Research on Safety Evaluation Method of Tunnel Visual Environment

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Abstract: Starting from the driver’s visual features, safety evaluation indicators and methods of tunnel visual environment are proposed against the tunnel visual environmental characteristics, providing scientific guidance for special lighting environment in the tunnel to increase visual stimulation, transforming previous subjective evaluation into quantitative evaluation and thus improving tunnel traffic safety level effectively. The method can also be extended to the safety evaluation of other scenarios such as tunnel decoration and light color temperature.

1. Introduction

Human visual comfort is of great significance to traffic safety. However, as the driver drives a vehicle for a long time in closed, tedious, single tunnel environment, special tunnel visual environment will have physiological and psychological effects on the driver, which in turn affects the reaction behavior and perception of environmental information. Especially for driving in long or extra-long tunnel, due to long-time driving inside the tunnel, the longer effect tunnel visual environment has on physiology and psychology, and the more prone the driver is to fatigue and cognitive errors, thus affecting driving safety in tunnel. As for this, in recent years, special light strips increasing visual stimulation have been proposed for improving driver's visual effects, reduce driving fatigue caused by monotony, and improve driving safety and comfort. However, its implementation effect can only rely on subjective evaluation, and it is difficult to conduct quantitative analysis due to lack of specific evaluation indicators and methods. Therefore, it is necessary to carry out research on safety evaluation of tunnel visual environment, so as to provide scientific guidance for tunnel special light environment construction.

2. Visual Environmental Characteristics of Tunnel

As a special structure of highway, the tunnel is of tubular structure, which makes its space environment cramped, with low visibility and intervisibility, so that the driver will obviously feel wall effect after entering the tunnel, full of certain sense of oppression and fear. When a vehicle passes, the driver shall be subject to light and dark adaptation in his vision, causing visual & psychological barriers and affecting driving behaviors. Specifically, there are the following visual environment characteristics:
1) There are great differences in internal and external brightness at the tunnel portal. During daytime hours, background brightness outside the tunnel portal is extremely high, while the brightness of electric lighting cannot completely replace the brightness outside the portal, thus presenting effects of “black hole” and “black box”.

2) There is visual adaptation hysteresis at the tunnel entrance. The visual adaptation lag caused by large differences between tunnel interior and exterior as well as rapid brightness changes makes the driver's vision unable to adapt to the brightness environment in the tunnel quickly. It will take some time to see the tunnel interior clearly.

3) The middle section of tunnel has low brightness and low brightness uniformity. The brightness of basic lighting in the middle section of tunnel is much lower than that outside the tunnel in daytime. Meanwhile, affected by automobile exhaust in the tunnel, visibility in the tunnel is low, which intensifies low lighting brightness and low uniformity inside the tunnel, affecting the driver's visual judgment.

4) There is “white hole” effect at the tunnel exit. Contrary to the "black hole" effect at the tunnel entrance, light and dark adaptation is needed at the tunnel exit due to low brightness inside the tunnel and high brightness outside the tunnel in daytime, affecting the driver’s visual comfort and thus affecting driving safety.

3. Analysis on Driver's Visual Features

3.1. Dynamic visual features
When the driver observes external things in the state of motion, visual features are significantly different from those under state of rest, mainly reflecting the following:

1) Attention is improved as speed increases. As the speed increases, the driver's psychological stress and concentration also increase.

2) Attention focus moves away with increasing speed. When the vehicle speed increases and the driver's attention focus moves away, far enough front road conditions shall be observed so as to take evasive actions if necessary.

3) The peripheral field of vision narrows down with increasing speed. When the driving speed is gradually increased, the driver is less likely to turn his head and attention is drawn to the lane. At this time, with the line of sight concentrated, fixation point gradually moves away and the field of vision gradually narrows down, forming the so-called "tunnel vision", so the range of driver's space recognition narrows down.

4) The foreground details gradually disappear as the speed increases. The faster the speed is, the faster the scene in the foreground moves backward relative to each other, and the more blurred the scene becomes. Therefore, the driver must look further to get a clear image.

5) The spatial awareness decreases as speed increases. With the gradual increase of driving speed, the range of driver's visual space becomes smaller, and the driver's spatial awareness will become blunted, especially on a flat road surface.

3.2. Features of light and dark adaptation
Visual adaptation is a sensory change caused by the continued action of stimuli. If the eye shifts from a bright light environment to a low-light environment, it becomes less sensitive, and after a period of time in low light environment, it becomes more receptive. This is called visual adaptation. For people, there is a process of adaptation to different brightness environment. The sudden movement from the light to the darkness is called dark adaptation, and the sudden movement from the darkness to the light is called light adaptation. The eye's adaptation to light changes is achieved through the pupil, but it cannot adapt immediately to sudden changes in light and darkness.

1) Dark adaptation: In case of sudden changes in light and darkness, there will be a short-term process of visual adaptation needed for eyes. The adaptation process of shifting from the light to the darkness is called “dark adaptation”. Dark adaptation generally takes about 15min.
2) Light adaptation: A process of short-term adaptation from the darkness to the light is called light adaptation. With short time, light adaptation takes a few seconds to a minute, usually no more than 5 minutes.

3) Glare: Glare is a phenomenon of visual dysfunction caused by sudden changes in light intensity. The visual effect of glare is mainly to destroy dark adaptation, reduce visual efficiency, cause visual disorder and distract attention.

3.3. Black and white psychology
In daily life, we are used to seeing things in black and white, so we pay less attention to this color matching. This is also the case with other color matching, because according to psychological research, repeat effect of any one stimulus is strongest at 10-12th time, after which no significant increase occurs.

3.4. Stroboscopic effect
The stroboscopic effect is a phenomenon in which the observed motion of an object differs from its actual motion at a certain frequency of light irradiation. The human eye can percept periodic changes of more than certain time limit (0.1s), and more than 60 flashes in 1s are completely imperceptible to man; For 20 flashes in 1s, the eye will percept flash; 10 flashes in 1s will cause eye strain and make people feel irritated.

3.5. Visual illusion
From an optical point of view, when a person observes an object, the light not only causes the nervous system to react but also has an influence of expanding the range laterally because the retina is stimulated by light, causing differences between visual impression and the actual size & shape of object. This is called visual illusion. Generally speaking, visual illusion is an inevitable visual experience that people have discovered in long-term practice. It is an inevitable erroneous visual image of people generated psychologically or physiologically under combined action of environment and conditions.

4. Safety Evaluation Indicators and Methods for Tunnel Visual Environment
Based on the analysis of tunnel visual environmental characteristics and the driver's visual features, the main factors affecting driving safety are human vision and its psychological and physiological reactions. Therefore, the eye movement-related indicators are selected from the visual indicators to represent the active or passive allocation of visual attention resources, and more useful or attractive information is selected. The physiological indicators such as heart rate, ECG, and GSR are selected to indirectly reflect the driver's psychological states.

4.1. Analysis on safety evaluation indicators for tunnel visual environment
Eye movement tracking is to track eye movements by measuring the position of eye fixation or the movement of the eyeball relative to the head. Testing the driver's driving behaviors using an eye tracker allows recording the driver's viewing (and non-viewing) position and time, and tracking and recording the process of gaze and glance to completely judge where the eye browses and stays, which will help to study the driver's physiological states in a long tunnel, including percentage of fixation time, average fixation time, saccade size and blink rate in details.

1) Percentage of fixation time, average fixation time: Gaze falls into fixation, saccade and blink as per people's visual behaviors. Percentage of fixation time is the percentage of total fixation time in total time of all visual behaviors, showing attention focusing. The average fixation time is the total time of fixation behavior divided by the total number of fixation behaviors, showing duration of attention to target object or area.

2) Saccade size: Saccade size is the conversion angle of saccade behavior between two fixation behaviors, showing amplitude of a driver's eye rotation.
3) Blink rate: The blink rate is the ratio of the driver's blinking time to the total time, showing the driver's cognitive load level (that is to say, the driver has energy or time to watch the scenery or not).

Conductive physiological signal is an important physiological parameter indicator widely used in fields such as physiology, psychology, human factors engineering and neuroscience. The multi-conductive physiological recorder can completely collect and record relevant information to help us analyze the driver’s physiological states, including heart rate, ECG and GSR in details.

1) ECG: ECG is the change of the bioelectricity produced by the heart in each cardiac cycle. Generally, the time interval between two peaks, i.e. RR interval is taken in data analysis.

2) Heart rate: Heart rate is the frequency of a person's heartbeat. The adult’s heart rate is generally about 70 beats/min. In the event of tension, fear, excitement and agitation, etc., the heart rate will increase.

3) GSR: GSR is a skin conductivity indicator. External stimuli can cause rather strong skin reactions, which can be measured by skin resistance or skin conductivity.

By collecting the driver's eye movement behavior parameters and physiological indicators using an eye tracker and a physiological recorder, we can establish the relationship between the visual environment in the tunnel and the driver's visual behavior characteristics as well as physiological responses, so as to further determine safety evaluation standards and methods for tunnel visual environment, scientifically guide the setting of special light environment in the tunnel, and improve the tunnel traffic safety level.

4.2. Safety evaluation methods for tunnel visual environment

As for specific evaluation method, it is recommended to use field evaluation method of real vehicle. The equipment shall be eye tracker and multi-channel physiological instrument (including GSR test and ECG test modules). The test vehicles may be various types of vehicles, e.g. car, off-road vehicle, truck to increase the breadth and effectiveness of evaluation. In order to reflect the driver's real visual behaviors and psychological states in specific driving operations, the driver is allowed to drive the vehicle freely without strict restrictions on his driving speed. Evaluation shall be conducted when fewer vehicles are running on the road. At this time, the traffic flow is basically free flow state, which is also easy to remove the test data of car-following road sections in later data processing.

5. Evaluation Data Results and Analysis Cases

5.1. Analysis on eye movement data

Taking a special light strip installed in a highway tunnel in China as an example, the method of multi-vehicle and multi-driver field driving evaluation is adopted. Collect eye movement data by an eye tracker and generate a scan path graph. The graph can continuously display information such as the position of fixation point and each fixation time point by point. In Fig. 1, the driver's fixation points are not only distributed in the pavement area directly in front of vehicle traveling direction and car area, but also partially in the special light environment area of vault. It shows that after the special light strips are provided, the driver's fixation point changes significantly, and the driver's viewpoints are dispersedly distributed, with increasing attention to the vault.
Collect eye movement data and generate a heat map. The map displays the dynamic changes in the time and position of fixation point with warm colors. That is to say, the closer the color is to that in bottom right of color bar, the longer the eyes stay in the area. In Fig. 2, the driver's fixation points are mainly distributed in the pavement area directly in front, with gaze on the special light environment area of vault. It shows that after the special light strips are provided, the driver's fixation point changes significantly, with increasing attention to the vault.

Collect eye movement data by an eye tracker and generate a screen position fixation infomap. This map divides the screen into a certain number of small squares. The closer the color of each square is to that in bottom right of color bar or the larger the value in square is, the longer the eyes stay in the area, as shown in the data in Fig. 3.
Collect eye movement data by an eye tracker and generate key performance indicators to obtain indicator parameters of each area. Fig. 4 shows that after the special light strips are provided, the driver's range of fixation becomes wider, with increasing attention to the vault and the driver's attention caught. However, the driver still focuses on obtaining information about the pavement ahead required for driving, and does not pay much attention to the details of special light environment.

Collect eye movement data and generate AOI sequence diagram and time bar chart. Each solid square is a fixation point, and different colors represent fixation points in different areas of interest. From this, the time and order of fixation point and the percentage of stay duration of fixation point in each interest area in current time interval can be obtained. Figs. 5 and 6 show that after the special light strips are provided, the driver's fixation points are distributed in the pavement area directly in front in most of time, with gaze on the special light environment area of vault.
Figure 5. Key AOI sequence diagram

Figure 6. Key time bar chart

5.2. Analysis on physiological signal data

1) ECG data

According to ECG data, compared to that in ordinary road section, the driver's heart rate does not change significantly in the special light environment section, and the ECG data are relatively stable.
2) GSR data

According to the measured data, the driver’s GSR was enhanced significantly in special light environment, showing that the driver's psychological load increases in the special light environment, which is equivalent to receiving a stimulus signal. In addition, the driver's sense of excitement was increased, helping to relieve the driver’s visual fatigue occurring in a long tunnel. The stimulation gradually trends to stability after the driver drives through the special light environment section, and will not cause the driver to be nervous due to long-term stimulus.

6. Conclusions

The determination of safety evaluation technologies and methods for tunnel visual environment and analysis & study on the measured data can scientifically guide the setting of special light environment in the tunnel. The determination of this method abandons the previous static subjective qualitative judgment method. This method starts from the driver’s vision and psychology to conduct quantitative evaluation on tunnel visual environment safety, making the visual experience inside the tunnel more safe and comfortable, and effectively improving the traffic safety level of tunnel. The method can also be extended to the safety evaluation of other scenarios such as tunnel decoration and light color temperature, and is worthy of further promotion and application.
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