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Urban Tunnel Body Landscape Driving Comprehensive Evaluation Study Based on Biomass-Sensing Automobile Field Experiment

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Abstract: Previously, in regard to tunnel design and research, the focus was primarily on traffic capacity and safety requirements, with less consideration given to cave landscape design and its impacts on drivers. This study addressed this gap by proposing a comprehensive evaluation system for urban tunnel landscape driving based on the Analytic Hierarchy Process (AHP) theory. Considering the information and perception aspects of the driving process and the unique landscape characteristics of urban tunnels, we utilized the drivers' perception of biomass as an index layer and performed a simulation using a machine learning algorithm. The proposed model was validated through vehicle field tests that were conducted in four urban tunnels along with a substantial amount of measured biomass data obtained during the experiments. The research demonstrated a strong correlation between the urban tunnel body landscape and the driving comprehensive index, particularly under relevant biomass conditions, which revealed the interactive relationship between urban tunnel body landscape design parameters and biomass. Furthermore, the study analyzed and proposed the impact degree of the urban tunnel body landscape on drivers' biomass indicators, which offered valuable insights into designing tunnel body landscapes with consideration for biomass perception.

Keywords: urban tunnel; tunnel body landscape; biomass; perception; machine learning; comprehensive evaluation

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1. Introduction

Highway tunnels are now widely used in China for their ability to overcome adverse terrain and other advantages [1]. Among those advantages are various characteristics of urban tunnels: the driving speed is relatively slow, and it takes a long time for vehicles to pass through the urban tunnel body part, which may even easily lead to traffic congestion during peak hours. Urban tunnels, especially the overall tunnel body section landscape environment, directly impact drivers' driving safety and road traffic safety. From the perspective of traffic aesthetics, excellent tunnel landscape design cannot only improve the effects of the road landscape and aesthetic value, but also help drivers form a good real-time line of sight to guide them and improve traffic safety [2]. The three-dimensional space form of the urban tunnel landscape comprises road facilities such as the tunnel's entrance, ceiling, side walls, road surface, lighting fixtures, signs and markings, and artificial structures formed by human processing of the natural landscape. Many researchers have conducted studies on the influences of lighting fixtures, traffic facilities and other landscape elements on visual features and have achieved some results [3]. Regrettably, the existing urban tunnel landscape design methods were made by designers and operators to design the parameters of the tunnel landscape or evaluate its design parameters only by biological indicators (such as eye movement), thus lacking a direct and systematic evaluation of the driver's driving status when driving a car through the urban tunnel, and failing to fully consider the safety of tunnel driving.

The evaluation of the urban tunnel landscape can ensure the safe and regular operation of urban tunnels so that drivers can obtain a better driving experience, thereby improving the operation level of the tunnels. From the perspective of tunnel entrance landscape design, many experts and scholars have assessed the impact on drivers' comfort and safety during driving [4–7]. Regarding tunnel landscapes, most evaluations primarily focused on single factors, such as lighting and induction systems to assess their influences on the driving experience [8], while a comprehensive evaluation of tunnel landscapes was rarely conducted. Due to the prolonged duration of vehicle passage, the tunnel body section constitutes the primary component of a driver's urban tunnel driving experience, and the landscape design of the body section in urban tunnels has significant impacts and effects on the overall driving experience.

According to the literature survey, altering the physical attributes (such as color and pattern) of the tunnel body sections impacts drivers' physiological indicators, thereby enhancing their speed perception ability, improving line-of-sight guidance within tunnels and ultimately enhancing driving safety [9]. Biomass serves as an external manifestation of human psychological changes, which is beyond subjective control. Evaluating drivers' psychological changes through objective and accurate means is crucial. Consequently, some scholars directly investigated drivers' biomass (such as ECG, EEG, reaction time and visual efficacy) to assess their safety and comfort by observing dynamic perception or biomass variations during driving [10,11]. As early as 1974, some researchers have used eye-tracking technology to record drivers' visual characteristics. These data focused on the partial eye movement features of drivers approaching tunnel entrances. According to the study, during the process of entering a tunnel, the drivers' gaze points gradually and frequently fixated on the entrance, from which the concept of a fixation point was proposed [12]. Afterward, research was conducted on the visual attention characteristics of drivers in the entrance section of tunnels. This study utilized an onboard video eye-tracking system to analyze visual parameters such as the fixation point density map, eye movement scan amplitude and average fixation time [13]. In addition to being able to discern the drivers' states, eye movement visual features, fixation points, eye movement scan amplitude and average fixation time can also serve as indicators for evaluating drivers' physiologies and behavior, which could provide a basis for designing tunnel entrances and exits with safety considerations [14–17]. In the context of indoor simulation experiments, pupil diameter and heart rate growth (HRG) were employed as indicators to investigate the influences of tunnel arch color on the drivers' behavior. These studies have revealed the significant impacts of tunnel arch color on both the drivers' pupil diameters and HRG, thereby concurrently affecting their operational performance and eye movement behaviors [18–20]. Research on eye movement parameters can provide further support for the safety design of tunnel entrances. Experiments were conducted using an eye-tracking system to obtain drivers' eye movement parameters when passing through highway tunnels. Analysis on the patterns of these parameters suggested that a rapid decrease in brightness can cause changes in fixation position and duration, so it was suggested to use measures that provide shade at tunnel entrances [21–23]. Eye movement parameters have also been utilized to investigate the illumination design within tunnels. In a study conducted by Kang [24], the participants' reaction times, rates of change in the pupil area and blink frequencies were measured through indoor visual performance experiments and quantitatively represented the antagonistic mechanism between luminance intensity and luminance difference. The researchers established the Lav-U1 curve, which adhered to the safety threshold for the comprehensive visual efficiency of drivers. Furthermore, Bourdy determined the length of the enhanced lighting section for the tunnel by examining the drivers' abilities to perceive target objects under dynamically changing lighting conditions [25].

Driving in tunnel segments not only affects eye-related visual parameters but also the psychological parameters of drivers. Nakazono pointed out that tunnel entrances and exits create psychological loads on drivers and affect their safety by compiling and summarizing data from 1119 tunnels in 37 motorways over a 32-year period. Therefore, it is recommended to optimize tunnel entrances and exits so as to ensure the safety of drivers in tunnels [26]. In addition to investigating tunnel entrances and exits, research scholars have also examined various human physiological responses in relation to tunnel slope, luminance of the tunnel light environment and the lowest point of river crossing tunnels. For instance, experimental findings on tunnel slope revealed its significant impact on heart rate variability and vehicle speed, thereby obtaining a safe gradient and travelling speed when driving uphill and downhill in urban underpass tunnels [27]. Regarding the study on the luminance of the tunnel light environment, researchers discovered a close relationship between drivers' perception of environmental brightness and their physiological as well as psychological states within long tunnels. To enhance illumination performance, driving safety and energy efficiency without increasing light source intensity, a method involving contour markers was proposed to regulate non-visual effects [28]. Furthermore, maximum heart rate variability and average heart rate variability can be used as physiological indicators to assess a driver's physiological load, and then to assess the safety of the lowest point in an urban river crossing tunnel [29].

The aforementioned contents revealed that visual feature data and psychological reactions constitute the primary focus of biomass research in tunnel studies. These investigations not only provide guidance for tunnel entrance construction but also inform the design of lighting environments in the tunnel structure and the enhancement of overall operational safety.

In the existing studies, there is no mature system for urban tunnel landscape evaluation and drivers' perception of biomass under the condition of a human-vehicle-tunnel light environment which, as a component of physical quantity information, is not fully considered. The evaluation was basically carried out from the single dimension of safety and comfort, and there was a lack of comprehensive evaluation combining safety and comfort and almost no evaluation from the perspective of biomass perception. Therefore, it has significant academic and practical implications to carry out a comprehensive evaluation of urban tunnel landscape driving based on biomass perception.

In conclusion, to qualitatively evaluate and quantitatively analyze the impact of tunnel body landscape design on driving reliability systematically, this study focused on the physiological factors of drivers and adopted machine learning methods. By leveraging statistics and algorithms, machine learning allows computers to automatically identify and understand patterns and make predictions or decisions based on past experiences. To the best of our knowledge, it is the first attempt to analyze the correlation between tunnel body landscape design and driving reliability. Meanwhile, based on this, a driving reliability evaluation system for urban tunnel body landscape segments was constructed, aiming to quantitatively assess the influences of urban tunnel body landscape on driving reliability. Additionally, this paper further explored the impact weights of drivers' physiological performance on driving reliability:

By integrating physiological factors and utilizing extensive experiments and data analysis, this study pioneers the construction of an evaluation system for driving reliability in urban tunnel body segments.

Using the SHAP model, the influences of urban tunnel body landscape on various physiological factors of drivers were systematically analyzed and quantified, which provides empirical evidence.

This paper provides theoretical references for related studies on urban tunnel body landscape design using physiological factors and for tunnel body landscape designers.

2. Related Works

The tunnel is an underground engineering structure and represents a human utilization of subterranean space, and thus it emphasizes the paramount importance of its engineering safety. In recent years, in addition to updating the hierarchical analysis model in the research on the safety evaluation of tunnel engineering, such as establishing a comprehensive evaluation system that combines the expert system evaluation model based on fuzzy mathematics and the hierarchical analysis method (AHP), it has also applied neural network operations to the evaluation system [30–33]. For example, a genetic algorithm combined with an AHP algorithm was used to construct a tunnel construction risk evaluation system [32]. Furthermore, novel probability distribution models have been developed by researchers by employing dynamic Bayesian networks and data from conventional construction to accurately assess the safety of tunnel projects [34]. Furthermore, some scholars have compiled and analyzed 246 instances of tunnel collapse accidents and developed a collapse risk assessment index system using artificial intelligence prediction methods including the random forest algorithm, radial basis function neural network, BP neural network model and the particle swarm algorithm for optimizing the BP neural network model [35].

The construction of tunnels necessitates consideration for both engineering safety and its crucial impact on the ecological environment. Consequently, numerous scholars have conducted relevant research on the ecological environment assessment of road tunnels. The research in this field was evaluated and analyzed using the following range of methods: Some scholars adopted a comprehensive evaluation index system and established a grading standard for the comprehensive evaluation index system of ecological and environmental impacts of highway tunnels [36]. In terms of dealing with a large amount of data, scholars have also proposed the establishment of an evaluation system based on the establishment of a comprehensive database and the use of decision analysis methods or tree structure theory (LAC theory) to stratify and evaluate the evaluation object and establish an evaluation system [37–39]. Also, in terms of the ecological environment, some researchers have established the SVR model using the environmental carrying capacity as the evaluation standard and then constructed the tunnel project environmental impact evaluation index system [40].

Apart from the evaluation of engineering and ecological safety, tunnels also require assessment in terms of operational safety. For instance, Ding conducted a study that integrated the four conventional indicators of "people, vehicles, roads and environment" and developed an evaluation system comprising 13 primary indicators primarily based on urban tunnel maintenance technology, tunnel transport management level, traffic environment and the conditions of people and vehicles [41]. Also, there are studies that have analyzed the main factors affecting traffic safety from the perspective of traffic safety risk and summarized the five major indicators of tunnel foundation condition, safety facilities, management, traffic and environment [42]. Meanwhile, other scholars have used a fuzzy theory to analyze traffic safety attributes and applied the fuzzy AHM (Attribute Hierarchical Model) method in comprehensive evaluation to establish a reasonable safety evaluation model [43].

As tunnels become increasingly integrated into urban life, the construction of tunnel landscapes has garnered greater attention, thus making evaluations related to these landscapes crucially important. Some studies have proved that the AHP method and fuzzy mathematical method can be used to make a comprehensive evaluation of the tunnel landscape and construct a comprehensive evaluation system [44,45]. Moreover, other researchers have directly adopted the fuzzy mathematical theory and constructed a fuzzy comprehensive evaluation method based on the diversity of tunnel landscapes and the surrounding environment [46,47].

Although tunnel landscape has become an integral component of contemporary tunnel construction, the evaluation system in this domain lacks systematic development due to delayed research initiation. In this study, after synthesizing the above traditional tunnel construction-related evaluation methods and tunnel landscape-related evaluation methods, a comparative study was conducted (Table 1). It was found that the tunnel landscape evaluation study was more influenced by traditional tunnel engineering and construction evaluation methods, which fail to consider the driver in the evaluation link, and thus the evaluation only focused on the aspects of safety or comfort without combining safety and comfort and, even more so, not taking into account the impact of the aesthetics of the tunnel landscape.

Table 1. Classification table of tunnel-related evaluation systems.

Classification	Evaluation System/Model	Primary Content
Tunnel Related Evaluation System	Tunnel construction risk evaluation index system	Contains 1 goal, 2 types of guidelines and 5 indicators
	Dynamic Bayesian Networks and traditional construction data	Probability distribution models for predicting tunnel construction processes
	Entropy theory	The likelihood of an accident in railway gas tunnel construction is classified as level 3
	AHP-expert scoring method	Risk evaluation study
	Fuzzy comprehensive evaluation theory using hierarchical analysis	Tunnel structural health and safety judgement model
	Structural safety evaluation of highway tunnels	Addressing the imprecision of human rationality
	AHP-Extenics Evaluation System	Evaluation system of workers' comfort during construction of high geothermal deep-buried tunnels
Ecological Environmental Impact Assessment System	Indicator system for comprehensive evaluation of ecological and environmental impacts of highway tunnels	7 secondary and 18 tertiary indicators
	TIS (Tunnel Impact on Springs)	Assessment of the impact of tunnelling on spring discharges and establishment of a comprehensive database
	LCA theory	Resource and energy consumption and solid waste generation at all stages of the tunnel's life cycle: construction, operation and dismantling
	Life cycle assessment thinking and impact pathway analysis methods	Quantitative relationship between NO2 and SO2 concentrations and health damage in tunnel construction
Tunnel Traffic Safety Evaluation System	Traffic safety evaluation of highway tunnels and urban tunnels	A total of 13 evaluation indicators for four major factors, namely, the state of maintenance technology, the level of tunnel operation and management, the traffic environment and the conditions of pedestrians and vehicles
	Potential loss of persons trapped in tunnels	Improved evacuation modelling for quantitative assessment of highway road fires
	Risk assessment	Five major indicators of tunnel infrastructure, safety facilities, management, traffic and environment
	Hierarchical analysis model	Safety evaluation model

3. Construction of a Comprehensive Evaluation Index System for Urban Tunnel Body Landscape Driving

3.1. Construction of Evaluation Index System

1. Analysis of the essence of an urban tunnel landscape. This research focuses on analyzing the nature and driving stability of the selected urban tunnel body landscape to confirm the selection of indicators and the determination of weights in the evaluation index system.

2. The establishment of the indicator system. This research aims to establish an index system for driving stability in accordance with the landscape conditions of urban

tunnels. However, in the actual implementation process, the indicators can be modified and improved according to the different characteristics of different urban tunnels.

3. The choice of an evaluation method. Whether the results of this research can correctly reflect the relationship between the nature of the urban tunnel body landscape and driving safety and comfort depends on whether the method is correct or not. Therefore, a machine learning model was selected as the evaluation and analysis method.

This study aims to analyze and evaluate the urban tunnel body landscape design and its impact on driving safety and comfort to further guide the tunnel body landscape design and improve tunnel driving safety and comfort. Given the insufficient quantification of traffic signs in the tunnel body, the marks inside the tunnel sidewalk and the complexity of the landscape in the tunnel body, it is not easy to construct a comprehensive driving evaluation index system comprehensively and systematically through the tunnel body landscape. This study draws on the existing research results, uses the quantified driving state biomass index of the driver when driving in the tunnel body, constructs a comprehensive evaluation index system for urban tunnel body landscape driving and then evaluates the advantages and disadvantages of the tunnel body landscape design.

It is a systematic project to build a comprehensive evaluation index system for urban tunnel landscape driving. A scientific and reasonable index system is the basis, and it guarantees an accurate evaluation of the system. It is also important to correctly guide a system to develop in the right direction. Therefore, the selection of indicators in this study follows four principles, namely people-oriented, systematic and scientific, measurable and comparable, representative and comprehensive. The target hierarchical framework construction method establishes the comprehensive evaluation index system framework of the urban tunnel body landscape by referring to previous research results and consulting relevant experts, professors, and tunnel industry practitioners. Figure 1 shows the construction steps.

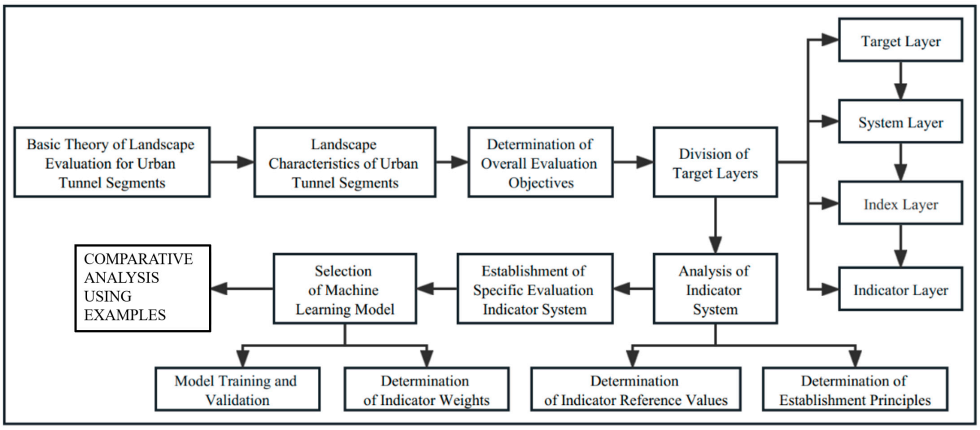


Figure 1. Construction steps of the comprehensive evaluation index system of the urban tunnel body landscape.

3.2. Hierarchical Establishment of Evaluation Index System

Based on the principle of data measurability constructed by the indicator system, the data can accurately indicate the typical principles of the urban tunnel body landscape. It can compare and reveal the advantages and disadvantages of different tunnel body landscape design principles, as well as the system nesting principle of a hierarchical classification of the system. In this study, the entire evaluation index system is divided into four levels using the target hierarchical framework method: the target layer, the system layer, the index layer and the indicator layer, as shown in Figure 2.

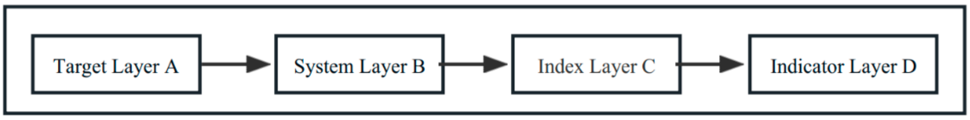


Figure 2. Hierarchical diagram of the evaluation system.

Target Layer A: A comprehensive index of the urban tunnel body landscape driving reflects the safety and comfort of urban tunnel body landscape driving.

System Layer B: This paper supports that driving reliability represents driving safety and is also related to driving comfort. Therefore, according to the comprehensive attributes of urban tunnel body driving, Target Layer A is decomposed into two systems: safety and comfort.

Index Layer C: It corresponds the system elements of the urban tunnel body landscape to the system layer.

Index Layer D: From the perspective of this research, the corresponding biological indicators are selected and corresponded to the index layer. The final screening determines 12 biomass indicators. Check Table 2 for details:

Table 2. Comprehensive evaluation index system of urban tunnel body landscape driving.

Target Layer	System Layer	Index Layer	Biomass Index Layer	Description
A. Comprehensive index of landscape driving in urban tunnels	B1 Safety	C1 Ocular data	D1 Eyelid movement parameters [6,48]	
			D2 Fixation count	A higher fixation count means that the driver's mental state is better and safer; a lower fixation count means that the driver starts to get tired and it is more dangerous.
			D3 Variation range of pupil diameter [6]	Under normal circumstances, the change range of the pupil is 1.3~8 mm. Light changes will cause pupil diameter changes. If the change is greater, the driving state will be risky.
		C2 Physiological data	D4 Heart rate [49,50]	The average heart rate of an adult is 75 beats/min in a steady state, and the heart rate increases to >100 beats/min when stress is dangerous.
			D5 Blood pressure	In a safe state, the blood pressure is stable; in a tense state, the blood pressure will rise slowly; and in a dangerous state, the blood pressure will rise rapidly.
			D6 Heart rate variability [51]	Heart rate variability < 20%, safe psychological hint; 20% < heart rate variability < 50%, nervous psychological hint; and heart rate variability > 50%, unsafe psychological hint.
	B2 Comfort	C3 Ocular data	D7 Blink frequency [6,48]	Blink frequency is used as the reference for comfort evaluation. Normal adults blink 10–20 times per minute. If blink frequency is higher than 20, the person feels anxious and uncomfortable; if blink frequency is lower than 10, the person is in a state of high tension.
			D8 Fixation count	In the comfortable state, the number of the fixation count changes little; in the tense state, the number of the fixation count decreases.
			D9 Pupil area change rate [6]	Under normal circumstances, the change rate of the pupil area is less than 20%; in a relatively tense state, 20% $\leq$ pupil area change rate $\leq$ 40%; and in a very tense state, pupil area change rate > 40%
		C4 Physiological data	D10 Heart rate [49,50]	The average heart rate is 75 beats/min in a comfortable state and >100 beats/min in an uncomfortable state.
			D11 Blood pressure	In a comfortable state, the blood pressure is stable; in a tense state, the blood pressure will rise slowly; and in a dangerous state, the blood pressure will rise rapidly.
			D12 Heart rate variability [51]	Heart rate variability < 20%, comfortable state; 20% < heart rate variability < 50%, nervous state; and heart rate variability > 50%, fear state.

4. Vehicle Field Test of Urban Tunnel Landscape

4.1. Experimental Tunnel

To ensure that the driver's physiological load is not affected by other factors in the tunnel, an urban tunnel without an uphill or downhill, sharp bends or branch roads was selected. The selected tunnel is a two-way lane with a length of 1~3 km and a design speed of 60~80 km/h.

4.2. Experimental Indicators

For the vehicle field test of the urban tunnel body landscape, the evaluation index system created in Section 3.2 can be referred to. The eyelid movement parameters, the number of fixation counts, the range of pupil diameter change, heart rate, blood pressure, heart rate variability, blink frequency and pupil area change rate were selected as test indicators. All of the above indicators can reflect the drivers' physiological information and represent the drivers' current driving state. Table 3 shows the specific determination range.

Table 3. The reference range of each physiological index.

	State	Safe	Relatively Safe	Unsafe
Safety	Eyelid movement parameters (PERCLOS)	0~0.075	0.075~0.15	0.15~1
	Fixation count	16~20	20–30	30+
	Variation range of pupil diameter	1.3~8 mm	1.0~8.5 mm	0.5~9.0 mm
	Heart rate	70~110	110~140	140~190
	Blood pressure (SBP)	120 mmhg−	120~180 mmhg	180 mmhg+
	Heart rate variability	0.2−	0.2~0.5	0.5+
Comfort	State	Comfortable	Relatively Comfortable	Uncomfortable
	Blink frequency	10~20	20+	10−
	Fixation count	16~20	20–30	30+
	Pupil area change rate	0.2−	0.2~0.4	0.4+
	Heart rate	70~110	110~140	140~190
	Blood pressure (SBP)	120 mmhg−	120~180 mmhg	180 mmhg+
	Heart rate variability	0.2−	0.2~0.5	0.5+

4.3. Experimental Objects and Experimental Equipment

In total, 120 drivers participated in the test, including 60 males and females aged between 20 and 50, with an average of one year or more of driving experience.

In selecting the test equipment, the German SMI eye tracker was used to collect the drivers' pupil areas, fixation counts, pupil area change rates and pupil area change ranges. The eye tracker has a sampling frequency 60 Hz and a gaze tracking accuracy of less than 0.1°. The pupil tracking accuracy is 0.5°~1°. The heart rate, blood pressure and heart rate variability were collected by the MP150 physiological recorder produced by the American BIOPAC company (Goleta, CA, USA). The sampling frequency is 400 kHz. The AcKnowledge software v5.0.8 was used to analyze the changes in physiological indicators. ECG patches were pasted onto different positions and connected to the ECG module with corresponding wires to collect accurate physiological indicators.

4.4. Experiment Process

Figure 3 shows the overall test flow during the real-time acquisition process. Before the test, the temperature inside the car was set to 26 degrees Celsius to ensure that the current driving environment was the best for the driver and staggered the morning peak, evening peak and foggy weather for the experiments. The first step was to plan the driving route and explain to and remind the drivers of the driving precautions, including keeping the lane still when driving at a constant speed according to the speed limit. The second step was for each driver to wear an eye tracker, with the tester sitting in the back row adjusting the computer, using the 1-point calibration method to calibrate the driver's gaze point and compare whether the driver's gaze area was consistent with the annotation area captured by the eye tracker in the live image and, if not, recalibrate until the eye tracker capture area was consistent with the driver's gaze area. The third step was for each driver to wear a multi-channel physiological recorder to test whether the collected data was normal and required the driver to test various driving actions to ensure that the physiological recorder acquisition equipment did not affect the driver's normal driving. The fourth step was to start the car and get ready to go. To avoid the impact of accidental errors, each driver was asked to drive the same vehicle, pass through the same tunnel five times in forward and reverse directions at the design speed of the tunnel, and the data with a heart rate variability greater than 50% was discarded. Finally, the average value of each driver's biomass was taken as the final test result of the tunnel.

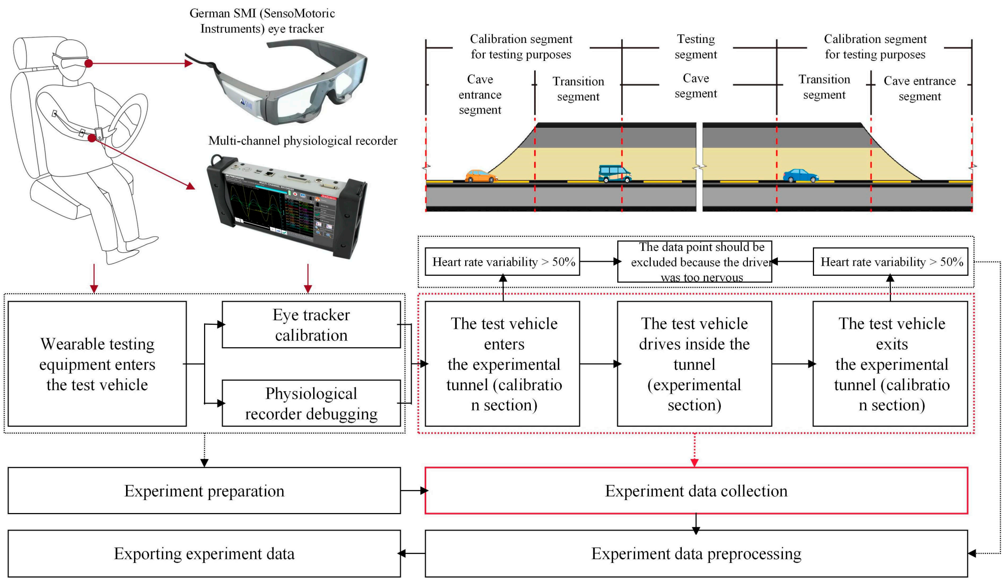


Figure 3. Flow chart of data collection.

5. Application of Machine Learning Model Evaluation Methods

5.1. Overview of the Architecture

In order to quantitatively and qualitatively analyze the impact of urban tunnel body landscape design on the driving comprehensive index systematically, the machine learning method was used to further analyze the correlation between the driver's driving state and the tunnel landscape design based on the comprehensive evaluation index system of urban tunnel landscape driving constructed in Section 3. The main framework of its research content is shown in Figure 4. In the analysis process, the data collected in Section 4 were first preprocessed. Secondly, the data were randomly divided into a training set and a test set at a ratio of 8:2. During the partitioning process, physiological data of various drivers driving cars through different types of tunnel cavern landscapes were present in both the training and testing sets, which guaranteed that the distributions of the training and testing sets were the same. Afterwards, the XGBoost algorithm [52] was used to establish a machine learning model for driving safety and comfort prediction. Finally, combined with the SHAP model [53], the specific influence degree of the tunnel body landscape on the driver's biomass was jointly explored. The main factors that cause different biomass effects on the tunnel driving comprehensive index were quantitatively and qualitatively analyzed from the data level.

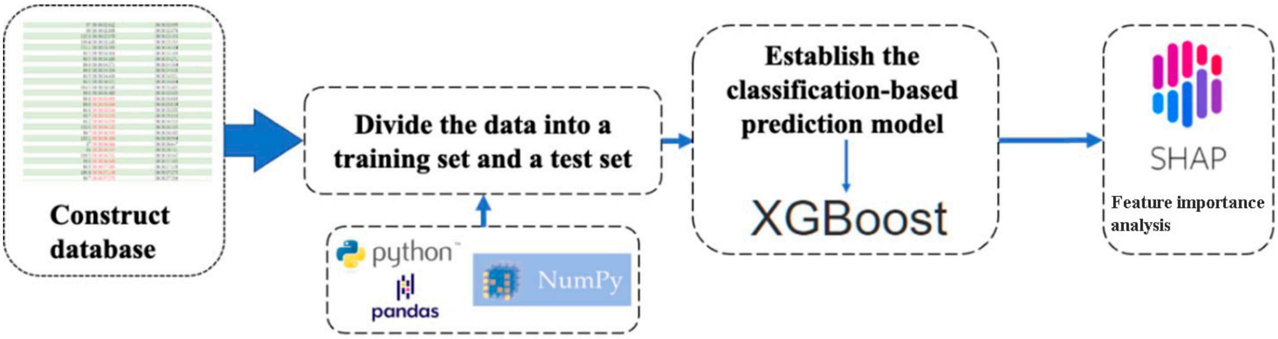


Figure 4. Overview of the architecture.

5.2. Data Preprocessing

Before model training, in order to avoid the model training deviation caused by the order of magnitude difference of each biomass and to accelerate the model convergence speed, the fixation count number, the blink frequency, the range of pupil diameter, heart rate and blood pressure (SBP) were normalized according to Formula 1, and mapped to the [0,1] interval, respectively.

$$h^* = \frac{h - \min(h)}{\max(h) - \min(h)} \quad (1)$$

wherein represents the original data; $\mathbf{max}(\boldsymbol{h})$ ***and*** $\mathbf{min}(\boldsymbol{h})$ represent the maximum and minimum values of the original data, respectively; and $\boldsymbol{h}^*$ represents the normalized value.

5.3. Model Training and Validation

In order to train the XGBoost model to quantitatively analyze the impact of the urban tunnel landscape on the driving comprehensive index, combined with the consultation opinions of many experts in the field, it divided the comprehensive evaluation index of urban tunnel landscape driving into four levels according to the biomass index values, namely Fail, Pass, Good and Excellent, and they were mapped to numerical labels and represented by 0, 1, 2 and 3, in turn. When four or more indicators are unsafe/uncomfortable, it is judged that the overall driving indicator of the tunnel body landscape is a Fail; when three or fewer indicators are unsafe/uncomfortable, it is judged that the overall driving indicator of the tunnel body landscape is a Pass; when four or more indicators are safe/comfortable, it is judged that the tunnel landscape driving comprehensive index is Excellent; when the three and below indicators are safe/comfortable, it is judged that the tunnel landscape driving comprehensive index is Good, and the tunnels are evaluated with index conflicts according to the minimum standard.

5.3.1. Evaluation Index

In terms of evaluation indicators, this paper selected the accuracy rate, F1 value, PR curve and ROC curve as indicators to measure the performance of the XGBoost model, aiming to evaluate the effectiveness and practicability of the proposed method more comprehensively.

TP represents the number of samples whose real labels are positive and are predicted to be positive by the model; ***FP*** represents the number of samples whose real labels are negative examples but are predicted to be positive examples by the model; ***FN*** represents the number of samples whose real labels are positive but are predicted to be negative by the model; ***TN*** represents the number of samples whose real labels are negative examples and are predicted to be a negative examples by the model.

Where the accuracy rate is expressed as:

$$\text{Accuracy} = \frac{TP + TN}{TP + FP + FN + TN} \quad (2)$$

Express the accuracy rate as:

$$\text{precision} = \frac{TP}{FP + TP} \quad (3)$$

Express the recall rate as:

$$\text{recall} = \frac{TP}{TP + FN} \quad (4)$$

Express the F1 value as:

$$\text{F1} = \frac{2 * precision * recall}{precision + recall} \quad (5)$$

The PR curve describes the changes in *precision* and *recall*, and its area under the curve reflects the performance of the XGBoost model. The larger the area under the curve is, the better the performance of the model is, which indicates that the data fitting is sufficient. Also, it can explain that from a physiological point of view, it is feasible to use machine learning methods to predict the comprehensive evaluation of urban tunnel body landscape design quantitatively or qualitatively for driving.

The ROC curve is used to evaluate the model's predictive ability. In the curve, the closer the ROC curve is to the upper left corner of the coordinate axis, the better the prediction effect is; the closer the ROC curve is to the diagonal, the worse the prediction effect is; and the larger the area under the ROC curve is, the better the prediction effect of the model is.

5.3.2. Tuning and Validation

In order to make full use of all the data in the training data set and objectively evaluate the model's performance and judge the feasibility of the quantitative and qualitative evaluation of the urban tunnel landscape driving comprehensive index, a ten-fold cross-validation was used to test the performance of a grid search on the model hyperparameters during training. Finally, the determined hyperparameters of the comprehensive index evaluation model are shown in Table 4.

Table 4. Hyperparameter values.

Name	Value
eta	0.05
min_child_weight	1
max_depth	7
gamma	0
subsample	1
colsample_bytree	1
colsample_bylevel	1
lambda	1
alpha	0
scale_pos_weight	1
objective	multi:softprob
eval_metric	auc
iter	1000

After using the above optimal hyperparameters to predict the validation set, the obtained model accuracy, precision, recall and F1 values are shown in Table 5.

Table 5. Validation results of the optimal model.

Norm	Accuracy	Precision	Recall Rate	F1 Value
Value	0.95	0.96	0.93	0.94

Figures 5 and 6 show the PR curve and AUC curve, respectively.

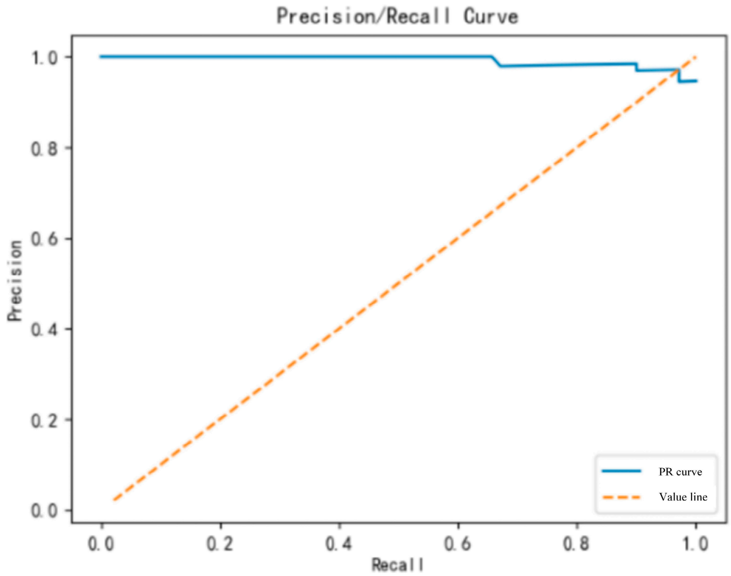


Figure 5. PR curve.

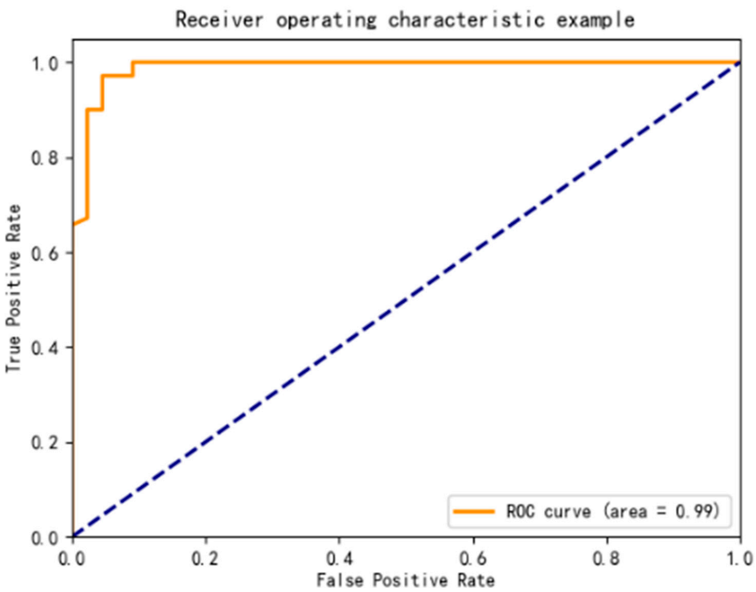


Figure 6. AUC curve.

It can be seen from the Figure that the area under the PR curve and AUC curve of the model during the training process is relatively large.

The model training is relatively sufficient, and the experimental prediction results are relatively accurate. It is proved that from the perspective of biological indicators, it is feasible to use machine learning methods to qualitatively predict the evaluation of the driving comprehensive index by urban tunnel body landscape design.

5.4. Quantitative Analysis of Feature Importance

Based on the comprehensive index prediction model of urban tunnel body landscape driving obtained through the XGBoost model training in Section 5.3, the SHAP model was used to conduct a detailed quantitative analysis on the relevant factors affecting the comprehensive evaluation index of driving. Algorithm 1 displays the steps of its feature importance quantification algorithm.

Algorithm 1 Feature Importance Quantification Algorithm

Input: XGBoost model $\{T_1, T_2, \ldots, T_m\}$
Output: Importance of each feature
Procedure:
Calculate the importance of feature j in a single tree $\hat{J}_j^2(T) = \sum_{t=1}^{L-1} \hat{\imath}_t^2 1(v_t = j)$, where L is the number of leaf nodes of the tree, $L-1$ is the number of non-leaf nodes of the tree (The constructed trees are all binary trees with left and right subsets), v_t is a feature associated with node t, and $\hat{\imath}_t^2$ is the reduction value of bisect loss after node t is split.
Calculate the global importance of feature j as $\hat{J}_j^2 = \frac{1}{M}\sum_{m=1}^{M} \hat{J}_j^2(T_m)$

As shown in Figure 7, through calculation, it can be finally concluded that the heart rate variation (hrv) accounts for the highest rate of 43% in the evaluation of the urban tunnel landscape driving comprehensive index, followed by blood pressure (bp), accounting for 10%.

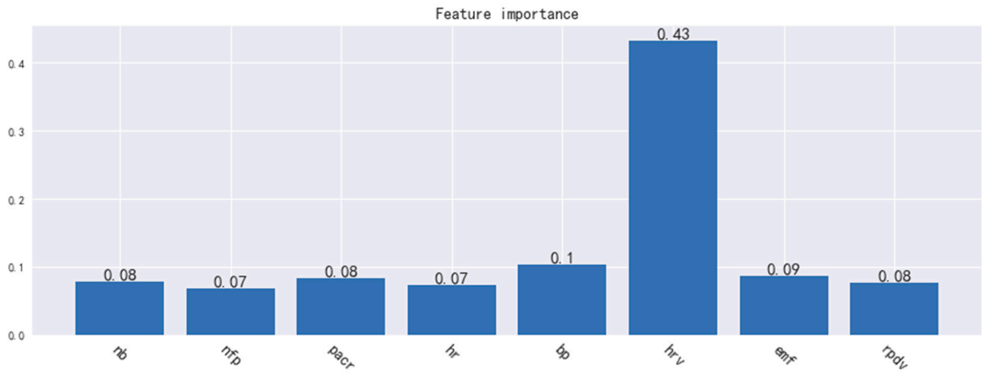


Figure 7. Feature importance.

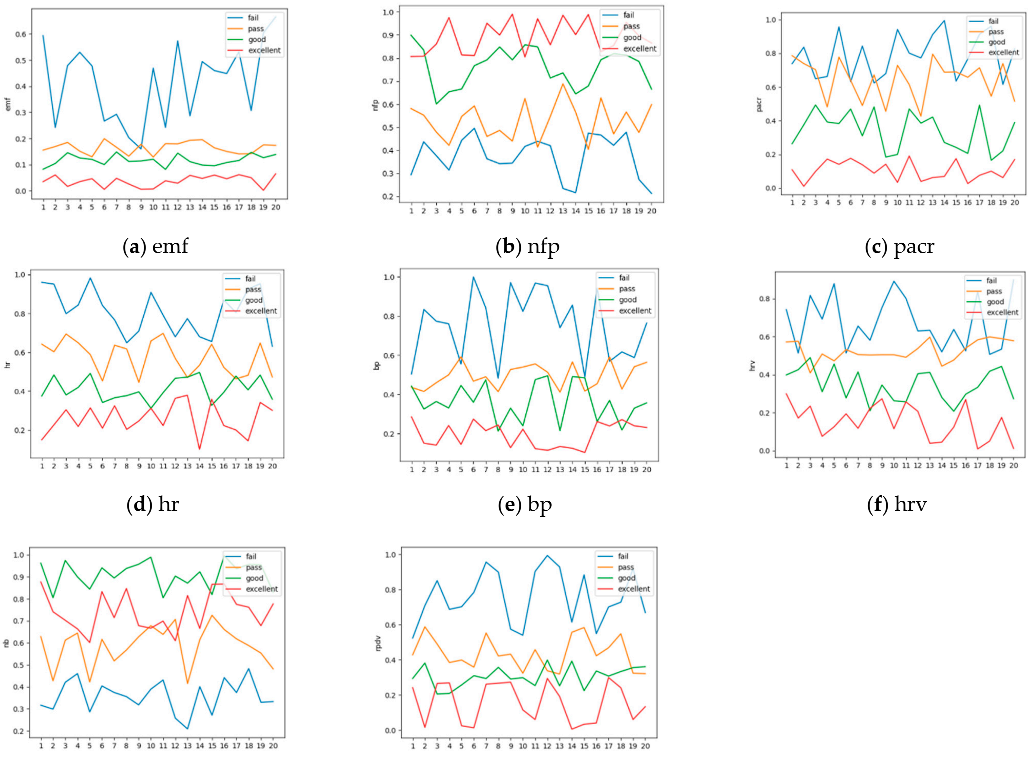
Eyelid movement parameters (EMF), number of blinks (NB), number of fixation counts (NFP), pupil area change rate (PACR), pupil diameter change range (RPDV) and heart rate (HR) account for 9%, 8%, 7%, 8%, 8% and 7%, respectively.

6. Case Verification

6.1. Urban Tunnel Case Determination

To further verify the accuracy and robustness of the method proposed in this paper, this paper refers to the division method of tunnel body landscape design indicators in Section 5.3. The experimental data of four urban tunnels whose cave landscape evaluations are Fail, Pass, Good and Excellent were analyzed and discussed. The selected actual driving data comes from 20 drivers, consisting of 10 males and 10 females, aged between 20 and 50 years old (the average age of all males and females is similar) to ensure the universality of the verification results.

Due to data privacy reasons, the actual name of the tunnel is kept private. The physiological data information of each driver passing through the above-selected tunnel is shown in Figure 8. It demonstrates multiple physiological data samples obtained from 20 selected drivers while driving through tunnel body landscapes of different categories. It is evident that there are significant variations in the numerical values of physiological information across different categories of tunnel body landscapes, which indicates the feasibility of evaluating the impact of the tunnel body landscape on driving reliability through a physiological information assessment.



(**a**) emf (**b**) nfp (**c**) pacr

(**d**) hr (**e**) bp (**f**) hrv

(**g**) nb (**h**) rpdv

Figure 8. Physiological data visualization.

6.2. Application of Comprehensive Driving Evaluation System

Based on the quantitative analysis of the importance of the features in Section 5.4, the comprehensive evaluation system for urban tunnel body landscape driving is finally constructed in this paper in Table 6.

Table 6. Comprehensive evaluation index system of landscape driving in urban tunnels.

Target Layer	System Layer	Index Layer	Indicator Layer	Weight
A. Comprehensive index of landscape driving in urban tunnels	B1 Safety	C1 Ocular data	D1 Eyelid movement parameters	0.09
			D2 Fixation count	0.07
			D3 Variation range of pupil diameter	0.08
		C2 Physiological data	D4 Heart rate	0.07
			D5 Blood pressure	0.1
			D6 Heart rate variability	0.43
	B2 Comfort	C3 Ocular data	D7 Blink frequency	0.08
			D8 Fixation count	0.07
			D9 Pupil area change rate	0.08
		C4 Physiological data	D10 Heart rate	0.07
			D11 Heart rate	0.1
			D12 Heart rate Variability	0.43

6.3. Driving Comprehensive Index Analysis

According to Figure 8, the advantages and disadvantages of urban tunnel body landscape design have a significant influence on the various biomass indicators of drivers. Among them, when a driver drives a car through a tunnel with a cave landscape evaluation grade of Fail, the eyelid movement parameters, heart rate, blood pressure and heart rate variability are significantly higher than those of other types of tunnels. Blink frequency, the number of fixation counts, and the change rate of the pupil area are significantly lower than those of other types of tunnels, which indicates that the biomass can genuinely reflect the driving state of the driver and then evaluate the advantages and disadvantages of the landscape design of the tunnel body. Subsequently, qualitative and quantitative analysis on the selected urban tunnel data was conducted according to the model obtained in Section 5 and the importance of features.

(1) Qualitative analysis

First, each urban tunnel driver's physiological characteristic information was input into the XGBoost model trained in Section 5.3, and the model prediction results are shown in Figure 9.

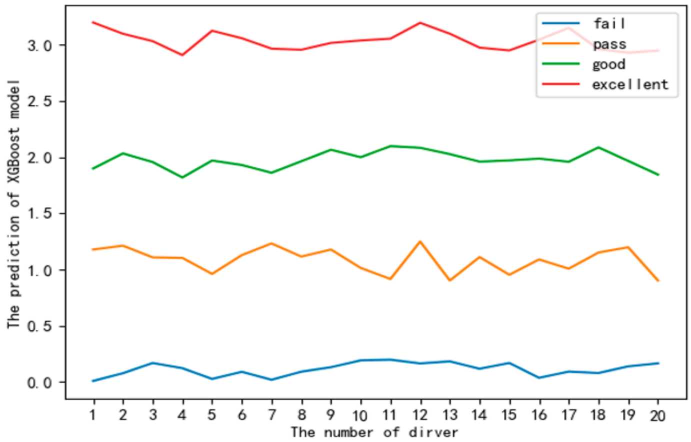


Figure 9. Model prediction results.

From Figure 9, the prediction results of the model are the same as the comprehensive driving index of the original tunnel landscape, which preliminarily proves the feasibility of applying machine learning methods to analyze the urban tunnel landscape quantitatively.

Secondly, the SHAP model was used to analyze the influences of each feature on the model's output globally and locally, as shown in Figures 10 and 11, respectively. In Figure 10, it can be observed that the heart rate variability feature of the drivers has the highest impact on the overall driving index evaluation, with fluctuations of up to 2.5 compared to other biological indicators. The individual heart rate variability feature spans almost the entire range of the tunnel driving index, with a significant effect, as indicated by the predominant red color on the right side, which suggests that when the tunnel landscape design is poor, there is higher heart rate variability. Next, the blood pressure feature is considered, which has a slightly lower influence compared to the heart rate variability feature. Additionally, the other six physiological features also have a certain degree of impact on the evaluation of the driving index. Figure 11 provides further support for the aforementioned analysis, which indicates that the evaluation of the driving index is determined by multiple factors rather than a single biological indicator alone.

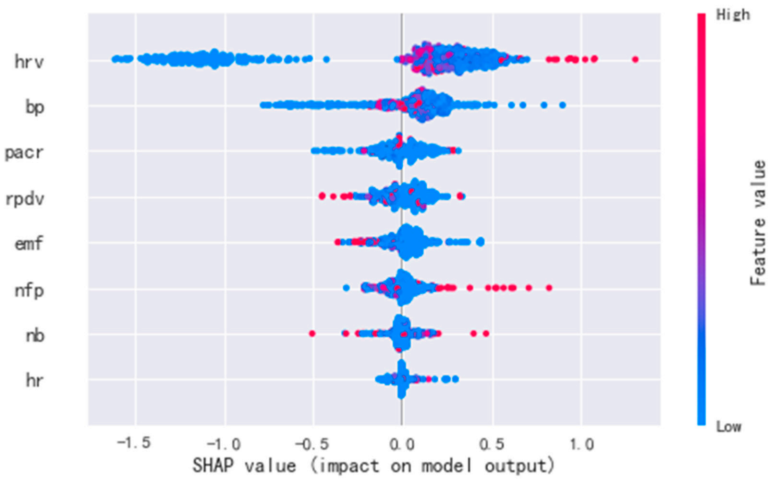


Figure 10. Global qualitative analysis of features.

Figure 11. Local qualitative analysis of features.

(2) Quantitative analysis

According to the comprehensive evaluation index system of urban tunnel body landscape driving obtained in Section 6.2, the box plot was used to visually analyze the selected data, as shown in Figure 12. When drivers pass through four types of urban tunnels, heart rate variability and blood pressure had relatively large changes, while the other six biomass had relatively minor changes, which shows that the two indicators of heart rate variability and blood pressure strongly reflect the landscape of the tunnel cave, and changes in the landscape of the tunnel cave have a greater impact on it. Eyelid movement parameters, number of blinks, number of fixation counts, pupil area change rate, pupil diameter change range and heart rate are weak. The change in tunnel landscape has little effects on them, which is like the conclusion in Section 5.4.

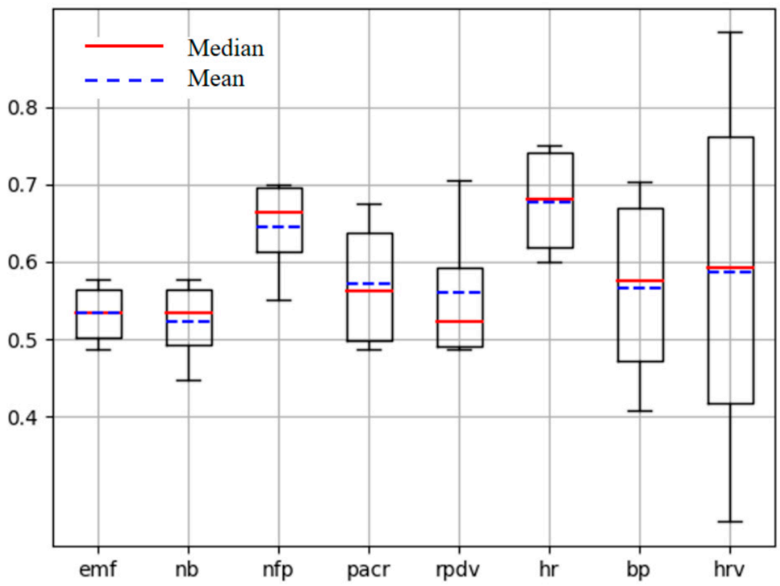


Figure 12. Physiological data visualization (Box Plot).

7. Conclusions

This study starts with the rationality of cave body landscape design and confirms the correlation between urban tunnel body landscape design and the driving composite index. Specifically, it starts with the rationality of tunnel body landscape design and utilizes the XGBoost model to analyze the correlation between urban tunnel body landscape design and driving reliability. Subsequently, it employs the SHAP model to explore the impact weights between driving reliability and various physiological factors in the evaluation system under different tunnel body landscapes in detail. Consequently, an evaluation system for driving reliability in urban tunnel body landscape design was constructed. Afterward, with ample data analysis results, it was demonstrated that it is feasible to use the proposed evaluation system to assess the merits and drawbacks of tunnel body landscape design. In the future, we will further investigate the relationship between safety and comfort in the evaluation system for driving reliability in urban tunnel body landscape design. Most importantly, we will delve into the modular design of the urban tunnel body landscape, enabling the assessment of the merits and drawbacks of each module design from a driving reliability perspective, which will promote rational, safe and comfortable urban tunnel body landscape design.

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