Study on the Simulation Experiment of Light Transmittance under Tunnel Smoke Environment

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Abstract: Tunnel smoke makes driving environment worse and interferes the procedure of the driver's visual cognition. Nowadays, tunnel lighting design method in China failed to consider the status of tunnel air. It has met a lot of problems that doing experiments of measuring the characters of illuminants and the visual cognition of drivers in tunnel, such as low security and unrepeatability. This experiment aims to simulate the environment with different concentration of smoke in the tunnel and measure the transparency of illuminants with different color temperature by using similarity model. By drawing fitting lines of different smoke concentration and different color temperature and comparing them with the lines of Lambert-beer Law, it proved the similarity of weakening light between smoke and the water mixed with ink. The result is capable to provide indoor references of illumination designing considering the smoke environment in tunnels.

Keywords: Tunnel Smoke, Smoke Concentration, Light Transmittance, Color Temperature, Simulation Experiment

1. INTRODUCTION

By the end of 2006, there are over 4100 highway tunnels, included 60 road tunnels more than 3km, 14 tunnels more than 5km and one tunnel more than 10km (Yan Guide, 2008.). Highway tunnel is a closed space, with problems such as limited traffic space, inadequate ventilation, noisy environment and brightness disparity inside and outside the tunnel, which result in traffic accidents in the tunnel and caused unimaginable consequences (Wang Shaofei, Chen Jianzhong, Tu Yun. 2009). It is important to protect the unimpeded traffic and security of the tunnel during the stages of tunnel design, operation and management. It has given the amount of ventilation and lighting design calculation methods in the Specifications for Design of Ventilation and Lighting of Highway Tunnel (JTJ026.1-1999). In recent years with substantial increased traffic in some mountain tunnels, especially in some long tunnels with large longitudinal slope, the increasing smoke emissions can produce serious interference to the drivers' visual when ventilation system is difficult to dissipate smoke quickly. Now we usually use the method of increasing the amount of ventilation and improving lighting levels to dilute tunnel smoke concentration in the current tunnel operations management in order to provide the driver better driving visual environment. But consequently the increasing ventilation and lighting costs become a huge burden of operation company, then the tunnel ventilation energy-saving lighting design become inevitable (Han Zhi, 2010). Determination of characteristics of the light source under tunnel smoke environment can provide a useful reference for the tunnel ventilation and lighting design.

2. TUNNEL SMOKE PROBLEM AND TUNNEL LIGHTING

2.1 The Ingredients of Major Pollutants and its Hazards of Tunnel Smoke

Tunnel smoke mainly includes vehicle emissions (especially large heavy vehicles) and the dust caused by the passing vehicles. The exhaust emissions of vehicles is a mixture of gas, liquid and solid particles, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx) and particulate matter (Carbon particles, heavy metal oxides such as lead oxides and soot, etc.) (Yan Guimei, 2008.). Wherein, CO, HC, NOx mainly generated by gasoline engine and black carbon particles is mainly produced by diesel engine.

Carbon monoxide (CO) is colorless and odorless generated by incomplete combustion of gasoline in the internal combustion engine. CO combines with hemoglobin more easily than oxygen in the human body, which making the content of oxygen in the blood inadequate, resulting in the body lack of oxygen, causing headaches, dizziness, vomiting, and other symptoms of poisoning, severely shock or even death. The carbon particles are the product of incomplete combustion of diesel engine (IARC, 1989), can be suspended in the air for some time, and reduce the visibility in the tunnel and interfere the drivers' visual tasks because of the effects of light refraction and scattering. The soot also contains a small amount of acetaldehyde, which has a special smell and results in dizziness, nausea and other symptoms.

2.2 Design Concentration of Tunnel Smoke

In order to describe the ability of light through the air in highway tunnel, E and E_0 respectively represent the luminance of the same light after passing 100m polluted air and clean air, then the transmittance through 100m air is (Gu Ming, 2009):

$$\tau_{100} = \frac{E}{E_0} \tag{1}$$

Where,

E_0: luminance after passing 100m in clean air,

E : luminance of the same light after passing 100m in polluted air.

PIARC proposed requirements of these indicators, if the traveling speed V = 40km/h, then τ_{100}=0.4，if V=60km/h，then τ_{100}=0.48，if V=80km/h， then τ_{100}=0.6.

In China the smoke concentration K is defined and calculated as follows in the Specifications for Design of Ventilation and Lighting of Highway Tunnel (JTJ026.1-1999):

$$k = -\frac{\ln \tau_{100}}{L} \tag{2}$$

The specification also provides the value of k as shown in Table 1:

Table 1. Smoke design concentration C

Driving speed（km/h）	100	80	60	40
C(m^{-1})	0.0065	0.0070	0.0075	0.0090

2.3 Tunnel Lighting Environment

Generally tunnel lighting level is measured by the average surface brightness, uniformity and glare level. Tunnel lighting design is classified in accordance with the length and importance of the tunnel, including entry section, transition section, the middle section and export section. But this lighting design method does not consider the effect of tunnel smoke interference.

The rule of transmission of light in the medium of air complies with the Lambert-Beer law, i.e. the intensity of light is reduced along with the increase in the transmission distance or increase of air medium extinction coefficient. The light intensity attenuation in the smoke can be described by Lambert-Beer law as follow (Feng Jiqing, 2006):

$$I_t = I_0 \exp(-\int_0^l \sigma(\lambda) dl) \tag{3}$$

Where,

I_0 : initial light intensity,

I_t : remaining light intensity,

$\sigma(\lambda)$: extinction coefficient, and

L : transmission distance.

If T represents the transmittance, then the above formula becomes:

$$T = \frac{I_T}{I_0} = \exp(-\int_0^L \sigma(\lambda) dl) \tag{4}$$

As can be seen from the formula, the transmittance of light is related to the wavelength of light (or light temperature), smoke extinction coefficient along the optical path.

3. LIGHT TRANSMITTANCE EXPERIMENT BASED ON SIMILAR SIMULATION METHOD

3.1 The Experimental Design of Light Transmittance

The way to solve the tunnel smog problem can be divided into two stages. The first is the tunnel design stage, including the tunnel line selection, profile design, ventilation system design. The second is the operational stage, including pollutant monitoring and ventilation control, equipment maintenance. But ventilation design and lighting design are designed separately. It will improve the tunnel driving vision environment that considering smoke affect in lighting design stage to choose a suitable light source.

Currently, due to the limitations of the experimental conditions, lighting characteristic measurement of the light source of the smoke tunnel experiment in the field is difficult for the following reasons:

(1) The experimental site is difficult to select. To achieve the simulation of the smoke-filled environment, and avoid affecting the normal operation of the transportation system, the only choice is doing the experiment in the tunnels which are under construction or completed but is not yet open for traffic;

(2) It is difficult to control the experimental conditions. As an important factor in the simulation, the state, composition and concentration of smoke are difficult to control;

(3) Security of the Experiment is too low. There are a lot of security risks when driving in high concentration of smoke, because the smoke has a serious impact on the driving vision,

(4) The cost of the experimental is high. The cost of closing traffic in tunnel is huge to do this driving experiment in smoke environment in tunnel.

Therefore, it is necessary to doing this experiment about light transmittance in smoke-filled environment of the tunnel by using simulation method in the laboratory. Some research about Indoor smoke simulation previously has been studied that smoke can be produced by chemical or physical methods, such as Song Zhen in the on-site detect smoke metering technology research, which choosing a stage aerosols as fuming smoke source (Song Zhen, Yu Guangzhi, Yong Yu, 2011). These methods meet the same problem exists in field experiments that it is difficult to control the dilution of smoke concentration and dissipating speed. This study use a similar model to simulate the different smoke concentration in the environment in the tunnel by the method of adding quantitative ink into purified water to simulate smoke environment in the tunnel. And then the characteristics of light source were measured. In the last the relation of light transmittance, different smoke concentrations and different color temperature of the light source is got by contrasting the indoor simulation fitting curve and Lambert - Beer's law curve to examine the effect of the attenuation of light in water mixed with ink and in smoke.

3.2 Experimental Apparatus and Materials

The XYC-1 digital colorimeter, 10cm * 10cm * 50cm glass tank, 12 kinds of LED light source (color temperature are shown in Table 2), DC power supply (voltage and current controlled), black ink.

Table 2. Values of color temperature of 12 different light source

light source No.	1	2	3	4	5	6
color temperature (K)	3554	3744	3913	4071	4522	4649
light source No.	7	8	9	10	11	12
color temperature (K)	4871	4768	5406	5318	5875	6279

3.3 Light Transmittance Experiment

The experimental device is laid out and fixed. Plus 3500ml distilled water into the glass tank, adjust the supply voltage to 9V and remain unchanged. Take ink 1ml, added to 200ml of distilled water, and dubbed in a concentration of 5% of the ink dilution. Add 5ml dilution to the glass tank per time to make 5 different concentrations of water ink (concentration shown in Table 3). Measure the luminance of 12 different color temperature light source passing through the five different ink dilution and record. The experimental apparatus is shown in Figure 1.

Table 3. Values of the concentration of 5 different ink density (volume ratio)

Concentration No.	1	2	3	4	5
Concentration（1e-6）	7.14	14.24	21.34	28.41	35.46

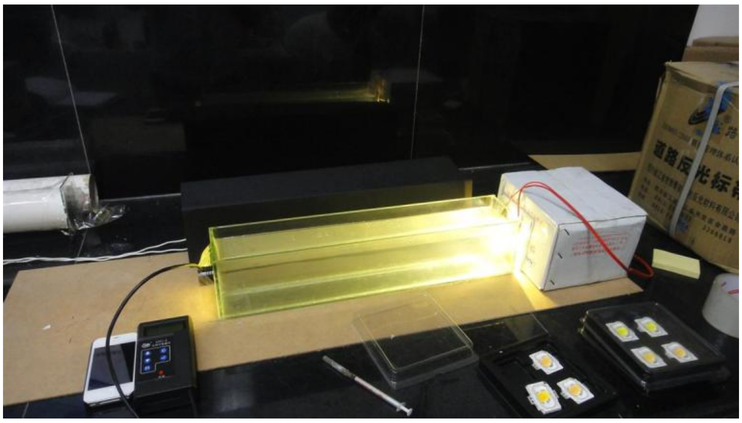

Figure 1. Experimental device

4 EXPERIMENTAL DATA ANALYSIS

4.1 Transmittance Calculations and Data Fitting

Data preprocessing steps:

(1) Dividing illuminance Ei in which added i ml ink by illuminance E0 in distilled water, getting the transmittance T.

(2) Fitting the data by Origin software and the fitting result for the F-test. Concentration C and color temperature K as the independent variable and transmittance T as the dependent variable, T-C function and T-K function were fitted with exponential and logarithmic functions.

4.2 The Fitting Results of Transmittance (T) and Concentration (C)

The fitting results of transmittance (T) and concentration (C) is shown in Figure 2 (No.1, No.4, No.7, No.10 and No.12 light source for representative).

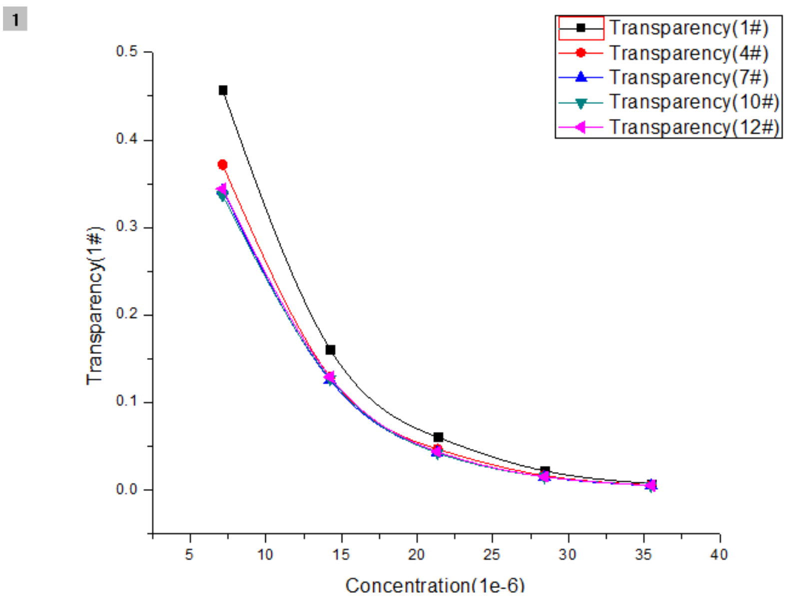

Figure 2. T-C fitting curve of 5 different lamps

As can be seen from Figure 2, the fitting effect is very good, and with the increase of the color temperature of the light source, the transmittance shows a decreasing trend.

The relationship between the light transmittance T and the concentration C of the 12 different color temperature light source is in accordance with the exponential function fitting in the form of $y = y_0 + Ae^{-x/t}$. The R-square average 0.9998 is much larger than 0.85, and all of the R-square values are greater than 0.85, this means explanatory power the independent variables on the dependent variable (transmittance) is very strong.

The orders of magnitude of Prob> F value is less than 1e-4 after F test, is much smaller than 0.05, the possibility of rejecting the null hypothesis is very large, this means the significance of the function is very good.

4.3 The Fitting Results of Transmittance (T) and Color Temperature (K)

The relationship of the transmittance (T) and color temperature (K) under different concentrations can be shown in Figure 3.

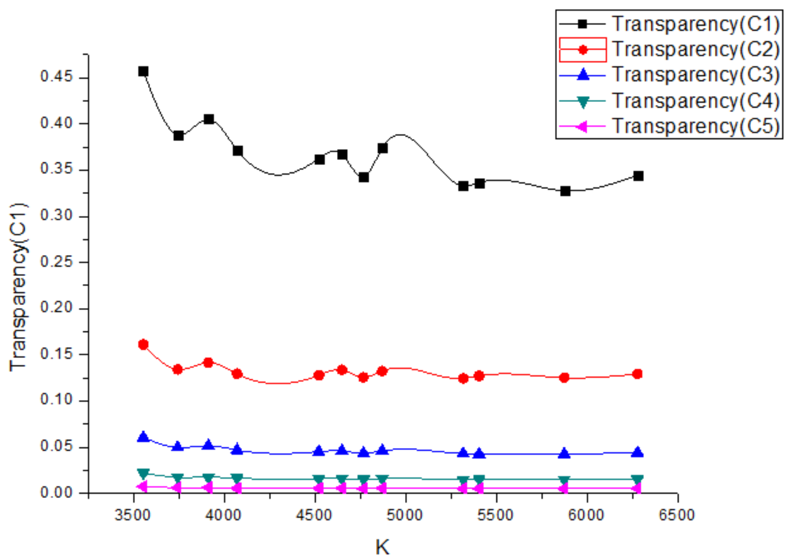

Figure 3. Relationship of the transmittance (T) and color temperature (K) under different concentrations

As can be seen from Figure 3, with the increase of color temperature K and the concentration C, transmittance T shows a decreasing trend. T-K curve fitting under different concentrations can be shown in figure 4(take No.3 concentration for example).

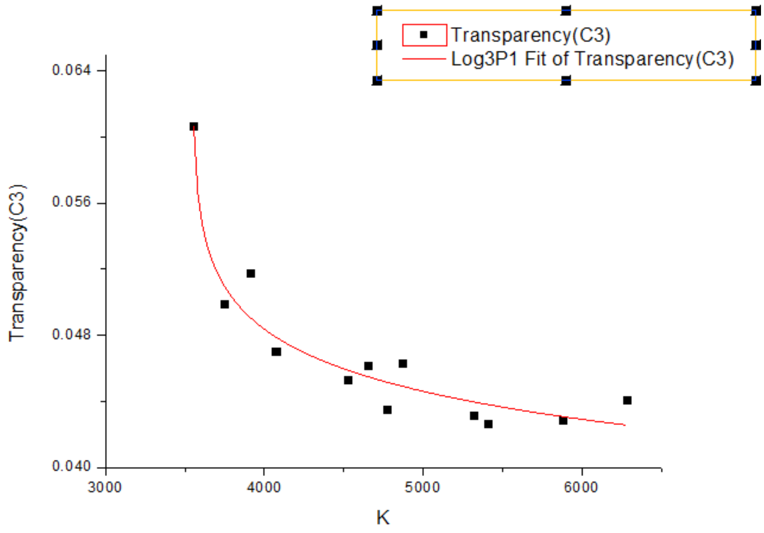

Figure 4. T-K curve fitting under the No.3 concentration

The fitting results of T-K fitting under No.3 concentration shows that the R-square value is 0.91998, means for y the explanatory power of the independent variable is very strong. Prob> F test shows that F value is 4.36318E-14, far smaller than 0.05, the possibility of rejecting the null hypothesis is very great, very good equation significantly.

Through the fitting, the five different concentrations of light transmittance (illuminance) - Color relations in accordance with the average of the R-square fitting in the form of a logarithmic function of 0.89982 greater than 0.85, and the addition all of the R-square of the concentration of 2 outer values greater than 0.85, the explanatory power of the independent variable y is very strong, fitting very good.

Prob> F test F value of orders of magnitude less than 1e-13, far less than 0.05, reject the null hypothesis, the possibility is very large, this means the significance of the function is very good.

5 CONCLUSION

This experiment is a sample method of using of different ink concentrations to simulated smoke environment inside the tunnel, and measuring the transmittance of the different color temperatures of the LED light source and then calculating transmittance T. Exponential relationship of $y = y_0 + Ae^{-x/t}$ between transmittance and concentration, and logarithmic relationship of $y = a - b\ln(x + c)$ between transmittance and color temperature were founded. The results of R-square and F test fitting verified the accuracy of the fit. The results also show that the relationship between transmittance T and the concentration C is similar to the form of the Lambert-Beer law. It verifies that the properties of the light source passing through the ink environment and tunnel with a smoke-filled environment are similarity. This experiment provides some data for further tunnel smoke indoor simulation experiments and field experiments.

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