challenges for new infrastructures. Tunnelling and Underground Space Technology 80, 38-43.

Pena-Garcia, A., 2022. Sustainable tunnel lighting: One decade of proposals, advances and open points. Tunnelling and Underground Space Technology 119.

Pervez, A., Huang, H., Han, C., Wang, J., Li, Y., 2020. Revisiting freeway single tunnel crash characteristics analysis: A six-zone analytic approach. Accident Analysis and Prevention 142.

Shen, Y., Ling, J.X., Li, T.C., Zhou, L., Feng, S.Z., Zhu, H.H., 2022. Diffuse reflection-based lighting calculation model and particle swarm optimization algorithm for road tunnels. Tunnelling and Underground Space Technology 124.

Wang, Y.G., Wang, L.J., Wang, C., Zhao, Y.D., 2016. How eye movement and driving performance vary before, during, and after entering a long expressway tunnel: considering the differences of novice and experienced drivers under daytime and nighttime conditions. Springerplus 5.

Zhao, J.D., Feng, Y.Z., Yang, C., 2021. Intelligent control and energy saving evaluation of highway tunnel lighting: Based on three-dimensional simulation and long short-term memory optimization algorithm. Tunnelling and Underground Space Technology 109.

Zhao, X., Liu, Q., Li, H., Qi, J., Dong, W., Ju, Y., 2022. Evaluation of the effect of decorated sidewall in tunnels based on driving behavior characteristics. Tunnelling and Underground Space Technology 127, 104591.