Research on key parameters of the Fatigue Arousal Zone in extra-long tunnels based on natural driving experiments

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Abstract

To effectively mitigate the short-term fatigue effects of driving in extra-long tunnels, this study conducted natural driving experiments in five extra-long tunnels of varying lengths and tunnel group sections. Utilizing data obtained from natural driving fatigue experiments, this study identified perclos P80, variable coefficient of pupil diameter, and acceleration as fatigue sensitivity indicators, determined through significance tests of difference and correlation analysis. This study employed an ordered multi-class Logistic model to investigate the factors that influence driving fatigue in extra-long tunnels. The most significant variable in the model was perclos P80, which served as an indicator for classifying and identifying fatigue levels in extra-long tunnels. Following this, a dimensionless quantitative metric, the Fatigue Driving Degree, was formulated, and the Threshold of Driving Fatigue was established. Using the quantitative framework for driving fatigue, this paper standardized the definition of the fatigue arousal zone in extra-long tunnels. The study analyzed the operational principles and validated the key parameters of the fatigue arousal zone in extra-long tunnels. These parameters encompass the placement location, length, form, and traffic induction design of the fatigue arousal zone. The research findings can serve as a theoretical reference for the development of fatigue arousal technology in extra-long highway tunnels in China.

Keywords: ITS; Traffic Safety; Optimization; Risk; Transportation Planning


Introduction

A highway tunnel is classified as an extra-long tunnel when its length surpasses 3 km[1]. Analysis of comprehensive tunnel traffic accident statistics reveals a clear correlation between the likelihood of traffic accidents and tunnel length. Long and extra-long tunnels experience significantly more accidents, both in terms of frequency and severity, compared to short and medium tunnels. Additionally, the longer the midsection of an extra-long tunnel, the greater the likelihood of traffic accidents[2]. When traffic accidents show the characteristics of agglomeration in some places or sections of the road (especially a specific type of accident), it means that there is a certain connection between these accidents and the road[3]. Primary factors contributing to traffic accidents in tunnel sections involve drivers experiencing visual illusions caused by the 'black and white hole' effect at tunnel entrances and exits[4], as well as a lack of stimulation in the midsection of the tunnel resulting in driving fatigue[5]. Sagberg[6] investigated the development of driving fatigue in distinct roadway setups and differing driving circumstances. The findings revealed that small sensory stimuli from the traffic environment, low traffic volume, and a single linear roadway segment contributed to driver fatigue. Fatigue experienced by drivers can be categorized into long-term and short-term fatigue[7]. Within extra-long tunnels, the enclosed environment, limited illumination in the middle section, absence of scenery, and a consistent color palette cause drivers to concentrate primarily on the road ahead, leading to short-term fatigue and restlessness over a brief period. With the widespread construction of extra-long highway tunnels in China, the rising frequency of traffic accidents attributed to driving fatigue induced by the monotonous tunnel environment underscores the pressing need to enhance traffic safety within these tunnels.

In an effort to combat short-term fatigue in extra-long tunnels and improve overall traffic safety, engineers from both domestic and international backgrounds have suggested widening a specific segment of the tunnel's cross-section. This segment incorporates various techniques, including painted natural landscapes, colored patterns, and colored LED strips. Unfortunately, existing regulations and engineering cases lack precise theoretical foundations and unified design methods for crucial parameters, including the location, length, and cross-sectional design of this technology. Domestic regulations[1,8] have only proposed measures to mitigate short-term fatigue through adjustments in the longitudinal and transverse profile design of extra-long tunnels and the inclusion of traffic-related facilities like reflective rings and contour marks. Unfortunately, these measures have limited effectiveness in addressing concerns related to the monotonous driving environment within extra-long tunnels. Consequently, there is a need to independently design particular sections within the middle segment of extra-long tunnels, segmenting them to minimize the impact of short-term fatigue on driving safety. Therefore, this paper...
establishes the concept of a ‘fatigue arousal zone’ and conducts research on its essential parameters using data obtained from natural driving fatigue experiments. This study introduces innovative perspectives for the application of fatigue arousal technology in extra-long tunnels.

**Review of fatigue arousal**

Presently, there is a body of theoretical research, both domestic and international, focusing on fatigue arousal technology in extra-long tunnels. Shimojo et al.\(^\text{[10]}\) conducted simulated driving experiments in the Hokkaido Nopporo Bay extra-long tunnel, suggesting that installing large distance signs every 5 to 10 km could reduce driving fatigue by providing additional traffic information. Pierre et al.\(^\text{[10]}\) conducted experiments by altering road environmental elements in various road environments to increase stimulation for drivers, suggesting that monotonous driving environments and excessively long driving times are prone to causing driving fatigue, which can be mitigated by enhancing stimulus intensity through increased landscape scale, color, shape, and other factors. Jayakumar et al.\(^\text{[11]}\) conducted research on driving fatigue in long tunnels based on electroencephalogram (EEG) data collection, suggesting that colorful tunnels can alleviate monotony, provide visual stimulation to drivers, and prevent fatigue while driving in tunnels. Ye et al.\(^\text{[12]}\) Patten & Mardh\(^\text{[13]}\), and Chen et al.\(^\text{[14]}\) have conducted comprehensive investigations on tunnel landscapes. The primary finding is that incorporating artificial landscapes within tunnels can effectively alleviate driving fatigue in monotonous environments and improve drivers’ perception of speed and distance. Building on the hypnotic effects within tunnels, Xu et al.\(^\text{[15]}\) and Qin et al.\(^\text{[16]}\) proposed a method for installing colored light strips in the middle section of tunnels. Research results indicated that when drivers pass through colored light strips, they tend to pay minimal attention to the patterns on the walls on both sides, and the fatigue-relief effect of the light strips has some limitations. Song et al.\(^\text{[17]}\), Du et al.\(^\text{[18]}\), and Luo et al.\(^\text{[19]}\) advocated the installation of unique patterns within tunnels, including inverted triangles, heart rate patterns, and rhythmic linear patterns. These patterns not only enhance drivers’ perception of space and speed but also help alleviate driving fatigue. In the realm of practical engineering cases, Kvaale & Lotsberg\(^\text{[20]}\) suggested the installation of an artificial landscape strip inside the Laerdal Tunnel in Norway. To achieve this, wash wall lights were employed to establish a predominantly blue driving environment. Likewise, the Qinling Zhongnanshan Highway Tunnel in China adopts a similar strategy with a dominant blue color scheme enhanced by purple lighting and cloud patterns, creating a simulated blue sky and white cloud effect.

Nevertheless, Kvaale & Lotsberg labeled the landscape strip in the Laerdal Tunnel as the ‘special light belt’\(^\text{[21]}\), while the Qinling Zhongnanshan Highway Tunnel in China pioneered the use of a ‘special light belt’, which they referred to as the ‘tunnel landscape belt’\(^\text{[22]}\). However, the terms ‘special light belt’ and ‘tunnel landscape belt’ are quite broad and may not be easily comprehensible to passengers and drivers, potentially leading to confusion. In contrast, the term ‘fatigue arousal zone’ directly conveys the area’s purpose and function. Furthermore, Professor Du\(^\text{[23]}\) of Wuhan University of Technology and Dr. Gao\(^\text{[24]}\) of Beijing University of Technology have frequently referenced this term, but they have not yet supplied a precise definition or comprehensive explanation. Hence, there is a need to define the fatigue arousal zone in a standardized manner, conduct research on its essential parameters, and offer a precise theoretical foundation along with a consistent setup method.

**Research gap and problems**

The majority of existing studies depend on indoor simulated driving experiments. Although these indoor tests closely replicate actual driving environments, differences in the psychological and physiological conditions of the participants may lead to disparities between test results and natural driving experiences. Additionally, a limited number of studies have employed natural driving experiments, primarily concentrating on long straight sections of open desert or grassland highways. There has been minimal investigation into driving fatigue within extra-long tunnel segments. Furthermore, the majority of existing research has concentrated on long-term fatigue resulting from time accumulation or monotonous fatigue experienced on extended straight road sections, such as monotonous grassland or desert landscapes. There is a noticeable deficiency in research on short-term fatigue within the confined spaces of tunnels. Additionally, both domestically and internationally, research on arousal techniques for extra-long tunnels has not established a precise theoretical basis or a systematic design framework. Particularly lacking are criteria for the positioning, length, and design of anti-fatigue facilities or technologies within extra-long tunnels, along with a shortage of objective quantitative data to support these aspects.

Consequently, conducting comprehensive research on the absence of key parameter design methods for fatigue arousal technology in extra-long tunnels is both essential and worthwhile. In this study, natural driving fatigue experiments were carried out in extra-long tunnels. Data collected included eye-tracking data, vehicle operational data, tunnel illumination data, and more. The study quantified the influence of the extra-long tunnel environment on driving fatigue. This research supplies valuable insights and strategies for guiding future investigations into fatigue arousal zones.

**Natural driving experimental methods**

**Experimental tunnel**

The Chongqing G69 Yinbai Expressway section extending from Wangjia Service Area to Kaizhou Interchange in Wanzhou, China, spans 120.5 km and is a dual-carriageway four-lane highway. The experimental section comprises a total of 17 tunnels, constituting 36.6% of the entire length, while the Kaizhou section exhibits a notably high tunnel proportion, reaching 55.2%. Referring to the research findings of Hu\(^\text{[24]}\), tunnels with a spacing of 250 m or less are defined as adjacent tunnels, while tunnels with spacing between 250 m and 1000 m are considered consecutive tunnels. Together, adjacent and consecutive tunnels form what is termed a ‘tunnel group’. From the perspective of drivers’ experiences, a section composed of tunnel groups can be considered as an extra-long tunnel\(^\text{[25]}\). A segment of open road is chosen as a comparative test section. Table 1 displays the details of the extra-long tunnels and tunnel groups within the experimental section.

**Experimental equipment**

The experimental vehicle of choice was the seven-seater Honda MPV car. Drivers’ eye-tracking data was collected using the Tobbi Pro Glasses 2-type eye tracker, operating at a 50 Hz
sampling frequency and a resolution of 1,280 × 960. Speedbox GPS non-contact vehicle speed sensors were employed to measure various parameters, including speed, acceleration, distance, and position of the moving vehicle, with a sampling frequency of 200 Hz. The TES-1339R illuminance meter was utilized to gather illuminance data within the tunnel, boasting a measurement range of 0.01~999,900 Lux and an accuracy of 0.01 Lux. Additional equipment encompassed a dash-cam, batteries, and more. The experimental setup is depicted in Fig. 1.

### Experimental participant

For the safety of real vehicle experiments, the approach of ‘fewer participants, multiple repetitions’, recommended by Liang et al.[28], was utilized for subject selection. Each driver was required to undergo a minimum of two tests on the experimental route. A total of 17 drivers participated in this experiment. To ensure the precision of eye-tracking data collection, all experimental drivers needed to have unaided visual acuity of 5.0 or higher and no visual impairments, including glare sensitivity or night blindness. Ten eligible participants, aged between 24 and 42, and possessing a minimum of 2 years of driving experience, were chosen. The minimum sample size for the experiment is calculated to be 14 using the formula for minimum samples. The experimental sample size in this paper meets the requirements.

### Experimental design

Owing to constraints imposed by the experimental conditions, it is not feasible to investigate driving fatigue levels across the entire 24-hr day. Monk et al.[27] indicates that between 1–3 am, 5–6 am, 7–8 am, 11 am–1 pm, 1–3 pm, and 6–7 pm, drivers are more susceptible to entering a state of fatigue. Drawing from the research conducted by Yajima et al.[28] and Lai & Craig[28] regarding the influence of human circadian rhythms on driving fatigue, two specific time intervals —namely, noon (10:00–12:00) and afternoon (13:00–15:00)— were selected for investigation. These time slots correspond to periods when drivers are more prone to experiencing fatigue due to their circadian rhythms. Furthermore, these times typically exhibit reduced traffic volumes, thereby minimizing the impact of traffic flow on fatigue during driving experiments.

Throughout the experiment, research assistants conducted subjective fatigue assessments on the participants at 10-min intervals using the Karolinska Sleepiness Scale (KSS), which complemented objective measurements. The KSS comprises a total of nine levels. According to the subjective fatigue level scale, these nine levels are categorized into three states: 1 ≤ KSS ≤ 3 for the awake state, 4 ≤ KSS ≤ 6 for the semi-fatigue state (a transitional phase before entering fatigue, still within an awake state), and 7 ≤ KSS ≤ 9 for the fatigue state (indicating formal entry into a fatigued state).[30]

### Experimental results

#### Selection of fatigue sensitivity indicator

As a result of driving fatigue, drivers experience decreased cognitive performance internally and impaired driving performance externally. Consequently, this study opts for eye movement indicators associated with cognitive performance and vehicle operating characteristics linked to driving performance as experimental parameters for conducting natural driving fatigue tests on the extra-long tunnel road section.

By combining the statistical findings from the KSS subjective scale with various eye-tracking indicators[31], including blink frequency, average blink duration, variable coefficient of pupil diameter, perclo, and average fixation duration, as well as vehicle operational state indicators[32] like speed and acceleration, a significance test of difference and correlation analysis was performed to assess their relevance to different states of fatigue. The objective was to evaluate the efficacy of these indicators in detecting driving fatigue and select fatigue sensitivity indicators.

#### Significance test of difference

Normality tests were performed on the eye-tracking data and vehicle operational data of the 10 participants in various states, including their awake state, semi-fatigue state, and fatigue

Table 1. Information of experimental tunnels.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tunnel name</th>
<th>Distance to upstream tunnel exit (m)</th>
<th>Length (m)</th>
<th>Road type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wadianzi tunnel-Tiefengshan expressway</td>
<td>–</td>
<td>13,800</td>
<td>Open road</td>
</tr>
<tr>
<td>2</td>
<td>Dashu tunnel group</td>
<td>Dashu tunnel</td>
<td>5,825</td>
<td>Tunnel group</td>
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<tr>
<td></td>
<td></td>
<td>Kuzhuba tunnel</td>
<td>320</td>
<td>Tunnel group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wangjia tunnel</td>
<td>220</td>
<td>Tunnel group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longquan tunnel</td>
<td>70</td>
<td>Tunnel group</td>
</tr>
<tr>
<td>3</td>
<td>Longjing tunnel group</td>
<td>Longjing tunnel</td>
<td>–</td>
<td>Tunnel group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Daping tunnel</td>
<td>80</td>
<td>Tunnel group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Guangchengshan tunnel</td>
<td>270</td>
<td>Tunnel group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yousha tunnel</td>
<td>322</td>
<td>Tunnel group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Xiaoling tunnel</td>
<td>112</td>
<td>Tunnel group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dongjiao tunnel</td>
<td>380</td>
<td>Tunnel group</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yanghegou tunnel</td>
<td>116</td>
<td>Tunnel group</td>
</tr>
<tr>
<td>4</td>
<td>Wadianzi tunnel</td>
<td>–</td>
<td>3,356</td>
<td>Extra-long tunnel</td>
</tr>
<tr>
<td>5</td>
<td>Tiefengshan tunnel</td>
<td>–</td>
<td>11,362</td>
<td>Extra-long tunnel</td>
</tr>
<tr>
<td>6</td>
<td>Nanshan tunnel</td>
<td>–</td>
<td>4,828</td>
<td>Extra-long tunnel</td>
</tr>
</tbody>
</table>

Fig. 1 Device used during the experiment.
state: The sample data for the variable coefficient of pupil diameter exhibited an overall normal distribution; however, the sample data for average fixation duration did not adhere to a normal distribution; Sample data for blink frequency, average blink duration, perclos P80, speed, and acceleration displayed a normal distribution in certain states but not in others. This study concludes that these indicators do not exhibit an overall normal distribution. Hence, during the significance test of difference, paired T-tests were employed for indicators conforming to a normal distribution, while paired non-parametric Wilcoxon signed-rank tests were utilized for indicators deviating from a normal distribution, as detailed in Table 2.

As per Table 2, blink frequency, perclos, variable coefficient of pupil diameter, and acceleration demonstrate noteworthy differences before and after fatigue; Nevertheless, no significant difference in average blink duration is observed between the semi-fatigue and fatigue states; Average fixation duration does not reveal significant differences before and after fatigue; Speed does not display significant differences between the awake and semi-fatigue states.

Correlation analysis

By conducting significance tests for differences, it becomes evident that certain indicator data do not exhibit significant variations before and after fatigue. Consequently, not all indicators can effectively portray the progression of fatigue. Therefore, it becomes imperative to identify the indicators with a stronger correlation to the fatigue evolution process through correlation analysis. Correlation analysis employed the Pearson correlation coefficient, and the calculated results are displayed in the heatmap presented in Fig. 2.

The correlation between the indicators increases as the area becomes redder, while an increase in negative correlation does not reveal significant differences before and after fatigue; Speed does not display significant differences between the awake and semi-fatigue states.

<table>
<thead>
<tr>
<th>Table 2. Significance test of difference.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test indicator</strong></td>
</tr>
<tr>
<td>Blink frequency</td>
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<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Average blink duration</td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Perclos P80</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Average fixation duration</td>
</tr>
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<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Variable coefficient of pupil diameter</td>
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<td></td>
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<tr>
<td>Speed</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
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<tr>
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<td></td>
</tr>
</tbody>
</table>

* indicates a significance level less than 0.05, indicating a significant difference between the two groups.
Logit (Py1) = \ln \left( \frac{\pi_1}{\pi_1 + \pi_2 + \pi_3} \right) = a_1 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_{10} x_{10} (1)

Logit (Py2) = \ln \left( \frac{\pi_1}{\pi_1 + \pi_2} \right) = a_2 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_{10} x_{10} (2)

Table 3. Summary of the analysis of each test indicator.

<table>
<thead>
<tr>
<th>Test indicator</th>
<th>Significance test of difference</th>
<th>Correlation analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blink frequency</td>
<td>Significant</td>
<td>Moderately relevant</td>
</tr>
<tr>
<td>Average blink duration</td>
<td>Insignificant</td>
<td>Irrelevant</td>
</tr>
<tr>
<td>Perclos P80</td>
<td>Significant</td>
<td>More relevant</td>
</tr>
<tr>
<td>Average fixation duration</td>
<td>Insignificant</td>
<td>Irrelevant</td>
</tr>
<tr>
<td>Variable coefficient of pupil diameter</td>
<td>Significant</td>
<td>More relevant</td>
</tr>
<tr>
<td>Speed</td>
<td>Insignificant</td>
<td>Irrelevant</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Significant</td>
<td>More relevant</td>
</tr>
</tbody>
</table>

These factors were meticulously controlled during the experimental phase. As a result, this study opts for factors including cumulative driving time, working condition driving time, tunnel length, and tunnel illuminance. The specific selection and encoding of variables are detailed in Table 4.

The model's effectiveness has been confirmed through goodness-of-fit and parallel line tests. Further analysis of the model parameters can be conducted. Based on variable selection, we establish an ordered multi-class Logistic model in this study, the dependent variable has three levels of fatigue, with corresponding probabilities \( \pi_1, \pi_2, \text{ and } \pi_3 \). The model is constructed by splitting it into two binary logistic regressions, namely (1 vs 2 + 3) and (1 + 2 vs 3). The model construction is as follows:

\[
\begin{align*}
\text{Logit } (P_{y=1}) &= \ln \left( \frac{\pi_1}{1 - \pi_1} \right) = \ln \left( \frac{\pi_1}{\pi_2 + \pi_3} \right) \\
&= -a_1 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_{10} x_{10} \\
\text{Logit } (P_{y=2}) &= \ln \left( \frac{\pi_1}{1 - \pi_1 - \pi_2} \right) = \ln \left( \frac{\pi_2 + \pi_3}{\pi_1} \right) \\
&= -a_2 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_{10} x_{10}
\end{align*}
\]

In formula (1) and (2), \( y \) is the fatigue level with values \( i (i = 1, 2, 3) \), \( x \) is the variable, \( P \) is the probability of a specific fatigue level occurring, \( a_i \) is the model intercept, and \( \beta_i \) is the model regression coefficient.

Model results

The objective behind constructing this model is to assess the extent of influence exerted by the independent variables on the dependent variable. When interpreting the model outcomes, it is crucial to focus on the impact weights of specific independent variables. Model parameters were analyzed using SPSS 22.0 software, and it was determined that acceleration in the explanatory variables did not exhibit a significant correlation with tunnel illuminance, horizontal curve CCR, or the...
null
FDD is a dimensionless metric, and the quantification model is as follows:

$$FDD_{ij} = \frac{(P_{ij} - P_i)}{P_i}$$  \hspace{2cm} (3)  

In formula (3), $FDD_{ij}$ is the fatigue driving degree of driver $i$ at driving time $j$ within the tunnel, $P_{ij}$ is the perclos P80 of driver $i$ at driving time $j$ within the tunnel, and $P_i$ is the initial perclos P80 value for the driver before entering the tunnel, which is represented by the mode.

Using formula (3), compute the FDD for the 10 participants across the five distinct working conditions (Conditions 2–6, as detailed in Table 1). Subsequently, conduct a significance test to assess differences in FDD among the participants in each condition. The results reveal that there are no notable differences in FDD among the 10 participants across each condition. This indicates that FDD can efficiently mitigate the impact of individual differences and initial fatigue. Lastly, Fig. 4 presents the variations in FDD over time for the 10 participants under varying conditions.

Upon examining the FDD change curves in Fig. 4, it is evident that the FDD trends exhibit similarities irrespective of the various lengths of the extra-long tunnel. While driving through extra-long tunnels, the FDD generally displays an ascending pattern, reaching a specific level before undergoing a gradual decline, which can be attributed to the driver’s resistance response to the onset of fatigue while driving. Nevertheless, relying solely on the FDD change curves remains inadequate for ascertaining the fluctuations in drivers’ fatigue levels during extra-long tunnel driving. Hence, there is a need to define the Threshold of Driving Fatigue (TDF) for each fatigue state. A box plot was generated to illustrate the distribution of FDD among the 10 participants, delineating upper and lower quartiles at 15% and 85%, as depicted in Fig. 5.

In the domain of traffic engineering, it is a common practice, guided by statistical principles, to establish the threshold value of a variable as the numeric value that fulfills the requirements of 85% or more of the driver sample data[37]. When the threshold value for driving fatigue can meet over 85% of driver safety, it indicates that the threshold is universally applicable. Figure 5 guides the determination of the Threshold of Driving Fatigue (TDF) for the extra-long tunnel, which is calculated to be 3.37. By adopting 50% as the threshold for the semi-fatigue state, the TDF is established at 2.01. This signifies that when a driver has spent some time driving in the tunnel and their perclos P80 has risen to 2.01 times the pre-tunnel value, the driver is classified as being in a semi-fatigue state. Upon reaching a 3.37-fold increase, it is determined that the driver has entered a state of fatigue. In this paper, the threshold signifying the onset of fatigue, denoting a semi-fatigue state, is denoted as $TDF_{1}$, while the threshold for the transition into a fatigue state is labeled as $TDF_{2}$.

### Table 6. Driving fatigue discrimination standard.

<table>
<thead>
<tr>
<th>State</th>
<th>Awake</th>
<th>Semi-Fatigue</th>
<th>Fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perclos P80 (%)</td>
<td>(0, 8)</td>
<td>[8, 17.5)</td>
<td>(17.5, ∞)</td>
</tr>
</tbody>
</table>

Key parameter design of the fatigue arousal zone

Definition and operating principles of the fatigue arousal zone

To standardize terminology, this paper defines the fatigue arousal zone within extra-long tunnels employing a purpose-oriented approach and fatigue arousal theory: The fatigue arousal zone in extra-long tunnels denotes a specific middle section within the tunnel, distinguished by a specific length. Within this zone, an array of sensory stimuli, encompassing visual, auditory, and tactile cues, is employed to expedite the driver’s return to an optimal arousal level. The objective of the fatigue arousal zone is to mitigate short-term fatigue challenges encountered by drivers in extra-long tunnels.

Drawing from the definition of the fatigue arousal zone and in alignment with the driver fatigue generation model based on arousal levels[38], this paper condenses the operational principles of the fatigue arousal zone in extra-long tunnels, as depicted in Fig. 6.
Upon the driver’s FDD reaching the threshold, it becomes imperative to promptly initiate fatigue arousal measures to restore the driver’s current arousal level within the optimal range. Consequently, the location where the driver’s FDD reaches the threshold should be regarded as the initial point for establishing the fatigue arousal zone. Utilizing TDF_1 = 2.01 to signify the semi-fatigue state and TDF_2 = 3.37 to denote the fatigue state within the extra-long tunnel, the average FDD values of the 10 participants in the five working conditions from Fig. 4 serve as the characteristic FDD values for all participants. The variations in average FDD are depicted in Fig. 7.

![Fig. 4 Variation in FDD over time under different working conditions for each participant.](image)

![Fig. 5 Distribution plot of FDD in extra-long tunnel.](image)

**Location setup of the fatigue arousal zone**

Upon the driver’s FDD reaching the threshold, it becomes imperative to promptly initiate fatigue arousal measures to restore the driver’s current arousal level within the optimal range. Consequently, the location where the driver’s FDD reaches the threshold should be regarded as the initial point for establishing the fatigue arousal zone. Utilizing TDF_1 = 2.01 to signify the semi-fatigue state and TDF_2 = 3.37 to denote the fatigue state within the extra-long tunnel, the average FDD values of the 10 participants in the five working conditions from Fig. 4 serve as the characteristic FDD values for all participants. The variations in average FDD are depicted in Fig. 7.

The change characteristics of the average FDD of the 10 drivers in Fig. 7 closely align with those of each of the 10 drivers’ FDD in Fig. 4. The fluctuation patterns of average FDD in the five working conditions are comparable. As driving distance increases within the tunnel, the driver’s fatigue level initially rises before decreasing. This is due to the driver’s resistance response to the onset of fatigue while driving. In each working condition, there exists a positive correlation between FDD’s maximum value and the length of the tunnel. For instance, the tunnel lengths in working conditions 2–6 ascend in values of 3,356, 4,828, 5,825, 11,362, and 13,448 m. The corresponding maximum values of FDD indicate a positive...
correlation with mileage traveled in the tunnel, with values of 2.26, 2.28, 3.25, 3.25, and 3.72 respectively. This is consistent with the conclusion drawn from the ordered multi-class Logistic model in this paper, which shows that the degree of driving fatigue is significantly affected by the length of the tunnel.

Guided by the distribution patterns in Fig. 7, in the realm of statistics, when the distribution function is unknown, the normal distribution is frequently regarded as the most probable form of distribution. Consequently, Gaussian functions were employed for the non-linear curve fitting of the data. Subsequently, additional formulas were developed to articulate the functional relationship between a driver’s FDD and time within an extra-long tunnel, presented from formula (4) to formula (8).

The adjusted goodness-of-fit ($R^2$) values following fitting are 0.934, 0.865, 0.899, 0.894, and 0.981, signifying a strong alignment with the non-linear curves.

\[
FDD_2 = 3.0238 + \left( \frac{-820.46}{212.39 \times \sqrt{\pi/2}} \right) e^{-\left( \frac{t - 41.48}{181.12} \right)^2} \tag{4}
\]

\[
FDD_3 = -27.3 + \left( \frac{75776.92}{1956.94 \times \sqrt{\pi/2}} \right) e^{-\left( \frac{t - 436.89}{181.12} \right)^2} \tag{5}
\]

\[
FDD_4 = 2.3037 + \left( \frac{-814.79}{181.12 \times \sqrt{\pi/2}} \right) e^{-\left( \frac{t - 424.21}{181.12} \right)^2} \tag{6}
\]
Key parameter design of the Fatigue Arousal Zone

\[ FDD_i = 2.689 + \left( \frac{-555.30.13}{516.57 \times \sqrt{t_i}} \right) \times e^{-\left( \frac{231.4143}{\sqrt{t_i}} \right)^2} \] \quad (7)

\[ FDD_b = 0.3211 + \left( \frac{-267.29}{105.52 \times \sqrt{t_i}} \right) \times e^{-\left( \frac{424.27}{\sqrt{t_i}} \right)^2} \] \quad (8)

In the formula, \( FDD_i \) is the FDD in extra-long tunnel under condition \( i \), \( t_i \) is the duration of driving inside the tunnel.

Using \( TDF_i = FDD = 2.01 \) in formulas (4) to (8), we compute \( t_2 = 116.886, t_3 = 119.932, t_4 = 119.807, t_5 = 113.718, \) and \( t_6 = 112.840 \). Rounding the times for each condition, we establish that the time frame in which the driver’s FDD surpasses the threshold spans from 110 to 120 s. Employing a speed of 80 km/h for computations, we ascertain that the driver initiates entry into a semi-fatigue state after covering a distance of roughly 2,444.44 to 2,666.67 m into the tunnel. Rounding to the nearest hundred meters, this translates to the commencement of experiencing fatigue at approximately 2,500 to 2,700 m into the tunnel. In this experiment, it was only in condition 3 that the driver’s FDD reached \( TDF_3 \). Thus, we calculate the time for condition 3 when the driver enters a fatigued state using \( TDF_3 = 3.37 \). This computation results in \( t = 318.455 \) s, rounded to 320 s. Employing a speed of 80 km/h for computations, we establish that the driver enters a fatigued state after covering a distance of approximately 320 × 80 = 2,511.11 m, rounded to 7,100 m, within the tunnel. In conclusion, drivers start to feel fatigued after driving approximately 2,500–2,700 m into the extra-long tunnel and enter a fatigued state after driving 7,100 m. Therefore, it is worth considering setting up the fatigue arousal zone at these distances.

Length setup of the fatigue arousal zone

The interval length of the fatigue arousal zone is determined by the driving speed of the driver within the zone, denoted as \( v \), and the time it takes to pass through the fatigue arousal zone, denoted as \( t_i \), as shown in formula (9):

\[ D_i = v \times t_i \] \quad (9)

In formula (9), \( D_i \) is the interval length of the fatigue arousal zone.

To ensure the efficacy of the fatigue arousal zone, there exists a minimum length requirement for the fatigue arousal zone interval. With a fixed interval length for the fatigue arousal zone, higher vehicle speed values will lead to a reduced time required to traverse the zone. Consequently, to ascertain the minimum interval length, it is imperative to take into account the maximum driving speed within the tunnel, assumed to match the tunnel’s speed limit of 80 km/h. Additionally, the minimum duration is linked to the driver’s visual adaptation process. As drivers navigate through the fatigue arousal zone, their visual adaptation process mirrors that of the adjacent tunnel section’s visual adaptation process[39]. Hence, the design of the fatigue arousal zone’s length can draw from the visual adaptation process in the adjacent tunnel section. It can utilize the association between brightness alterations and human eye adaptability and comfort to compute the minimum longitudinal extent of the fatigue arousal zone.

Zhang et al.[39] investigated the correlation between visual adaptability and comfort in response to brightness variations.

According to their research findings, when brightness increases and is associated with a comfort rating greater than 1, the visual adaptation time required to achieve human eye comfort is estimated to be less than 0.73 s through regression analysis. In contrast, a comfort rating of −2 signifies discomfort and implies an adaptation time exceeding 2.03 s. In scenarios involving decreasing brightness, the visual adaptation time necessary to attain human eye comfort is computed as 0.75 s. However, when the visual adaptation time surpasses 3.70 s, it signifies driver discomfort. When applying these research findings to the visual adaptation process experienced by drivers as they traverse the fatigue arousal zone, an increase in brightness represents the drivers’ entry into the fatigue arousal zone, whereas a decrease in brightness signifies their exit from the fatigue arousal zone. To calculate the minimum length of the fatigue arousal zone, the visual adaptation times of 2.03 s for increasing brightness and 3.70 s for decreasing brightness are inserted into formula (9). The calculation yields \( D_{min} = v \times (t_1 + t_2) = 22.22 \times (2.03 + 3.70) = 127.32 \) m, which is rounded to 130 m. Consequently, the minimum length requirement for the fatigue arousal zone, denoted as \( D \), is determined to be 130 m. It should be noted that when the length of the fatigue arousal zone is equal to or less than 130 m, rapid fluctuations in brightness may not align with the criteria for driver visual comfort.

Form setup of the fatigue arousal zone

Increasing visual information stimuli is the most effective and safest method for addressing short-term driver fatigue and enhancing current arousal level[65]. Within the extra-long tunnel’s fatigue arousal zone, the method of reconstructing the driver’s visual frame of reference can be employed to amplify visual information stimuli for the driver. This is primarily achieved through specialized design of visual reference objects within the fatigue arousal zone, including parameters such as color type and brightness.

Optimal color type

Given that drivers are highly sensitive to the color of visual reference objects, with color accounting for up to 80% of their attention. Moreover, various color temperatures elicit distinct visual sensations in drivers, resulting in different levels of visual stimulation among cold, warm, and neutral colors for drivers. Therefore, the choice of colors will directly impact the current arousal level of drivers. According to the research conducted by Ye et al.[36] on the color schemes of highway tunnel decorations nationwide, it’s found that tunnels primarily use neutral colors, with a balanced proportion of cold colors represented by blue and warm colors represented by yellow. Research from Song et al.[37] indicates that cool colors such as blue and green used for decorating tunnel arches and sidewalks are less likely to make drivers accelerate, while neutral colors like gray and white are more likely to encourage acceleration. However, cool colors can give drivers a sensation of sidewalls expanding outward, creating a sense of openness in the tunnel space, which can help alleviate drivers’ feelings of confinement. Compared to cool and neutral colors, warm colors provide drivers with relatively stronger visual stimulation. At lower speeds, drivers have better control over driving, and the influence of color temperature on drivers is not significant. However, as speed increases, the temperature perception of colors intensifies the driver’s level of tension, making the choice of color tones particularly important.
Choosing cool color tones for decoration not only serves the purpose of awakening but also minimizes the level of tension for drivers. This can be directly applied to the design of color types for fatigue arousal zones within extra-long tunnels. Therefore, the optimal color type for fatigue arousal zones should be cool color tones.

**Brightness requirement**

Brightness is another crucial component of visual perception for drivers during the driving process, alongside color. It collectively determines the intensity of visual stimuli. The greater the brightness of a color, the stronger the visual stimulus perceived by drivers\(^1\). While ensuring that the fatigue arousal zone has a certain awakening effect, the interval brightness of the fatigue arousal zone should neither be too high nor too low, prioritizing a smooth transition for drivers during changes in brightness. According to the 'Guidelines for Design of Lighting of Highway Tunnels'\(^2\), which is based on the CIE luminance adaptation curve, when designing brightness transitions between the entrance and middle sections of a tunnel, three transition sections are set, and the brightness in these sections decreases in a 3:1 ratio. Following this principle, when transitioning the brightness between the fatigue arousal zone and the regular environment, the brightness of the fatigue arousal zone should not exceed three times that of the regular environment. Due to variations in the reflectance coefficients of materials in different parts of the tunnel's middle section, the brightness values for different parts of the tunnel's middle section can be calculated. Subsequently, the maximum brightness values for various parts of the fatigue arousal zone can be derived, as shown in Table 7.

**Traffic induction design of the fatigue arousal zone**

Inside the extra-long tunnel, if a driver enters the fatigue arousal zone without any prior warning, rapid changes in the external driving environment can lead to safety issues. Therefore, before a driver enters the fatigue arousal zone, relevant induction information should be provided. According to the Light-emitting Diode Changeable Message Signs of Motorway\(^4\), this article intends to set up variable message signs (VMS) in the area ahead of the fatigue arousal zone as dynamic traffic information facilities.

To ensure that drivers can effectively recognize the VMS, it is necessary to calculate the minimum recognition distance for drivers within the tunnel. The minimum recognition distance is related to the process of drivers recognizing signs within the tunnel, as shown in Fig. 8. The sign recognition distance L inside the tunnel is given by formula (11):

\[
L = L_1 + L_2 + L_x
\]

In formula (11), \(L_1\) is the sign recognition distance, \(L_2\) is the sign disappearance distance, and \(L_x\) is the distance from when the driver recognizes the sign to when the sign disappears. The minimum value of \(L_2\) can be 0, and \(L_1\) and \(L_x\) need to be calculated separately. The recognition distance \(L_1\) of signs is related to the driver's reaction time and the vehicle's speed, as shown in formula (12):

\[
L_1 = \frac{V}{3.6} \times t_1
\]

In formula (12), \(V\) is the vehicle's operating speed, and \(t_1\) is the sign recognition reaction time. According to the research

### Table 7. Maximum brightness values for various parts of the fatigue arousal zone.

<table>
<thead>
<tr>
<th>Tunnel section</th>
<th>Middle section illuminance (lux)</th>
<th>Selected material</th>
<th>Reflectance coefficient</th>
<th>Luminance (cd/m²)</th>
<th>The fatigue arousal zone luminance (cd/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road surface</td>
<td>64.89</td>
<td>Asphalt road surface</td>
<td>0.14</td>
<td>9.08</td>
<td>27.24</td>
</tr>
<tr>
<td>Ceiling</td>
<td>36.26</td>
<td>Cement road surface</td>
<td>0.31</td>
<td>20.11</td>
<td>60.33</td>
</tr>
<tr>
<td>Ceiling</td>
<td>36.26</td>
<td>Gray-black paint</td>
<td>0.41</td>
<td>14.87</td>
<td>44.61</td>
</tr>
<tr>
<td>Ceiling</td>
<td>36.26</td>
<td>Gray paint</td>
<td>0.63</td>
<td>22.84</td>
<td>68.52</td>
</tr>
<tr>
<td>Ceiling</td>
<td>36.26</td>
<td>Light gray paint</td>
<td>0.69</td>
<td>25.02</td>
<td>75.06</td>
</tr>
<tr>
<td>Ceiling</td>
<td>36.26</td>
<td>White paint</td>
<td>0.73</td>
<td>26.47</td>
<td>79.41</td>
</tr>
<tr>
<td>Side wall</td>
<td>45.50</td>
<td>Gray paint</td>
<td>0.63</td>
<td>28.67</td>
<td>86.01</td>
</tr>
</tbody>
</table>

**Fig. 8** Diagram of the sign recognition process.
Key parameter design of the Fatigue Arousal Zone

According to the geometric relationship of the line-of-sight triangle, the formula for calculating the disappearance distance \( L_2 \) is shown in formula (13):

\[
L_2 = \frac{d}{\tan \omega}
\]  

In formula (13), \( d \) is the vertical distance between the sign and the viewpoint, and \( \omega \) is the angle between the sign and the driver's line of sight when the sign disappears.

When the vehicle is traveling at a speed of \( V = 80 \text{ km/h} \), according to formula (12), \( L_1 = 88.89 \text{ m} \), rounded to 89 m. The driver's viewpoint height is 1.2 m, the height of the single-line text sign is 0.9 m, and the distance from the lower edge of the signboard to the ground is 5.0 m, resulting in \( d = 4.25 \text{ m} \). When the sign disappears within the driver's field of view, \( \omega \) is approximately \( \approx 7^\circ \). Substituting this into formula (13) yields \( L_2 = 34.61 \text{ m} \), rounded to 35 m. The minimum recognition distance of the sign, \( L = L_1 + L_2 = 124 \text{ m} \), rounded to 130 m. Therefore, to ensure the recognition effectiveness of the fatigue arousal zone, it is necessary to maintain unobstructed driver visibility within a range of 130 m before the introduction sign for the fatigue arousal zone.

Validation of key parameters for the fatigue arousal zone

To verify the rationality and effectiveness of the key parameter design for the fatigue arousal zone in this paper, it is necessary to compare and validate it with engineering examples. As of the end of 2022, there are a total of 1,752 extra-long tunnels in China\(^{(43)}\), and most of these extra-long tunnels do not have traffic facilities for fatigue arousal. This section compiles statistics on extra-long tunnels in China that have longer lengths and use fatigue arousal technology inside the tunnels. The design parameters are shown in Table 8.

From Table 8, first, it can be observed that for the location setup of the fatigue arousal zone, if only one such zone is set up within the tunnel, it is mostly located in the middle of the tunnel. However, if two or more fatigue arousal zones are set up, they are mainly concentrated at distances of 3500-4500 m and 7000-9000 m from the tunnel entrance. This paper utilizes the non-linear curve fitting of FDD to calculate the setup location of the fatigue arousal zone, which are situated at 2,700 m and 7100 m from the tunnel entrance. As the positions of fatigue arousal zones in the engineering examples are relatively dispersed, comparing to theoretical calculation results, it can be considered that the positions of fatigue arousal zones in this paper are relatively reasonable and align with engineering reality. Moreover, these theoretical positions align with the research results of Li et al.\(^{(46)}\). Second, regarding the length of the fatigue arousal zone, the lengths are mostly concentrated at 150 and 200 m, with a few at 100 and 120 m. Based on the correlation between visual adaptability and comfort in response to brightness variations and driving speed, the calculated minimum limit in this paper is 130 m, which is consistent with the research results of Chen\(^{(49)}\). For the fatigue arousal zone of tunnels less than 130 m in length, it is necessary to consider the actual illumination of the project with the theory of human eye adaptation for further verification. Third, regarding the design form, the colors in the fatigue arousal zones are mainly cool tones such as starry sky and blue sky with white clouds, or warm tones such as colorful light strips combined with 3D decorations like rockeries and flowers. The use of auditory and tactile stimuli is less common in extra-long tunnels. Fourth, for traffic induction design, as the definition of the fatigue arousal zone had not been standardized and design regulations were not explicitly specified before this, most extra-long tunnels have not set up relevant advance signs for the fatigue arousal zones, and further improvements are needed.

In conclusion, this paper has demonstrated the rationality and practical applicability of the key parameters designed for the fatigue arousal zone.

### Table 8. Design parameters statistics of the fatigue arousal zone of some extra-long tunnels in China.

<table>
<thead>
<tr>
<th>Tunnel name</th>
<th>Tunnel length (m)</th>
<th>Amount</th>
<th>Interval (m)</th>
<th>Length (m)</th>
<th>Form</th>
<th>Introduction signs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhonganshan highway Tunnel</td>
<td>18,200</td>
<td>3</td>
<td>4,500</td>
<td>150</td>
<td>Blue sky and white clouds, sunset glow, 3D decorations</td>
<td>Doesn't exist</td>
</tr>
<tr>
<td>New erlangshan tunnel</td>
<td>13,459</td>
<td>3</td>
<td>4,000</td>
<td>120</td>
<td>The five-starred red flag, starry sky, maple leaf</td>
<td>Exist</td>
</tr>
<tr>
<td>Dapingni tunnel</td>
<td>12,300</td>
<td>2</td>
<td>4,000</td>
<td>100</td>
<td>Blue sky and white clouds</td>
<td>—</td>
</tr>
<tr>
<td>Chengkai tunnel</td>
<td>11,456</td>
<td>4</td>
<td>2,500</td>
<td>100</td>
<td>Four seasons landscape, 3D decorations</td>
<td>Exist</td>
</tr>
<tr>
<td>Yunshan tunnel</td>
<td>11,403</td>
<td>1</td>
<td>5,500</td>
<td>200</td>
<td>Color light strip</td>
<td>Doesn’t exist</td>
</tr>
<tr>
<td>Baojiaoshan tunnel</td>
<td>11,200</td>
<td>1</td>
<td>—</td>
<td>200</td>
<td>Color light strip, 3D decorations</td>
<td>Doesn’t exist</td>
</tr>
<tr>
<td>Baotashan tunnel</td>
<td>10,200</td>
<td>2</td>
<td>3,500</td>
<td>200</td>
<td>Color light strip</td>
<td>Exist</td>
</tr>
<tr>
<td>Six pangshan special tunnel</td>
<td>9,981</td>
<td>1</td>
<td>5,000</td>
<td>200</td>
<td>Blue sky and white clouds, underwater world</td>
<td>Doesn’t exist</td>
</tr>
<tr>
<td>Yanglin tunnel</td>
<td>9,460</td>
<td>1</td>
<td>4,700</td>
<td>150</td>
<td>Landscape painting scroll, 3D decorations</td>
<td>Exist</td>
</tr>
<tr>
<td>Baodingshang tunnel no.2</td>
<td>8,775</td>
<td>2</td>
<td>3,000</td>
<td>120</td>
<td>Blue sky and white clouds, rockery stone scenery</td>
<td>—</td>
</tr>
<tr>
<td>Wunvfeng tunnel</td>
<td>7,930</td>
<td>1</td>
<td>4,000</td>
<td>120</td>
<td>Blue sky and white clouds, color light strip</td>
<td>Doesn’t exist</td>
</tr>
<tr>
<td>Malanshan tunnel</td>
<td>7,904</td>
<td>2</td>
<td>—</td>
<td>200</td>
<td>Underwater world, mountain and river scenery</td>
<td>Doesn’t exist</td>
</tr>
<tr>
<td>Qiganshan Tunnel</td>
<td>7,630</td>
<td>1</td>
<td>3,600</td>
<td>300</td>
<td>Mountain and river scenery</td>
<td>—</td>
</tr>
<tr>
<td>Xuefeng mountain tunnel</td>
<td>7,040</td>
<td>14</td>
<td>3,500</td>
<td>—</td>
<td>Blue sky and white clouds</td>
<td>Doesn’t exist</td>
</tr>
<tr>
<td>Huayan Tunnel</td>
<td>5,100</td>
<td>4</td>
<td>1000</td>
<td>100</td>
<td>Blue sky and white clouds</td>
<td>Doesn’t exist</td>
</tr>
<tr>
<td>Dushu lake tunnel</td>
<td>3,460</td>
<td>1</td>
<td>1,500</td>
<td>100</td>
<td>Color light strip</td>
<td>Doesn’t exist</td>
</tr>
</tbody>
</table>
Conclusions

In order to effectively counteract short-term fatigue effects in extra-long tunnels, based on the theory of fatigue arousal, this paper defines the fatigue arousal zone as follows: ‘the fatigue arousal zone’ within extra-long tunnels refers to a designated section in the middle part of the tunnel, characterized by a certain length. Within this zone, various sensory stimuli, including visual, auditory, and tactile cues, are provided to the driver to induce a rapid return to the optimal arousal level. The purpose of the fatigue arousal zone is to alleviate short-term fatigue issues experienced by drivers in extra-long tunnels.

Based on data collected from natural driving fatigue experiments, this paper has constructed a quantitative dimensionless index of fatigue driving degree (FDD) and the threshold of driving fatigue (TDF), and conducted a study on the key parameters of fatigue arousal zones in extra-long tunnels. The research results are as follows: First, regarding the location setup of fatigue arousal zones, when the tunnel length is between 3–5 km, one fatigue arousal zone should be placed in the middle of the tunnel. When the tunnel length is between 5–10 km, a fatigue arousal zone should be placed at a distance of 2,700 m from the tunnel entrance, with a second one considered based on the actual tunnel conditions. When the tunnel length exceeds 10 km, two or more fatigue arousal zones should be set up, located at distances of 2,700 and 7,100 m from the tunnel entrance. Second, for the length of the fatigue arousal zones, the minimum limit is 130 m. For the fatigue arousal zone of tunnels less than 130 m in length, it is necessary to combine the actual illumination of the project with the theory of human eye adaptation for further verification. Third, regarding the form setup, the optimal color type for the fatigue arousal zone is the cool color tone. The maximum brightness values for different parts of the fatigue arousal zone are as shown in Table 7. Fourth, for traffic induction design, we set up the variable message signs (VMS) in the area ahead of the fatigue arousal zone, and the minimum recognition distance for traffic induction signs inside the tunnel is 130 m. Through a comparative verification with engineering examples, this paper concludes that the design of key parameters for fatigue arousal zones is reasonably sound and practical.

The research findings can provide a theoretical reference for fatigue arousal technology in extra-long tunnels. The main limitation of this study is that only the setting parameters of visual stimuli in the fatigue arousal zone were investigated, and the setting parameters and arousal effects of auditory and tactile stimuli were not experimentally verified. In future research, critical parameters such as stimulation methods, stimulation frequency, and stimulation intensity for auditory and tactile stimulation can be explored and validated.

Author contributions

The authors confirm contribution to the paper as follows: conceptualization: Lian G, Xie L; data curation: Lian G; formal analysis: Lian G; funding acquisition: Shang T; investigation: Lian G, Zhou A; methodology: Lian G; resources: Shang T; supervision: Shang T; validation: Zhou A; visualization: Xie L; writing – original draft: Xie L; writing – review & editing: Xie L, Zhou A. All authors reviewed the results and approved the final version of the manuscript.

Data availability

The data that support the findings of this study are available on request from the corresponding author.

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Conflict of interest

The authors declare that they have no conflict of interest.

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