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Original Paper

Drivers in Expressway Superlong Tunnels: The Change Patterns of Visual Features and the Discriminant Model of Driving Safety

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Abstract

A real-vehicle experiment was carried out in the superlong highway tunnel environment to study the change patterns of driver's visual features, tracked by eye tracking devices, and the discriminant model of driver's safety status. On the basis of statistical analysis, a single index and a comprehensive index discriminant model, both based on a C4.5 decision tree, were established. The results showed that compared with the non-tunnel highway sections, the driver's pupil size was larger, and the gaze duration was longer in the tunnel section. Driver's pupil size was larger in mid-tunnel section than in the entrance section and exit section. Gazes at the exit section were mainly short gazes. Compared to the exit section, driver's pupil size changed more dramatically in the entrance section, and the gaze duration was longer. The single visual parameter indicator could clearly discriminate the driver's safety status in the mid-tunnel section and the non-tunnel sections, while the dual-index-based identification model could clearly discriminate the safety status in each highway sections. The study deepens the research on the driver information perception model in superlong highway tunnels. Also, the study provides a theoretical basis for establishing a visual-feature-based real-time safety status discriminant.

Keywords

traffic safety, highway, superlong tunnels, visual features, discriminant model

1. Introduction

Due to the rapid environment switching while driving through highway tunnels, a driver's visual features would change drastically, which makes highway tunnels accident-prone sections. In the entire transportation system, the driver manifests as an organic whole of human-car-road-environment. Statistics have shown that over 50% of tunnel traffic accidents were caused by drivers directly. In the process drivers perceiving, judging and processing environmental information, perception error accounted for 45% of total errors, and the problem of the reliability of information transmitted by visual channel was held responsible for more than 80% of the perception errors. Therefore, how to improve driver's visual perception accuracy while considering driver's visual and psychological needs, and based on which to adopt a velocity and path operation suitable for the tunnel environment, is of great significance for a higher tunnel traffic safety level.

Results have been obtained in the research on the influence of tunnel environment on driver's visual features. Existing studies mostly focused on indicators like driver gaze, saccade, pupil size, and heart rate. Most of these indicators were not in the same dimension, requiring statistical processing. Also, the tunnel environment studied was mainly the entrance and exit sections of a single tunnel or tunnel groups, lacking systematic exploration on superlong tunnel environment. The existing results were far from being universal. Superlong tunnels feature higher accident-proneness and complexity. Therefore, their influences on drivers are worthy of further attention.

Previous studies have proven that the gaze duration of a driver on a fixed area reflects the driver's attention level and information perception level. Some indicators, such as pupil size, change rate, and oscillation of change, were often used for measuring a driver's psychological tension level and characterizing the attention to visual information. Thus, the objective of this study was listed as follows:

a) The measure of the impact of superlong tunnels environment in visual characteristics of drivers.

b) The real-time driving safety status identification model in Superlong Tunnels.

In view of the above, a real-vehicle eye tracking experiment was carried out to probe in the change patterns of the visual features of drivers in superlong highway tunnels. By comparing the dynamic visual features of drivers inside and outside the superlong tunnel environment, the reasons for the differences in visual features were determined. Based on the founding and by applying data mining algorithms, a safety status identification model was established. In short, it is eventually aimed to provide a theoretical basis for the real-time safety status identification model in different traffic environments.

2. Experimental Design and Data Collection

Given the particularity of the experimental highway section, a total of 8 male drivers (in average 46 years old and with 23-year driving age) of different occupations, ages, and driving ages, all holding a Class B license or above, were included. They all had normal visual functions, with no physical defects nor serious accident experience.

The Qinling-Zhongnan Mountain Superlong Highway Tunnel was selected for the experiment. The selected tunnel is located in the Xi (An)-Zha (Shui) section (in Shaanxi Province) of the Bao (Tou)-Mao (Ming) Highway, a twin-tunnel two-lane highway section. The speed limits are 100 km/h (non-tunnel section) and 70 km/h (tunnel section). By the time the experiment was started, the highway was not yet in full operation, as the highway construction was not completed. Hence the traffic was flowing slightly and drivers were allowed to drive freely.

The experiment was designed conforming to the double-blind principle and had the influences of other factors on driving behavior controlled as much as possible. EyeLink II head-mounted eye tracker manufactured by SR Research, a Canada company, was used to measure and record the driver's eye movement parameters. Upon connecting and calibrating the experimental equipment, the drivers were informed to drive as usual, freely, abiding by traffic signs, and passing through the target tunnel. In order for data validity and eliminating the influence of relevant factors, two experiment sessions were carried out to and fro the target tunnel. The average value of the data collected from the two sessions was taken as the final visual feature change data.

3. Visual Feature Parameters Analysis

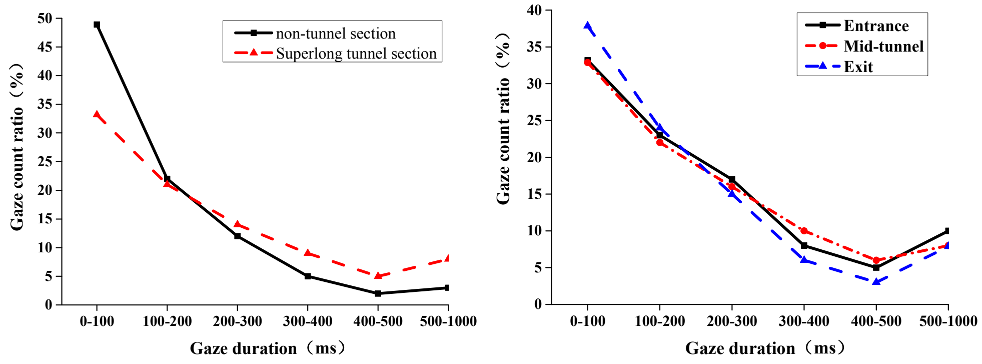
In this paper, the gaze duration and pupil size were selected as the indicators of visual information processing. Both indicators were real-time and could be used as real-time predictors for safety status identification.

3.1 Gaze Duration

The target tunnel was divided into several sections by national standards and related studies. The entrance section composed of 400 m, i.e., 200m before the tunnel entrance plus 200m after. Similarly, the 200m before the tunnel exit plus 200m after was defined as the exit section. The middle part was defined as the mid-tunnel section. The tunnel entrance and exit were set as the coordinate origin. The driving direction was a positive direction.

3.1.1 Gaze Duration Distribution Curve

Figure 1 (a) is an average distribution diagram of gaze duration of participant drivers in non-tunnel sections and superlong tunnel sections. Figure 1 (b) is a gaze duration distribution diagram of drivers in the entrance section, the mid-tunnel section, and the exit section.



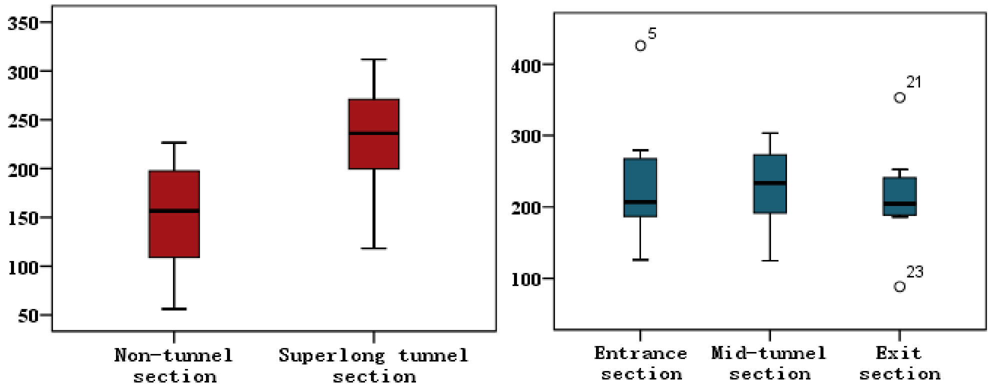
(a) Non-tunnel sections and superlong tunnel sections (b) Tunnel entrance, mid-tunnel section, and exit section

Figure 1. Gaze Duration Distribution Curves

Gaze duration values of drivers driving in non-tunnel highway sections and superlong highway tunnel sections were exponentially distributed (non-tunnel sections, R^2=0.995; tunnel sections, R^2=0.981). The ratio of gaze duration less than 100ms was 48.89% and 33.17%, respectively, indicating that for most of the time, drivers gazed a short time. Except for 0-100ms and 100-200ms segments, drivers in superlong tunnel sections gazed more in all the rest segments than in non-tunnel sections. In other words, in superlong tunnels, drivers need more time to obtain target information due to environmental factors such as lighting and ventilation. Compared to entrance section and mid-tunnel section, drivers mainly have short gazes in exit section.

3.1.2 Average Gaze Duration

The difference in average gaze duration in different highway sections was observed. In tunnel sections, drivers averagely gazed longer than in the non-tunnel sections, in that it was harder in tunnel sections for the drivers to extract information. The distribution of the average gaze duration in the exit segment was more centralized The highest average gaze duration was in the mid-tunnel section.



(a) Non-tunnel sections and superlong tunnel sections (b) Entrance section, mid-tunnel section and exit section

Figure 2. The Box Plot of Average Gaze Duration

The influence of different road conditions on the average gaze duration was quantitatively analyzed by statistical analysis. The K-S test resulted a normal distribution (non-tunnel section, Sig.=0.783; entrance section, sig.=0.949; mid-tunnel section, sig.=0.994; exit section, sig.=0.801), consistent with variance homogeneity (Sig.=0.812). The results of the one-way ANOVA analysis showed that the impact of different road conditions on the average gaze duration was not significant (Sig.=0.105). T-test of two paired samples was given to determine the difference, and the test results were shown in Table 1. There was a significant difference in the average gaze duration between the non-tunnel section and the tunnel sections (the entrance section, the mid-tunnel section, and the exit section). It could be seen from the t-test results that the difference of average gaze duration in the entrance section, the mid-tunnel section, and the exit section was not significant.

Table 1. T-test Table of Average Gaze Duration

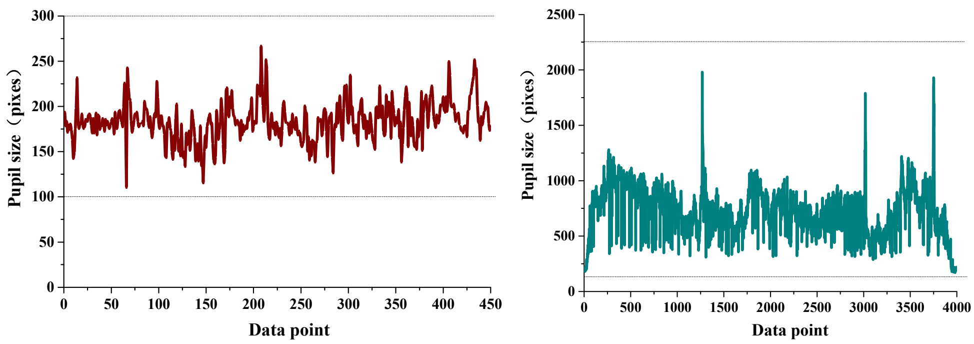
Section	t	Sig. (two-sided test, α=0.05)	Conclusion
Non-tunnel section and entrance section	-3.137	0.016	Mean difference: significant
Non-tunnel section and mid-tunnel section	-5.105	0.001	Mean difference: significant
Non-tunnel section and exit section	-2.846	0.025	Mean difference: significant
Entrance section and mid-tunnel section	0.227	0.827	Mean difference: not significant
Entrance section and exit section	1.337	0.223	Mean difference: not significant
Mid-tunnel section and exit section	0.644	0.540	Mean difference: not significant

3.2 Pupil Size

3.2.1 Pupil Size Change Curve

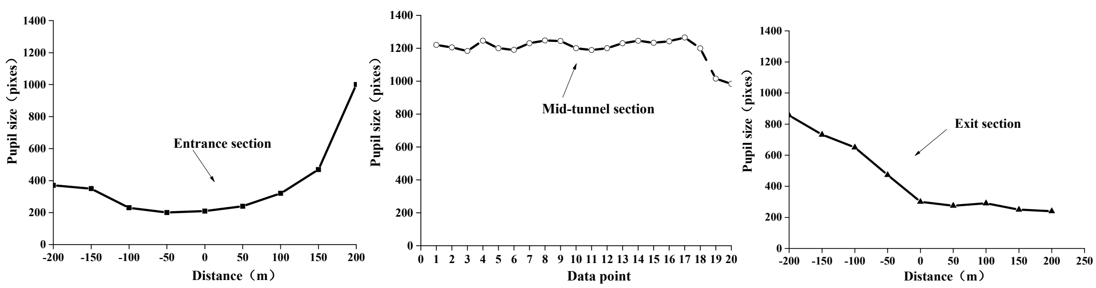
Pupil size is affected by factors such as light, emotion, and cognitive load. The change of pupil size between the non-tunnel sections and the tunnel sections is mainly caused by illumination, an involuntary pupil change to adapt to the external environment. The pupil size change also characterizes different degrees of visual load.

It was found that the eight drivers had similar pupil size change patterns in each road section. Figure 3 showed the changes in pupil size of driver 1. The non-tunnel section had sufficient and stable illumination. Thus the driver's pupil size barely changed-mostly between 100-300 pixels. Observing the pupil size changes throughout the entire tunnel sections, namely from the entrance section to the exit section, the changes were found large, and the distribution ranged wildly. The pupil size change diagram of the tunnel entrance section, the mid-tunnel section, and the exit section was drawn in 50m intervals.



(a) Non-tunnel sections **(b) Superlong tunnel sections**

Figure 3. Driver 1's Pupil Size Changes



(a) Entrance section **(b) Mid-tunnel section** **(c) Exit section**

Figure 4. Changes of Pupil Size in Superlong Tunnel Sections

Figure 4 showed the changes of pupil size in superlong tunnel sections. When approaching the tunnel entrance, as seeing the tunnel clearly, the driver's tension reduced and the pupil size gradually narrowed. After entering the tunnel, illumination weakened and the pupil size gradually increased to adapt to the tunnel environment. At 100-200 meters after entering the tunnel, in particular, the sharp illuminance change caused the pupil size to expand rapidly. Related studies also revealed that in the 100-200 meters after entering the tunnel was more prone to accidents. 20 data points in the mid-tunnel section were picked to observe the pupil size changes. It was found that the driver's pupil size value remained at a high level. When approaching the tunnel exit and entering into ambient brightness suddenly, the driver's pupil size decreased rapidly. After exiting the tunnel, the driver's pupil size remained around 250 pixels with slight fluctuation.

3.2.2 Average Pupil Size

Mean values of all participant drivers' pupil size in various sections were taken to draw a descriptive curve. Among all the sections, the largest average pupil size of all the drivers except for the Driver 5 was observed in the mid-tunnel section. Descriptive analysis revealed a slight difference in the pupil size in non-tunnel sections, entrance section, and exit section.

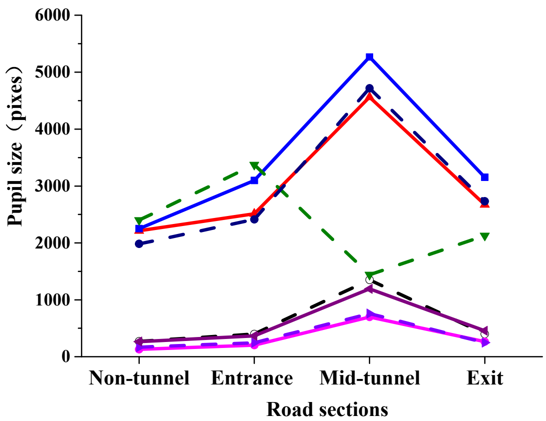


Figure 5. Average Pupil Size of Each Section

K-S test (significance level=0.05) was used to test the normality of average pupil area of drivers in four sections. The overall distribution was normal (non-tunnel section, Sig.=0.433; entrance section, sig.=0.465); mid-tunnel section, sig.=0.351; exit section, sig.=0.492). The Levene test indicated that the variances were not uniform (sig.=0. 002). The nonparametric Friedman test showed that there was a significant difference in the average pupil size in the four road sections (Sig.=0.002). Furthermore, the Wilcoxon signed rank test on two paired samples demonstrated that there was a significant difference in the average pupil size between the non-tunnel section and the entrance section and the mid-tunnel section (Sig.=0.012; Sig.=0.050). Drivers in the non-tunnel section had an obviously smaller pupil size than in other road sections. The difference of pupil size between the tunnel entrance section and the mid-tunnel section was not significant (Sig.=0.069), while that between the mid-tunnel section and the exit section was significant (Sig.=0.036).

4. Comprehensive Discriminant Model Based on C4.5 Decision Tree

4.1 Classification Algorithm of C4.5 Decision Tree

A decision tree is a classification and decision support tool composed of internal nodes and leaf nodes. It tests and analyzes data by defining nodes and generating readable rules through inductive algorithms. As a typical machine learning method in data mining, the C4.5 algorithm applies the principle of information entropy and select the information gain rate as a measure of the decision tree's classification discriminative ability, and then determines the node attributes and recursively expands the branches of the decision tree, until completing the decision tree construction. The C4.5 algorithm is simple and easy to calculate, suitable for dealing with large-scale classification problems.

4.2 Model Structure

The C4.5 algorithm uses information gain values to measure the ability of a given attribute to distinguish training examples. At each step of extending a decision tree, the maximum information gain value would be used to select attributes from the candidate attributes. The decision attribute's information gain value is calculated by the following method:

Denote S as the dataset of the training sample, and $p_i\left(i=1,2,...,m\right)$ as the frequency of classification attribute C, with m category labels, appearing in all samples. Then the expected information amount of S in the classification is defined as:

$$Entropy(S)=-\sum_{i=1}^{m}p_i\log_2 p_i \tag{1}$$

Suppose A to be a discrete type with k different values, then the attribute A would divide S into k subsets, namely $\left\{S_1,S_2,...,S_k\right\}$, based on the k different values. Then the information entropy of S divided by the attribute A is:

$$Entropy_A(S)=\sum_{i=1}^{k}\frac{|S_i|}{|S|}Entropy(S_i) \tag{2}$$

Where $|S_i|$ and $|S|$ are the number of samples included in S_i and S.

The attribute A as a measure of the decision classification attribute (i.e., information gain) is defined as:

$$Gain(S,A)=Entropy(S)-Entropy_A(S) \tag{3}$$

Split information of the attribute is included to adjust information gain:

$$SplitE(A)=-\sum_{i=1}^{k}\frac{|S_i|}{|S|}\log_2\frac{|S_i|}{|S|} \tag{4}$$

And the information gain rate is:

$$GainRatio(A) = \frac{Gain(A)}{SplitE(A)} \quad (5)$$

The C4.5 algorithm calculates the information gain of each attribute, and the attribute with the maximum information gain rate value would be used as the split node. The branch nodes then would be established by each value used by the attribute. In this manner, the decision tree is constructed from the top to bottom.

5. Model Training and Testing

Drivers' psychological changes can be measured by multiple physiological indicators. Electro oculogram (EOG) provides important parameters for quantitative judgment of drivers' attention level and direction. The experimental data were grouped into the entrance, mid-tunnel, exit section, and non-tunnel section. On a single indicator of gaze duration or pupil size, and the combination of the two, the decision tree was applied to identify the safety status. To prevent overfitting, the ten-fold cross validation was adopted. The training results were shown in Table 2.

Table 2. Decision Tree Training Results of Different Indicators

Input indicator	Test option	Correctly classified test case	Correct classification ratio	ROC value
Gaze duration	Training set	13966	96.4%	0.901
	Cross-validation (10% off)	13502	93.2%	0.895
Pupil size	Training set	13047	98.1%	0.974
	Cross-validation (10% off)	13502	98%	0.971
Gaze duration and pupil size	Training set	12802	99.3%	0.99
	Cross-validation (10% off)	12765	98.9%	0.98

The ROC value was used to evaluate the accuracy of the decision tree classification. Using the single indicator of gaze duration could clearly identify the data in the non-tunnel section and mid-tunnel section, but couldn't significantly identify data in the entrance and exit sections. The 10-fold cross-validation results were listed as follows: the non-tunnel section ROC: 0.93; the entrance section ROC: 0.55; the mid-tunnel section ROC: 0.90; and the exit section ROC: 0.88. Similar results were seen when using the single indicator of pupil size. The non-tunnel section and the mid-tunnel section showed typical pupil size differences, while the difference between the other sections was not significant.

When using the comprehensive indicators of gaze duration and pupil size, the non-tunnel section and tunnel sections could be effectively identified (ROC 0.99 for non-tunnel section, ROC 0.97 for entrance section, ROC 0.99 for mid-tunnel section, and ROC 0.98 for exit section). The complexity of the external environment caused constant changes in drivers' attention, which was closely manifested by eye movements. In this paper, only the pupil size and gaze duration were used as input rules. When it was necessary to identify the driving safety status in varying sections under multiple conditions, the model would be more complicated.

Based on the test on the established dual-indicator input model (correct classification ratio 98.7%, ROC=0.921), and the ranking of the split properties by the information gain rate values, the pupil size played a more critical role in identifying safety status compared to the gaze duration (0.417; 0.206).

6. Comments

When drivers' physiological indicators were changed by the external environment or the subtasks brought to bear, the single indicator-based model was simpler but insufficient. In actual applications, it was necessary to collect various physiological indicator information and extract visual indicator rules from a large amount of data, so as to discriminate driver status under similar conditions in real time or stages, and to predict the following status based on existing data.

7. Conclusions

In this study, drivers' eye movement data were obtained through a superlong tunnel experiment. The real-time indicators, gaze duration, and pupil size, were applied. The safety status discriminant model, based on a single indicator or comprehensive indicator, was established through descriptive analysis and C4.5 decision tree. At the same time, the change patterns of drivers' visual features were explored. The main conclusions were as follows:

Compared with non-tunnel sections, drivers in superlong tunnel sections gazed longer and had a larger pupil size. In tunnel sections, the mid-tunnel section witnessed the longest gaze duration and the largest pupil size.

The average gaze duration was significantly different between the non-tunnel section and the tunnel sections. The difference between the entrance section, the mid-tunnel section, and the exit section was not significant. As to the average pupil size, a significant difference was found between the non-tunnel section and the tunnel entrance and mid-tunnel sections. The difference between the entrance section and mid-tunnel section was not significant, while the difference between the mid-tunnel section and the exit section was significant.

Based on the C4.5 decision tree, a single indicator discriminant model was established for the gaze duration and pupil size, which better distinguished the safety status of non-tunnel and mid-tunnel sections, except for other sections.

The comprehensive discriminant model of gaze duration and pupil size could clearly discriminate the safety status of the non-tunnel section, entrance section, mid-tunnel section, and exit section, with an accuracy rate of 98.7%. Pupil size showed a greater weight for safety status identification compared to gaze duration.

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