

Chapter 2

The Relationship between Driver Fatigue and Monotonous Road Environment

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Driver fatigue is a significant contributing factor to numerous traffic crashes, which brings great socioeconomic concerns to policy makers, the general public as well as transportation professionals. There is an emerging consensus that the monotonous road environments are the major exogenous factor causing driver fatigue. This study aims to reveal the relationship between the road environment and driver fatigue. Furthermore, the optimal stimulation interval of the road environment to prevent driver fatigue is proposed. A driving simulated experiment study is conducted to evaluate the impact of the monotonous road environment on driver fatigue. The experimental scenario of the road environment is designed based on the real-life environment. The physiological indicator of heart rate (HR) is used to measure driver fatigue. The MPEG (Moving Picture Expert Group) video compression technique is applied to assess the monotony of the road environment. Furthermore, the changing pattern of driver fatigue under different levels of monotony of the road environment, which can be reflected by different stimulation densities, is exhibited. In this study, the relationship between driver fatigue and stimulation density is established. The results of this study are consistent with the Hancock and Warm U model. The results of this study suggest that the optimal stimulation interval in the road environment should be no more than 8 minutes. The findings are further discussed with reference to the design of the road environment in order to mitigate driver fatigue. The potential application of this research is to develop an evaluation system of the road environment based on the driver fatigue.

2.1 Introduction

Driver fatigue is one of the major contributing factors to fatal traffic crashes. According to the National Transportation Safety Board (NTSB), 31 percent of fatal truck crashes related to drivers were caused by driver fatigue in the U.S. (Philippa *et al.*, 2006). The National Road Safety Committee (NRSC) reported at least 12 percent of fatal crashes were caused by driver fatigue and estimated 24 percent of all crashes were fatigue-related

(Mckernon, 2008). Research undertaken in some member states in Europe indicated that driver fatigue was a significant factor in approximately 20 percent of commercial transport crashes. The reports from various surveys carried out at different times showed over 50 percent of long-haul drivers reported that they had fallen asleep at the wheel at some time (McDonald *et al.*, 2001). Statistics from the Traffic Management Bureau of the Ministry of Public Security of China showed that 14.8 percent of fatal crashes could be attributed to driver fatigue.

The factors that cause driver fatigue are complex and can be divided into two categories: “endogenous” factors and “exogenous” factors (Fletcher *et al.*, 2005). The endogenous factors are related to the driver’s internal state and circadian cycle. These factors include time of day, sleepiness, the time on task, individual characteristics. The exogenous factors are related to tasks performed, which may impair driver performance. Examples of exogenous factors include road geometry, road environment, and task complexity.

Numerous research studies have focused on the relationship between “endogenous” factors and vigilance. Circadian variations, trip time, and sleep deprivation have been extensively studied as the “endogenous” factors that are detrimental to vigilance. Actually, the vigilance could be dependent on the interaction between “endogenous” factors and “exogenous” factors. The ecological approach pointed out that fatigue should emerge as a function of the driver with respect to the environment. “... it (fatigue) is no longer regarded solely as something within the brain ... , it depends on what you are, what you are doing and where you are doing it” (Nelson, 1997). For the above reason, this study focuses on one of the exogenous factors – the road environment, concerns the effect of the road environment on driver fatigue, determines the evaluation criteria of the monotony of the road environment and establishes the relationship between monotony and driver fatigue. The study also classifies monotony quantitatively and determines a reasonable interval of stimulation in the road environment.

2.2 Literature Review

Monotony is related to visual stimulation emerged in a specific environment. Thiffault and Bergeron (Thiffault and Bergeron, 1997) pointed out that monotony means stimulation does not change or changes within a predictable range.

The impact of road environment monotony on driver fatigue can be explained by several theories. Resource theories and adaptive models of stress or performance provided the con-

trasting explanations for effects of task. Resource theory proposed that an individual can be characterized by a finite resource capacity for attention processing and the depletion of that capability as a function of the performance of a task over time. Dynamic models of stress and sustained performance were based on the notion of adaptation to task demands. They suggested that it may be difficult to adapt to conditions of both underload and overload. The dynamic models indicated that the drivers can maintain a specific skill level under a certain change in the load environment, but these models had a lower adaptability for underload/overload conditions, as shown in Fig. 2.1. Many driving simulator experiments were used by Desmond Matthews (1997) and Oron-Gilad and Hancock (2005) to test the hypotheses of resource theories and dynamic models of stress and sustained performance. The results showed that dynamic models were consistent with the matching effort to driver fatigue in the underload situation.

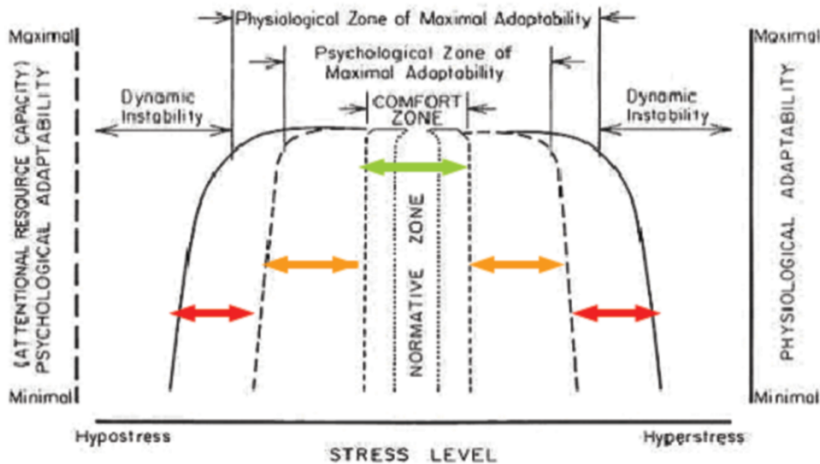


Fig. 2.1 The extended-U model of stress and performance (Oron-Gilad and Hancock 2005)

Oron-Gilad *et al.* (2008) simplified the adaptive model and deemed that the demand of driving task could be divided into three states: underload, optimal load and overload, as shown in Fig. 2.2. The horizontal and vertical axes represent situational demands and driver states, respectively. Driver states include the driving experience, driver characteristics, and driving conditions. The situational demands include a series of continuous flow of information or uncertain conditions with which the driver must deal. When the situational demands are high (such as in a complex traffic environment) and the driver feels

unfit (for example, a novice driver), the driver is in the condition of overload; when the situational demands are low (for example, monotonous scenes) and the driver enjoys driving (for example, an experienced driver), the driver is in the condition of underload. There is an optimal operating region between these two extremes.

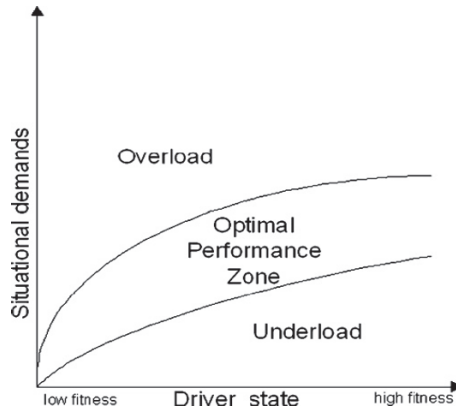


Fig. 2.2 A model of portraying the demand of the driving task as a function of situational demands and driver state (9)

According to the situational demands, driver fatigue can be divided into two categories (Dyani, 2007): passive fatigue related with underload, and active fatigue related with overload. For two different types of fatigue, Oren-Gild gave the directions of fatigue countermeasures (Oran-Gilad *et al.*, 2008), as shown in Fig. 2.3. Based on this theory, one of the fatigue countermeasures for the underload situation is to increase the extra demand of driving task. But the demand of driving should not distract the driver's attention from the primary driving task. In contrast, increasing task demand to fatigued-overload situations is not recommended. In the overload situation, the countermeasure is to improve the driver's fitness level rather than changing the task demands of driving.

The monotonous environment is one external factor of driving, and relates to the sensory stimulation that is presented in a specific situation. Thiffault and Bergeron (2003) pointed out that the roadside visual stimulation had a certain influence on driver fatigue, and the decrease in monotony would relieve the fatigue caused by the low stimulation road environment or the high repetition road environment. In China, several studies have been conducted about how to determine stimulus intervals in monotonous environments. Some research results proposed in monotonous sight region, the length of the same sight region

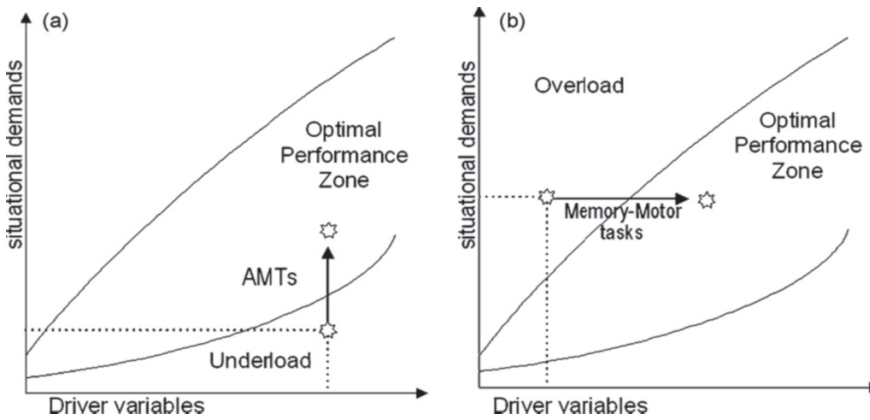


Fig. 2.3 Countermeasures to fatigue in under load and overload situation (9)

should be more than 5 kilometers (km) to provide the enough stimulation to the driver. Another researches in China also pointed out that speed should be considered when determining visual stimulation points. It is also suggested that there should be new visual stimuli for every 5 to 10 minutes to change the driver's attention.

The objective of this study is to establish the relationship of the monotonous road environment and driver fatigue, and develop the optimal stimulus interval in monotonous environments based on the driver fatigue. Thus, how to quantitatively evaluate the monotony of the road environment is especially important in identifying the effect of the monotonous road environment on driver fatigue. The definition of monotony was introduced in the 1970's, but little progress has been made in this area. The qualitative analysis is still widely used in most research studies [see e.g., Liu and Wu (2009) and Antonson *et al.* (2009)]. It is found that the characteristics of monotony and the degree of monotony are determined qualitatively, but the reasonable evaluation criteria are missing. Flecher *et al.* (2005) proposed applying MPEG image compression technology to measure the monotony of road environment and provided a guideline for determining the monotony. This study is based on the method (Mao *et al.*, 2010). Moreover, the road environments with different monotony levels are developed in the driving simulator. The simulated experiments are employed to carry out this study.

2.3 The Road Environment Monotony Evaluation

2.3.1 Basic principles

MPEG (namely, Moving Picture Expert Group) is one of the international organizations specialized in developing multi-media video and audio compression coding standard. The principle of MPEG image compression depends on two attributes of image: spatial correlation and temporal correlation. These two properties provide the image with so much redundant information. If this redundant information can be removed and only a limited amount of essential information for transmission is retained, then the transmission bandwidth for the image data can be reduced greatly. Compression technology is to remove the redundant information maximally in the video image.

Road environment monotony usually refers to the environment that remains unchanged or will change in a predictable pattern. Namely, if the road environment ahead is easily predictable by the driver perception of environment, the road environment is monotonous. According to the above analysis, the key of monotony evaluation is how to measure the differences of road environment quantitatively. The MPEG image compression algorithm can be employed to obtain these differences. This method will capture the video image of the road environment and describe environment changes by the variation between frames. Thus, according to the compression algorithm, if the road environment changes more frequently, the difference between the motion compensated prediction value and the actual pixel value will be greater, and the size of the corresponding compressed file will be greater. Accordingly, when the changes in the road environment are smaller, the size of the compressed file is also smaller. MPEG encoding is a way of lossy compression, which means it can remove the time-domain and spatial-domain redundancy. The test results demonstrate that the loss of MPEG compression has no significant effect on the results in the previous experiments.

2.3.2 Verification

The world second road tunnel—Qinling-Zhongnanshan tunnel in the western region of china is taken as an example. The video lasted for 20 minutes, the sampling rate was 15 frames/s, and the sequence length (referring to the video length calculated by MPEG encoding) was 10 seconds. The result is shown in Fig. 2.4. The ordinate is the ratio of the file sizes in each 10 seconds to that in the first 10 seconds. It is found that this method can detect road environment stimulation effectively; five positions of larger file size correspond

to the larger environment change, particularly entering into tunnel after 11 minutes. The environment change is smaller, but the change becomes larger in 16 minutes and 19 minutes as a result of the emergence of man-made tree.

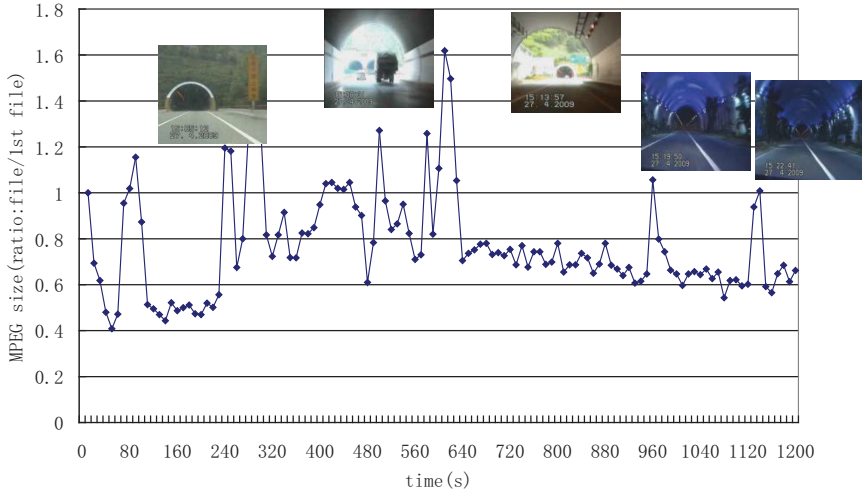


Fig. 2.4 MPEG compression validation

2.3.3 Relevant parameters selection

To investigate how to best use MPEG encoding to represent monotony we encoded a set of 20 min video on varying the sampling rate and sequence length. We tested samplings at frequencies of 5, 10, 15, 20 and 25 frame/s with sequence length of 5, 10 and 20 s. Fig. 2.5. shows sampling frequency has a great influence on the absolute result of compression, but relatively little effect on the relative result, so the graphics are basically similar when sequence length is fixed. However, taking into account that the smaller the sampling frequency is, the larger the compression absolute result is, the sampling frequency is proposed as 15 frames/sec. Similarly, sampling frequency was fixed and the compression results were calculated in the sequence length of 5, 10, and 20s. In theory, the smaller the sequence length is, the better the road environment change is reflected. The recommended sequence length taking into account the computational problem is 10 s.

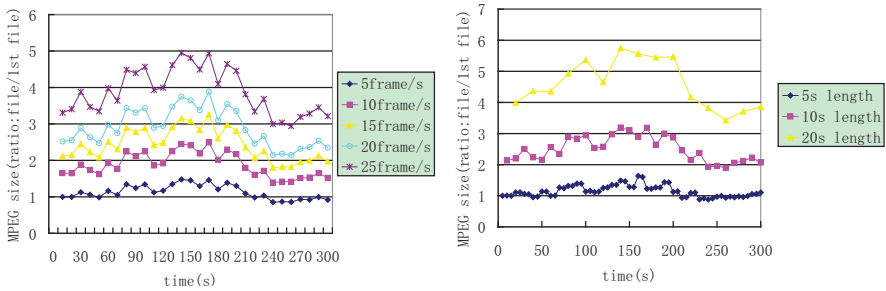


Fig. 2.5 Compression results with different compression frequency and sequence length

2.3.4 Considering diver observation region correction

The study has revealed that on the whole drivers spend 80% of their time looking into a ‘forward’ area (Brackstone *et al.*, 2004), while have less time in other regions. Therefore, the change of different regions in the driver’s field has a different influence on driver. The driver’s observation region was divided and corresponding weights were given to the different regions based on drivers’ gazing time to achieve the integration of an objective assessment of road environment and driver’s subjective concern region.

In order to analyze the distribution of the driver’s observation and process testing data easily, Victor’s regional division method was employed (Victor *et al.*, 2005). In the horizontal direction, $-20 \sim -10$ degree area was defined as the left side of the region, $10 \sim 20$ degree region was defined as the right side of the region, and the 20×15 degrees rectangle area including from $(-10^\circ, -7.5^\circ)$ to $(10^\circ, 7.5^\circ)$ was defined as road center region which was divided into the above region and below region in the vertical direction, shown as Fig. 2.6.

According to the gazing time in different regions, the weights of road center region, left region, and right region were given as 0.8, 0.1, and 0.1. The Open CV technique was used to extract and divide the video images. The road environment change was calculated as the weighted sum of environment change of all regions. Fig. 2.7 showed the difference between normal and weighted compression. Though the trends are similar, the environment change was not the same within the length of each sequence. To 580 s-590 s periods, for example, a vehicle appeared in front of the road center region and will turn to enter the section, so environment change of weighted compression is larger than that of normal compression (shown as Fig. 2.8).

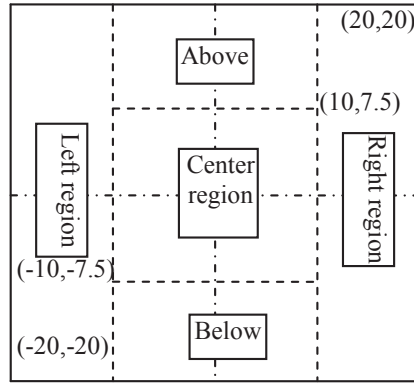


Fig. 2.6 Victor observation region division

2.3.5 Evaluation indicator

Mao *et al.* (2010) estimated the default parameters of road environment monotony based on the MPEG compression technique. The correction of driver gazing area division was fully considered in processing video images (16). According to the mean and standard deviation of the MPEG compression results within the evaluated video clips, the location can be identified with Equation (2.1). This location is the place where the road environment changes greatly (be called the stimulation point). Furthermore, the stimulation density is defined as the number of stimulation points within a unit length of video clips.

$$X = \{x_i \mid x_i > M + \sigma, x_i \in E\} \quad (2.1)$$

where: M — The mean of environment change during the evaluation length;

σ — The standard deviation of environment change during the evaluation length;

x_i — The environment change of the i -th sequence length using MPEG compression technique.

To the video in verification analysis above as an example, the mean of environment change was calculated as 0.56 within the video of twenty minutes (average the ratio with the file size with the first ten seconds), and the corresponding locations of larger changes (or stimulation points) were shown as round area in Fig. 2.9.

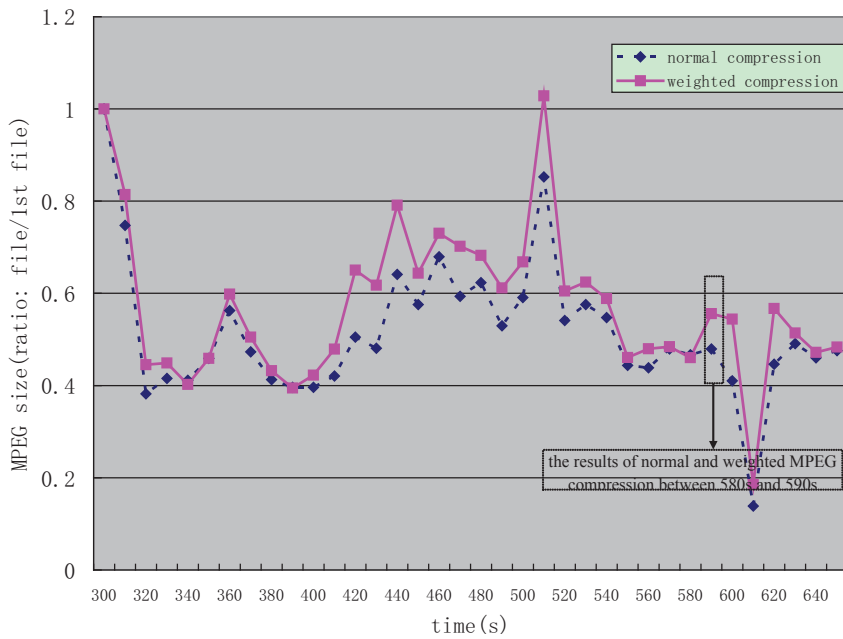


Fig. 2.7 The difference between normal and weighted MPEG compression



Fig. 2.8 Road scene image between 580 s and 590 s

2.4 Methodology

Stimulation density of road environment and heart rate (HR) of drivers are used to evaluate the road environment monotony and driver fatigue, respectively. The distribution of driver fatigue (represented by HR) according to the different stimulus densities is exam-



Fig. 2.9 Road scene monotony evaluation

ined, and the relationship between driver fatigue and stimulation density is established. Furthermore, this study develops an optimal interval between successive stimulation points in road environment based on the relationship.

2.4.1 Scenario design

The scenario with a two-way two-lane road is developed. In order to separate the impact of roadway geometric design features, the scenario includes two long tangents and two horizontal curves. Each tangent is 10 km long and the radius of horizontal curves is 3,138 meters (m). According to the Chinese Roadway Design Standards, the horizontal curve radius without transition curves is the same as the horizontal curve radius without superelevation. For the design speed of the 60 km/h, the radius of horizontal curves without superelevation should be at least 1,500 m. The experimental curve radius is 3,138 m, which is greater than the critical value of 1,500 m. Therefore, the horizontal curves are directly attached to end of tangents without transition. The lane width is 3.5 m; the shoulder width was 1.5 m; the total length of experimental road is 40 km, as shown in Fig. 2.10.



Fig. 2.10 Graphic design scene

2.4.2 Stimulus type

To disrupt the monotony of the environment, the stimulus type is determined by varying roadside tree planting and setting a certain kind of signs within a certain interval. The representative species in northwest and north China, such as pine, arborvitae, poplar, and elm are planted on both sides of the road. Semi-closed forms are used as the planting pattern, as commonly seen on arterial roads in north China.

For the semi-closed planting forms, the spacing of the trees is determined by the size of the diameter of grown-up trees. Usually, spacing of the trees is 1.5 to 2 times the crown of the grown-up trees; the distance between the crowns is the same as the diameter of the crown. Therefore, the corresponding distance spacing is calculated by a semi-closed plant formation of crown.

There are two kinds of signs selected as stimuli for the experimental road. One is to prevent driver fatigue, the second to limit the speed. The size and setting method of the signs are designed according to the Chinese Road Traffic Signs and Markings Standard.

2.4.3 Stimulus setting

The previous psychology research showed that the effect of the stimuli will decrease if there are too many stimuli per unit time. That is, for a short period of time, a driver is able to adapt to the change on the landscape, but this change cannot stimulate significant visual response from the driver. Therefore, the stimulus setting interval should be in a reasonable range. According to the previous research results (Mao *et al.* 2010), the stimulus setting interval ranges from 0 to 40 minutes. Thus, when the speed is 60 km/h, the spacings of

stimuli range from 0 to 40 km. On this 40 km stretch of road, scenarios with five spacings are designed: 40 km, 20 km, 10 km, 5 km and 1 km. The scenario with 40 km means that there are no stimuli on this entire 40 km stretch; the scenario with 1 km represents that there is a stimulation point for each 1 km interval. The scenarios with the five different settings are shown in Fig. 2.11.



Fig. 2.11 Road scene when setting stimulus

2.4.4 Participants

There are 12 participants. They are all chosen from the full-time and experienced driver pool. Their average age is 35 years old, and these drivers have at least 3 years driving experience. All of them are with good health condition and none of them have sleep-related symptoms. At the same time, it is necessary to ensure that the driver needs to have 8 hours of sleep night before the experiment and does not drink any alcoholic beverages 24 hours prior to the experiment. It also requires that drivers are not allowed to drink tea, coffee or other drinks with caffeine before the experiment. The experiments start at 12:00 noon. Drivers are more susceptible to drowsy driving at this time of day.

2.4.5 Experiment procedure

The subjects are required to drive three times along the road at a speed of 60km/h and each driver completes five experiments for the five scenarios accordingly. In accordance with the balance principle of experimental design, the subjects are required to randomly select a scenario to drive at the same time each day. Before the first experiment, all subjects are required to drive 30 minutes to get familiar with the driving environment of the simulator. Before each experiment, each subject is required to fill out the questionnaire:

Table 2.1 Stimulation density of different scenarios

Experiment	1 km	5 km	10 km	20 km	40 km
Stimulus density (number/km)	40/40	8/40	4/40	2/40	1/40

Swedish Occupational Fatigue Inventory-20 in the Chinese version (referred to as SOFI-C) (Leung *et al.*, 2004). After the ECG device is installed on the driver, the driver drives three times in the fully closed simulation environment without any interference.

2.5 Data Analysis and Results

2.5.1 Monotony of scenario

The simulated scenarios are analyzed according to the evaluation method of monotony based on the MPEG image compression technique. It is found that the image compression results remain stable in the scenarios without any stimulus. When the stimulus is present, the compression results fluctuate significantly. For example, for the experimental scenario of 1 km, significant fluctuations are found to be associated with the stimulus, as shown in Fig. 2.12. According to Eq. (2.1), it is trivial to obtain the stimulus density of the scene, as shown in Table 2.1.

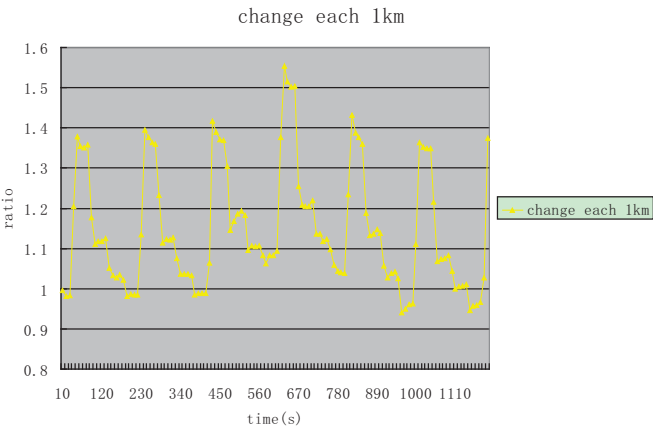


Fig. 2.12 Calculate the environmental change in different scenarios with MPEG compression technology

2.5.2 *Fatigue rating pre-driving*

From the previous analysis, the causes of driver fatigue can be divided into two categories: endogenous factors and exogenous factors. In order to better capture the impact of the monotonous environment on driver fatigue, it must ensure that the impact of endogenous factors on driver fatigue have no significant difference in driving experiments for different scenarios. In the experimental process, the drivers are required to remain in the same mental state as much as possible before each experiment. In order to verify whether the subjects have the same mental state and ensure the accuracy of post-data processing, the subjective survey form of SOFI-C is used to determine whether the driver has a significant difference in mental state among the five experiments. The results are shown in Fig. 2.13.

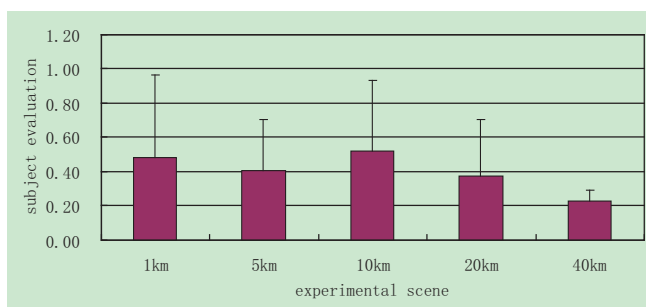


Fig. 2.13 Subjective fatigue assessment pre-driving

The SOFI-C subjective evaluation form characterizes the degree of driver's fatigue using scales from 0 (minimal level) to 10 (maximum level). The degree of all drivers' fatigue is found at around 0.5, which indicates that all drivers are in good condition before the experiments. Paired t-test results show that there is no significant difference in mental states of the drivers prior to any two driving tests.

2.5.3 *The HR change in different driving scenarios*

Although the heart rate (HR) of the driver is affected by driver's physiological state, driving time, road condition and other factors, the heart rate of the same driver varies significantly in different experiments. Therefore, the heart rate has been used to describe the impact of different environments on driver fatigue in previous research. In each experiment scene, the average heart rate of the drivers for every minute of driving time is calculated

Table 2.2 Stimulation density and heart rate declination under different scenes

Experiment	1 km	5 km	10 km	20 km	40 km
Stimulus density (number/km)	40/40	8/40	4/40	2/40	1/40
Start driving 5 minutes, heart rate (beats/minute)	88	88.8	88	89	88
Driving 115 minutes continuous heart rate (beats/minute)	79.2	83	82.8	81.5	78.5
Heart rate decreasing percentage (%)	8.8	5.8	5.2	7.5	9.5

and a regression analysis of average heart rate with respect to driving time is performed, as shown in Fig. 2.14. The results show that the average heart rate declines most rapidly when there are no stimuli in the scene. The experiment with the stimulus interval of 1 km experiences the fastest declining heart rate. The slowest declining rate of the heart rate occurs when the stimulus interval is between 5 and 10 km. It is also found that the heart rate decreases sharply at the beginning experiment. Fig. 2.8 also shows that there are several crossovers among the fitted curves for the five different scenarios. These crossovers may be caused by the drivers who need more warm-ups for driving. Therefore, the data after first five minutes is used in the analysis.

2.5.4 Road environment monotony according to driver fatigue

Stimulation density is introduced to characterize the road environment by the number of stimulation points per unit length. The level of driver fatigue is represented by the decreasing rate in the heart rate (i.e., drops in the heart rate per unit time). The calculation period is from 5 minutes to 115 minutes of driving because some subjects speed a little bit at the end of driving and their driving time may not reach 120 minutes. The stimulation density and the declining rate in heart rate under different experimental scenarios are obtained and shown in Table 2.2.

Relationship between the declining rate of heart rate and logarithm of stimulation density is shown in Fig. 2.14. The Hancock and Warm U model of the adaptive theory illustrates that within a certain driving load, the driver can maintain a certain level of performance. However, driver's adaptability decreases at the lower or higher levels of driving load. Therefore, when other factors are kept constant, the external environment will become an important factor affecting the levels of driving load. In this situation, the effect of the external environment on driver fatigue should also be consistent with U model. Ac-

According to the relationship between the declining rate of heart rate and stimulation density, it can be seen that the heart rate drops quickly when the stimulus interval increases from the 5 km to 40 km. This finding is consistent with the Hancock and Warm U-model. The Hancock and Warm U-model theoretically shows that the heart rate drops rapidly when the stimulation interval changes from 1 km to 5 km. Although there are not enough experiments conducted for the stimulation interval between 1 and 5 km, this pattern can be indirectly verified by the experiment with 1 km stimulation intervals.

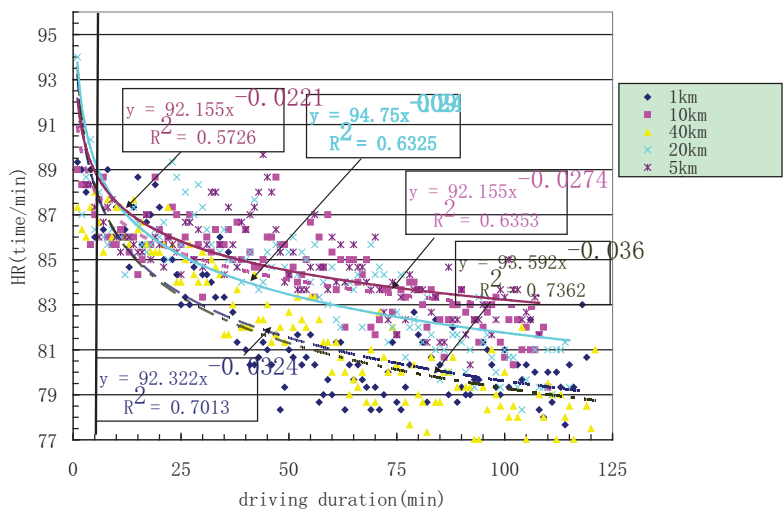


Fig. 2.14 Heart rate variations with driving time under different scenes

When the 5% of decreasing rate in the heart rate is selected as the threshold, the logarithm of the corresponding stimulation density is -0.92 , which represents an 8 km stimulation interval. The corresponding time interval is 8 minutes given a speed of 60 km/h, which can be used as the evaluation criteria of road environment monotony. That is, the road environment is considered monotonous when there are no stimuli for at least 8-minute driving. This interval is also the maximum distance for the stimulus setting. The results are shown in Fig. 2.15.

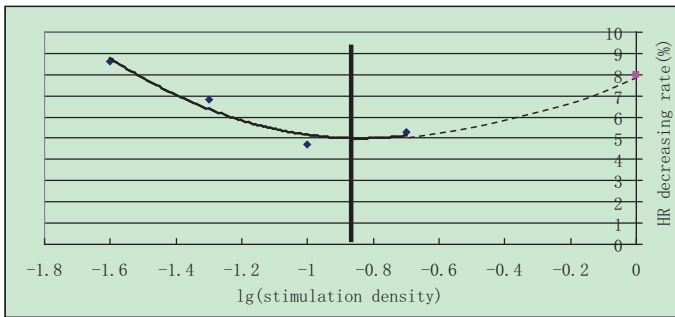


Fig. 2.15 Monotony and heart rate fitting

2.6 Conclusions

Driver fatigue is caused by the interaction of exogenous and endogenous factors. Driver fatigue is not only related to driver's physiological states, but also affected by driver characteristics, driving environment and other factors. The road environment, one of the most important exogenous factors has gained more and more attention in studying driver fatigue.

Lal and Craig (2001) showed that the heart rate was a reasonable physiological indicator to measure driving load. Lal and Craig (2001) found that significantly lower heart rates were associated with driver fatigue. Therefore, based on the MPEG image compression algorithm, this study evaluates the road environment monotony by characterizing the driver fatigue using changes in heart rates for different road scenes.

The contributions and findings of this study can be summarized as follows:

- (1) Establish a criterion to assess the monotony of the road environment applying the image compress technology;
- (2) The heart rate is found to change significantly under different road environments with different monotony;
- (3) The relationship between stimulation density and heart rates based on this study is consistent with the U-model theory of Hancock and Warm.
- (4) The maximum stimulation interval is 8 minutes of driving based on driver fatigue.

This study confirms that stimulation in the monotonous environment has a significant influence on preventing driver fatigue. In the future, more effective form and meaning of these stimuli should be further studied to eliminate driver fatigue.



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