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Investigating the effect of long trip on driving performance, eye blinks, and awareness of sleepiness among commercial drivers: A naturalistic driving test study

Y. Wang[a,*], **J. Ma**[a], **and L. Wei**[b]

a. *School of Highway, Chang'an University, Xi'an 710064, Shaanxi, China.*
b. *School of Materials Science and Engineering, Yancheng Institute of Technology, Yancheng 224051, Jiangsu, China.*

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Abstract. A total of 120 commercial drivers from four age groups participated in the expressway driving test in Shandong, China, to perform continuous driving tasks of 2, 3, and 4 h and collect the data on the driver's blinking, driving performance, and self-reported level of sleepiness. A two-way repeated measures ANOVA was used to evaluate the effects of driving duration on the variation of the eye-blink behavior, driving performance, and subjective feeling of sleepiness across the different age groups over the time periods tested. Additionally, Pearson product-moment correlation was used to quantify the association between the variations of the dependent variables. The results showed that there was significant difference between groups, significant effect over time, and significant interaction between the age and driving duration in the variations of the driver's blink frequency, blink duration, closure duration, speed perception, choice reaction time, the number of incorrect action judgments, and subjective level of sleepiness. However, a significant difference varied over time, yet no effect of the interaction between groups and time was found in the variation of the driver's attention allocation value. Furthermore, driver's eye blink measures were more sensitive to sleepiness, and older drivers were more likely to get sleepy in long distance driving.

1. Introduction

Nowadays, sleepiness while driving is the leading cause of traffic fatalities and injuries throughout the world [1-4]. In the United States, the National Highway Traffic Safety Administration (NHTSA) estimated that at least 100,000 automobile crashes occurred annually due to falling asleep while driving, resulting in roughly 1,550 fatalities and 40,000 nonfatal injuries. In the European Union-27 countries, about 10∼20% of all the road traffic crashes are caused by sleepiness while driving [5]. Similarly, about 15% of all road automobile crashes in China are caused by or partially due to driver's sleepiness, particularly among commercial long distance drivers [6].

Undoubtedly, commercial long distance drivers are often engaged in frequent and long driving tasks, which can make them tired or sleepy [7]. As evident, sleepiness generally deteriorates the driver's driving performance by affecting vision, judgment, and reaction time, thus increasing the likelihood of serious

*. *Corresponding author. Tel.: +86 1377 2064 901*
E-mail address: wangyg@chd.edu.cn (Y. Wang)

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crashes [8]. Numerous previous studies have shown that the duration of continuous driving without rest was significantly associated with the deterioration of the driving performance [9-12]. Accordingly, many researchers have focused their attention on identifying the symptoms and level of sleepiness experienced by the driver while driving, among which visual behaviour variables are the most frequently used measures [13,14]. They found that sleepy drivers exhibit certain observable visual changes, such as slow eyelid movement, small degree of eye opening (or even closed), longer blink time, frequent nodding, gaze, etc., which can be used to detect the level of sleepiness [7,15-17].

In addition, visual characteristics of the driver are often combined with physiological parameters (e.g., heart rate, breathing, body temperature, brain waves) or indirect vehicle behaviors (e.g. movement of the steering wheel of the vehicle, time to line crossings, and deviation of lateral position) to evaluate the sleepiness state [18,19]. For example, Bergasa et al. monitored six variables, including percent of eye closure, eye closure duration, blink frequency, nodding frequency, and face position, to assess the level of vigilance of the driver [20]. Furthermore, some findings showed that drivers of different age groups have significant differences in driving behaviors due to their differences of physical, psychological, and driving experience and ability to handle a real emergency situation [21,22]. Wherefore, it is imperative to divide the drivers into groups by age and test the characteristics of different age groups.

Extensive research suggests that driver's sleepiness is a relatively slowly changing process with the decline of the physical and mental alertness of the driver to the driving task. Thus, understanding how the level of sleepiness of the driver varies during long trips and extensive periods of continuous driving is particularly important to avoid driving while sleepy. To achieve this objective, 120 commercial truck drivers were recruited to participate in a real driving test on the expressways in Shandong, China to monitor and collect data on the driver's blink rate, driving performance variables, and subjective feeling of sleepiness after a certain driving task.

2. Methods

2.1. Participants

A total of 120 commercial truck drivers (102 males and 18 females) were invited to participate in the real driving test. Each participant had a Chinese A2 or B2 driving license (truck driving) valid for at least 5 years and an annual mileage of 50,000 km or more.

The average age of the participants was 33.7±5.1 years for females and 38.2±6.8 years for males. All participants were required to have normal vision, not major accidents records and no alcohol or drugs consumption that might affect their driving performance during the last three days. For the test and data analysis, all participants were classified into four groups by age: the '<30' group, the '30-40' group, the '40-50' group, and the '>50' group.

2.2. Dependent variables

The driving performance of the driver mainly consists of speed perception (s), attention allocation (s), decision-making/reaction time (s), and the number of incorrect action judgments (times/100 s) [12]. Speed perception value examined the ability of the driver to estimate the vehicle velocity ahead and distance to the front, sides or rear of his/her vehicle. Attention allocation measured whether or not the driver paid sufficient attention to the road ahead. Reaction time evaluated the ability of the driver to respond to unexpected events and make decisions about actions to take. The number of incorrect action judgments assessed the driving proficiency ability of the driver, particularly in emergency driving situations. These performance variables were tested by speed-perception tester, attention tester, reaction-time tester, and action-judgment instrument, respectively.

The Stanford Sleepiness Scale (SSS) was used to quantify the level of self-reported sleepiness by the driver [23] and was divided into seven categories (see Table 1) with an index score between 1 and 7.

Since the eye-blink variables of the driver were found to be more sensitive to sleepiness than fixation and saccade measures in our previous study [22], this study chose the blink frequency (times/s), blind duration (s), and closure duration (s) to establish

Table 1. The Standford Sleepiness Scale (SSS).

Level of sleepiness	Scale rating
Feeling active, vital, alert, or wide awake	1
Functioning at high levels, but not at peak; able to concentrate	2
Awake, but relaxed; responsive but not fully alert	3
Somewhat foggy, let down	4
Foggy; losing interest in remaining awake; slowed down	5
Sleepy, woozy, fighting sleep; prefer to lie down	6
No longer fighting sleep, sleep onset soon; having dream–like thoughts	7

the occurrence of sleepiness. These three eye blink measures were collected at a frequency of 200 HZ through the Smart Eye Pro 6.0 eye tracking system with four cameras mounted in front of a windscreen.

2.3. Data collection

Three routes, namely *a*, *b*, and *c* (Figure 1), with speed limit of 100$\sim$120 km/h along major expressways in Shandong, China were selected to carry out the driving test.

The driving test was conducted from September to October in 2015. Before the formal test session, participants took part in the training session and learned how to use the Smart Eye Pro 6.0, driving performance testers (speed-perception tester, attention tester, reaction-time tester, and action-judgment instrument), and the SSS as well as other matters needing attention.

Then, they gathered at 6:30 p.m. to have a pre-test, in which their driving performance values, blink characteristics, and sleepiness awareness were determined as the baseline. After the calibration of the equipment, each participant left Jinan at 7:00 p.m. along route *a* and arrived at Jining after 2 h driving, where the driver's blink rate, driving performance, and self-reported sleepiness level were recorded through the eye-tracker, driving performance testers, and SSS questionnaire, respectively. After full recovery, at 10:00 p.m., the participant drove to Rizhao along route *b*; after arriving at Rizhao Interchange after 3 h driving, they were asked to take the same test as described above. After taking adequate rest, the participant started the 4 h driving task to Jinan at 4:00 a.m. along route *c* and ended the test session after recording the blink rate, driving performance, and subjective level of sleepiness. During the subsequent days, all the other participants took part in the road driving test along routes *a*, *b*, and *c*.

The two-way repeated measures ANOVA was used to evaluate the effects of driving duration on the dependent variables (eye-blink frequency, driving performance, and subjective level of sleepiness) across

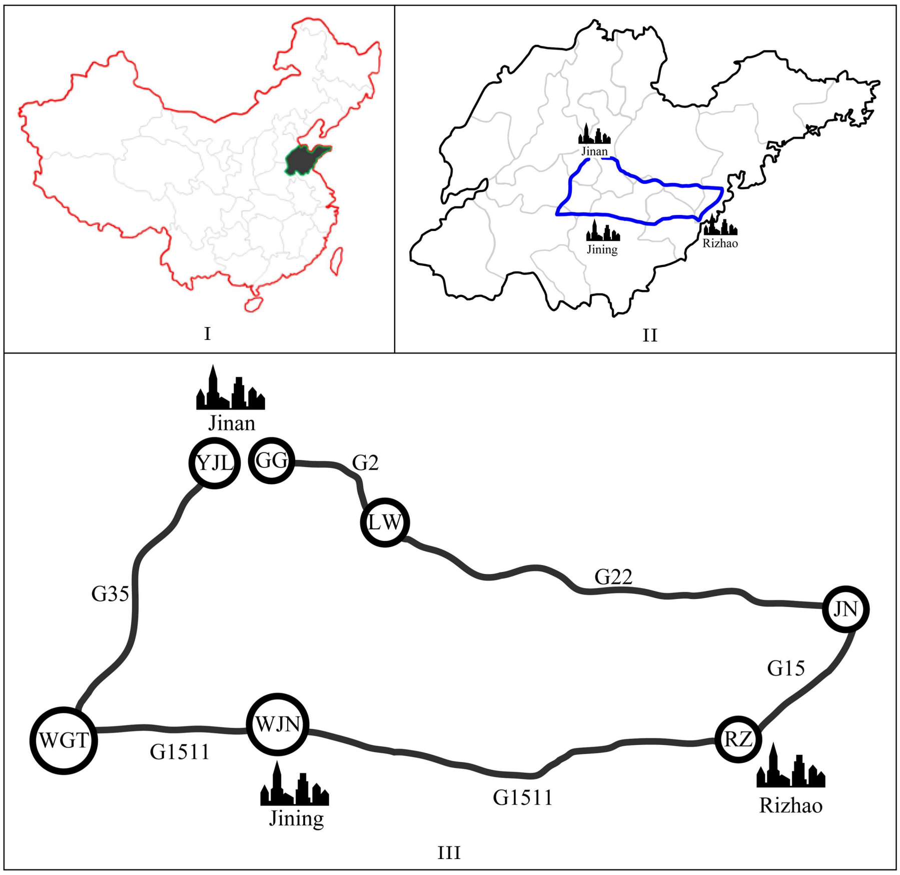

Figure 1. Illustration of driving test route: (I) Location of Shandong, China, (II) location of driving test routes in Shandong, China, (III) three test routes along the expressways. Route *a*: from Yinjialin Interchange (YJL) of Jinan along G35 to Wangguantun Interchange (WGT) along G1511 to West Jining Interchange (WJN) of Jining, 189.1 km, 2 h driving; Route *b*: from West Jining Interchange (WJN) of Jining along G1511 to Rizhao Interchange (RZ) of Rizhao, 283.9 km, 3 h driving; Route *c*: from Rizhao Interchange (RZ) of Rizhao along G15 to Laiwu Interchange (LW) and from Laiwu Interchange (LW) along G2 to Ganggou Interchange (GG) of Jinan, 403.2 km, 4 h driving.

independent groups (between subjects factors) over a period of time (within subjects factor) at a 5% significance level. Additionally, the Pearson product-moment correlation was used to quantify the association among the driver's eye blink rate, driving performance, and subjective level of sleepiness.

3. Results

3.1. Variation of driving performance

The evaluation with two-way ANOVA revealed that the effect of driving duration on the driver's driving performance and sleepiness awareness varied significantly across the age groups (Figure 2):

- Speed perception: $F_{(1,118)} = 0.271$, $p < 0.001$;
- Attention allocation: $F_{(1,118)} = 0.184$, $p < 0.001$;
- Choice reaction time: $F_{(1,118)} = 0.249$, $p < 0.001$;
- Number of incorrect action judgments of speed perception: $F_{(1,118)} = 1.340$, $p < 0.001$.

In particular, the driving performance of elderly drivers appeared to be significantly affected, as compared to that of the younger drivers. For example, after 2, 3, and 4 h of continuous driving (see Figure 2), the speed perception of drivers in the '<30' group increased by 5.13, 17.70, and 30.29%, respectively, compared with the original data before the driving test, whereas the values of drivers in the '>50' drivers increased by 6.98, 22.54, and 32.72%, respectively. Two-way ANOVA showed that there was statistically significant difference in the change rates of this variable between these two age groups for the 2 h and 3 h of driving periods ('2 h': $F_{(1,58)} = 48.465$, $p = 0.022$; '3 h': $F_{(1,58)} = 9.898$, $p = 0.003$), but not for the 4 h of driving period ($F_{(1,58)} = 0.639$, $p = 0.427$).

Of the within-subject effects, continuous driving duration was found to have statistically significant effects on the driver's driving performance:

- Speed perception: $F_{(3,116)} = 0.959$, $p < 0.001$;
- Attention allocation: $F_{(3,116)} = 1.351$, $p < 0.001$;
- Choice reaction time: $F_{(3,116)} = 5.725$, $p < 0.001$;
- Number of incorrect action judgments of speed perception: $F_{(3,116)} = 9.139$, $p < 0.001$.

For the '>50' group, for example, the driver's attention allocation value dropped significantly ('2 h': $F_{(1,58)} = 19.740$, $p < 0.001$; '3 h': $F_{(1,58)} = 64.086$, $p < 0.001$; '4 h': $F_{(1,58)} = 198.101$, $p < 0.001$), compared with the baseline values before the driving tasks.

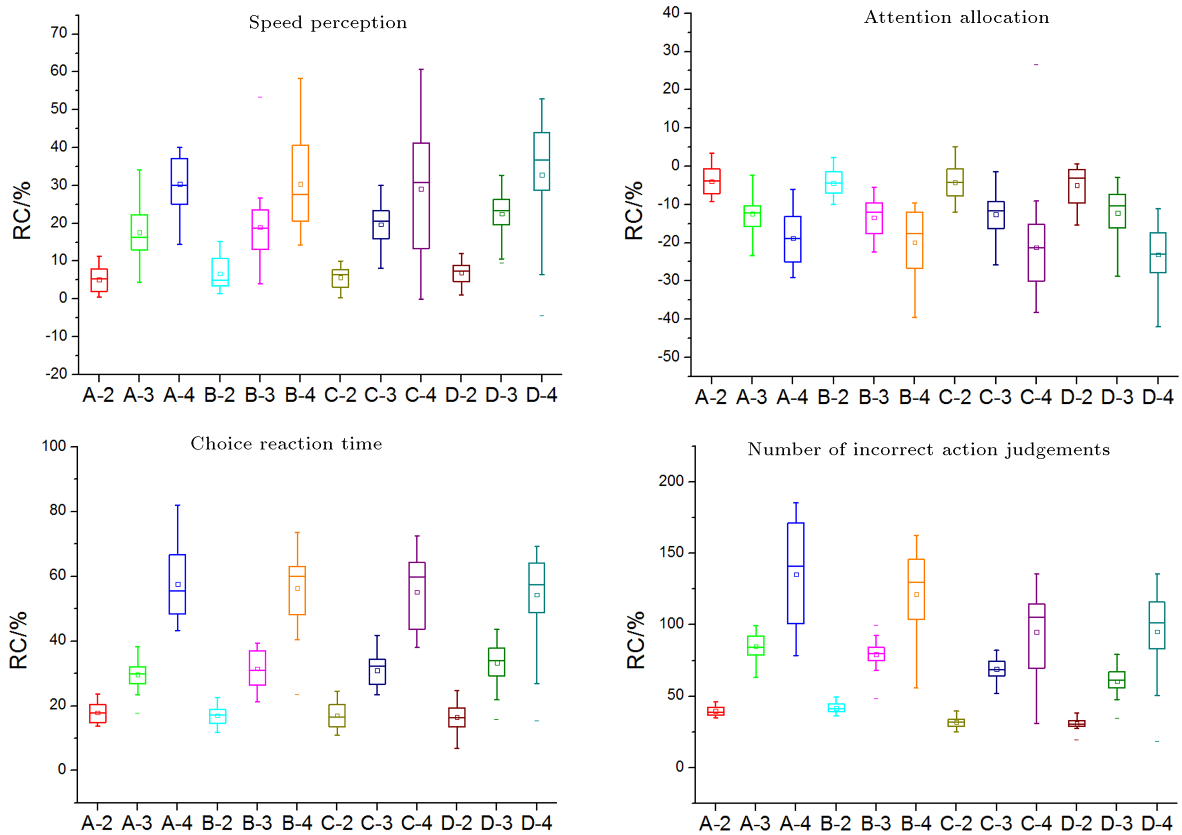

Figure 2. Rate of change of driving performance variables.

Furthermore, a statistically significant interaction was observed between age and driving duration in the change of speed perception, $F_{(3,116)} = 0.142$, $p = 0.002$; choice reaction time, $F_{(3,116)} = 0.225$, $p < 0.001$; number of incorrect action judgments of speed perception, $F_{(3,116)} = 0.098$, $p = 0.013$, but not in the change of attention allocation, $F_{(3,116)} = 0.057$, $p < 0.092$.

3.2. Variation of driver's blinks and sleepiness awareness

The driving duration had significantly different effect on the subjective feeling of sleepiness by the drivers across the age groups (Figure 3), $F_{(1,118)} = 0.404$, $p < 0.001$; in addition, such effect was also evidently different within each age group, $F_{(3,116)} = 1.452$, $p < 0.001$. Additionally, a significant interaction between the age group and driving duration was found for the subjective feeling of sleepiness by the drivers (see Figure 3), $F_{(3,116)} = 0.462$, $p < 0.001$. For the '<30' group, as shown in Figure 3, the score for the sleepiness level increased by 42.22, 100.00, and 153.33%, respectively, after 2, 3, and 4 h of driving task, while the level for the '>50' group drivers extended to 57.41, 114.81, and 190.7%, respectively, after finishing the same driving task.

As reported in our previous study [22], the effects of continuous driving duration on the driver's blink were observed not only across different age groups (blink frequency, $F_{(1,118)} = 0.440$, $p < 0.001$; blind duration, $F_{(1,118)} = 0.808$, $p < 0.001$; closure duration, $F_{(1,118)} = 1.059$, $p < 0.001$), but also within each age group (blink frequency, $F_{(3,116)} = 0.865$, $p < 0.001$; blind duration, $F_{(3,116)} = 0.291$, $p < 0.001$; closure duration, $F_{(3,116)} = 0.369$, $p < 0.001$). Additionally, a statistically significant interactive effect was also observed in the change of these three blink variables (blink frequency, $F_{(3,116)} = 0.117$, $p = 0.005$; blind duration, $F_{(3,116)} = 0.663$, $p < 0.001$; closure duration, $F_{(3,116)} = 0.992$, $p < 0.001$).

3.3. Association between visual behavior and sleepiness level

Table 2 shows the Pearson product-moment correlation coefficient (r) among the change of visual behavior, driving performance variable, and SSS value. Evidently, the driver's subjective feeling of sleepiness was positively correlated with his/her blink frequency, blind duration, closing duration, speed perception value, choice reaction time and number of incorrect action judgments, and negatively correlated with his/her attention allocation value.

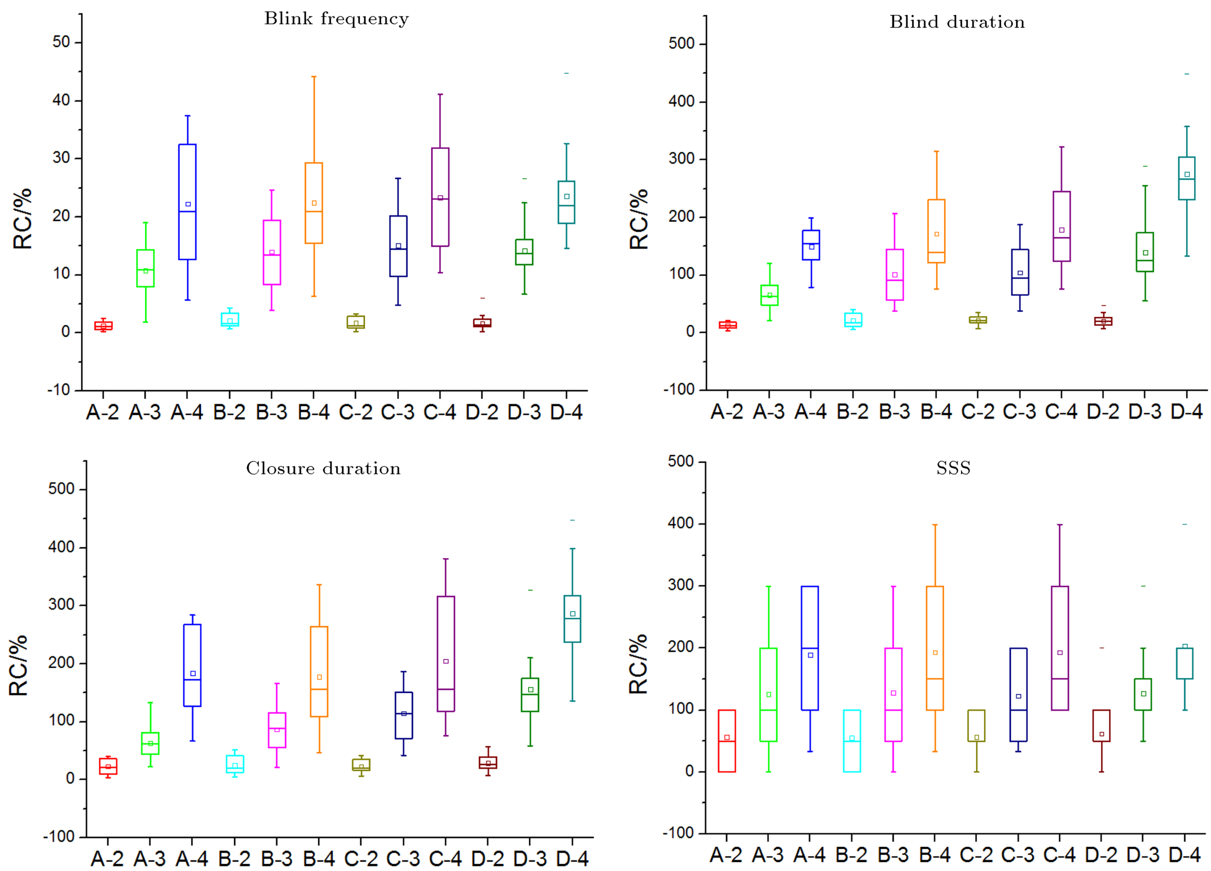

Figure 3. Rate of change of SSS and eye blink variables.

Table 2. Pearson coefficient between variations of driver's driving performance and subjective sleepiness level.

Variables*	"<30" group			"30∼40" group			"40∼50" group			">50" group		
	2h	3h	4h	2h	3h	4h	2h	3h	4h	2h	3h	4h
BF	0.958	0.853	0.969	0.921	0.943	0.937	0.920	0.929	0.941	0.931	0.936	0.938
BD	0.933	0.849	0.933	0.928	0.818	0.916	0.918	0.738	0.943	0.916	0.865	0.925
CD	0.922	0.849	0.961	0.928	0.838	0.917	0.940	0.687	0.948	0.909	0.921	0.906
SP	0.881	0.948	0.919	0.785	0.737	0.849	0.780	0.481	0.863	0.844	0.747	0.830
AA	−0.823	−0.772	−0.848	−0.796	−0.802	−0.823	−0.803	−0.710	−0.755	−0.706	−0.736	−0.691
CR	0.833	0.763	0.782	0.839	0.701	0.764	0.852	0.531	0.798	0.768	0.784	0.833
NIA	0.848	0.790	0.853	0.815	0.716	0.878	0.841	0.531	0.850	0.843	0.849	0.819

*BF: Blink Frequency; BD: Blind Duration; CD: Closing Duration; SP: Speed Perception value;
AA: Attention Allocation value; CR: Choice Reaction time; NIA: Number of Incorrect Action judgments.

The driver's subjective level of sleepiness was found to be more sensitive to the eye's blink movement. For example, for the '>50' group of drivers, the change in blink frequency had a rather strong positive correlation ($r = 0.931{\sim}0.938$) with their perception variation of driving sleepiness; in other words, the greater the increase of the variation of the blink rate is (frequency), the higher the level of subjective sleepiness will be, as might be expected. In view of the driving performance variables, the absolute value of r varies between 0.6 and 0.9, except for those among the variation of speed perception, choice reaction time, number of incorrect action judgments, and self-awareness of sleepiness level for the '40-50' group after 3 h of driving.

4. Discussions and practical implications

The findings of this study showed that driving duration has obvious effects on driver's eye blink behavior, driving performance, and personal feeling of sleepiness, which varied significantly across different age groups. Accordingly, it is necessary to limit the continuous driving duration among commercial drivers, including the number of continuous driving time, total number of driving hours per day, and number of driving and working hours per week.

As claimed by extensive previous research, monotonous driving condition makes drivers fall asleep at the wheel more easily and quickly [24,25]. The selected line route b passes through Yimeng Mountain area containing lengthy tunnels; therefore, drivers may feel more seriously impaired with higher subjective sleepiness, quicker eye blink movement, and poorer driving performance values. Though routes a and c lie in plain areas, roadside visual sceneries are changeable; thus, drivers do not feel bored and monotonous and the test results are reliable.

Since commercial drivers have to remain behind the wheel for long hours, drivers should be educated to recognize the risk of long distance driving without adequate rest and must take a rest break after 3-4 hours of continuous work, especially at night under monotonous road conditions. Moreover, expressway service centre should provide suitable sleeping facilities to attract drivers to take regular rest breaks when driving long distances. The government should implement stricter rules and regulations to set limits on driving hours (i.e., daily driving limit, maximum driving limit, daily rest period, weekly driving limit, and fortnightly driving limit) for the commercial drivers, especially for those performing long distance tasks. Of course, drivers of different ages should enjoy different rules. The elderly, for example, can drive less hours per day, yet need to rest more, compared to their young colleagues. More importantly, employers in cooperation with the local government should be required to provide the periodical training [26] and alleviate the heavy burdens on employees with a reliable support system, including living allowances, on-job injury insurance, medical insurance, housing provident fund, and low-rent house, etc.

More importantly, the findings indicated that driver's sleepiness during driving could be identified from the change of eye blink behavior or driving performance variables. Therefore, drivers can be alerted by seat vibration or sound if sleepiness comes on while long distance driving and, if necessary, should be forced to break down within a short period. However, it never means that drivers can drive as long as they want, relying on the alert to warn them, rather than take a rest, which is actually the best way to avoid a crash when sleepy.

This study has some methodological limitations. First, the sample size was small and the shift workers were not considered; thus, the test results may not reflect the overall conditions of commercial drivers in China. Second, the driver's eye blink movement and driving performance were dramatically affected by environmental conditions (i.e., weather, traffic flow and roadside facilities, etc.) and individual circadian rhythm. If a participant is in high spirits, for example, he/she may feel less sleepy, even after a long distance driving task. Consequently, future studies should systematically focus on how to capture precise data using accurate test techniques, such as through the driving simulator [27]. Third, self-reporting of individual sleepiness level through validated questionnaires may not be accurate due to drivers' faulty memory or incorrect judgment at the time of reporting, at which point they could have a short attention lapse and experience microsleep. Lastly, those engaged in fatigued driving often exhibit the symptoms of sleepiness [28]; thus, their feeling of sleepiness may be overestimated in the questionnaire survey. Accordingly, future study will focus on the need to systematically identify which visual indicators are the best predictors and feasible in practice and find a better measurement of sleepiness instead of using the SSS, etc.

Ethics approval and consent to participate

This research was conducted in full compliance with the laws and after obtaining approval from each individual driver who took part in the naturalistic driving test to collect his or her eye movement and fatigue awareness data. All data were recorded and analyzed anonymously.

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Biographies

Yonggang Wang received his BSc (1997-2001) degree in Civil Engineering at Shijiazhuang Tiedao University, MSc (2001-2004) degree in Hydraulic Engineering at Ocean University of China, and PhD (2005-2009) degree in Transportation Engineering at Harbin Institute of Technology. He is currently an Associate Professor of Transportation Engineering at School of Highway, Chang'an University, Xi'an, China. His research interests are in the area of traffic data modeling, traffic accident analysis and prevention, and simulation-based optimization of rail transit network reliability. He has published more than 20 articles in international journals, such as Transportation Letters, Traffic Injury Prevention, and Transport, etc.

Jingfeng Ma is currently an MSc candidate in Transportation Planning and Management at Chang'an University. He received his BSc degree in Transportation Engineering from Shandong Jiaotong University in 2016. His research interests include channelization design of intersection, comprehensive traffic planning, traffic accident analysis, and traffic signal optimization.

Lingxiang Wei is an Assistant Professor of Transportation Engineering at School of Materials Science and Engineering, Yancheng Institute of Technology, Yancheng, China. He received his MSc degree in Transportation Engineering from Chang'an University in 2016. His research interest is traffic safety analysis and evaluation.