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DETECTION OF FATIGUE IN LONG-DISTANCE DRIVING BY HEART RATE VARIABILITY

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Abstract. *Traffic accidents caused by fatigue or overwork when driving for long periods have not diminished. Thus, a method for detecting fatigue is needed, and we are attempting to evaluate and estimate fatigue. Three participants drove for about an hour on a highway comprising a slow lane and passing lane and their R–R intervals were measured. Fatigue levels were analyzed based on LF/HF, which is calculated using a Fast-Fourier-Transformed (FFT) R-R interval. From experiments and data analysis, two participants were found to be in a fatigued state, judging from an increase in LF/HF. Thus, it was observed that the fatigue state of a driver can be detected by analyzing his heart rate variability.*
Keywords: Fatigue, Heartbeat, LF/HF

1. **Introduction.** The 4000-km highway network in Japan has been opened and extended from 1989 to 2013, making it suitable for driving for long periods (Figure 1) [1].

The number of fatal traffic accidents caused by fatigue and/or overworked-driving has tended to decrease because of legal and business efforts. However, there are cases in which fatigue and/or overwork has caused major fatal traffic accidents; such accidents occurred in April 2012 and March 2013 [2,3]. Thus, traffic accidents caused by fatigue and/or overwork when driving for long periods have not diminished; therefore, we attempt to evaluate and estimate driver fatigue.

Evaluating fatigue via heart rate, breathing, perspiration [4], or brainwaves is a common physiological method [5]. Nowadays, a fatigue detection system using a flicker test is being developed based on the correlation between a low flicker value and the occurrence of an incident [6]. We attempt to evaluate and estimate fatigue based on heartbeat from the viewpoint of the cost of the system and the probability of real-time detection and evaluation.

We describe the experiment in Section 2 and the results of the experiment and analysis using heart rate variability such as LF/HF in Section 3. Section 4 contains the conclusions of this paper.

2. **Experiment.** Three participants (A, B, and C) joined the experiment to help evaluate the heart rates when driving for a long period. Two participants were 21 years old, and the other was 19 years old. All participants were shown how to wear a wearable-type heart rate monitor (WHS-1, Union Tool Co.) and measure their pulse wave and R-pressure pulse interval (also known as the R–R interval). They were also taught how to drive using a driving simulator (D3Sim, Mitsubishi Precision Co., Ltd.).

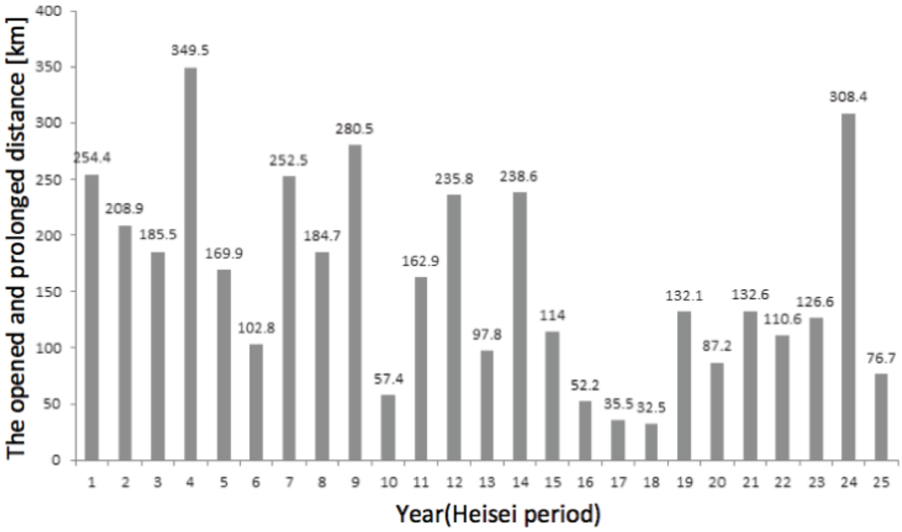

Figure 1. Open and prolonged distances of the highway network in the Heisei period

Figure 2. Driving scene: A highway course comprising a slow lane and passing lane

First, all the participants rested with their eyes closed and their R–R intervals were measured. Next, they drove on a simple urban course for about five minutes and became accustomed to driving before the experiment. This training period was provided because they were not used to driving using a simulator. After that, all participants drove for about an hour on a highway course comprising a slow lane and passing lane (Figure 2). Some obstacles were set on the course, and the participants were instructed to avoid these obstacles or entering a drowsy state because of monotonous driving. In addition, a "Jikaku-sho Shirabe (questionnaire on subjective fatigue)" and "Hirou-bui Shirabe (questionnaire on fatigued body parts)", which are used in the study of work fatigue by the Japan Society for Occupational Health, were implemented before and after the experiment in order to verify matching the result of heart rate variability and questionnaire. The subjective fatigue of all the participants was surveyed through these questionnaires. "Jikaku-sho Shirabe" classifies subjective fatigue in five categories: sleepiness, nervousness, discomfort, sluggishness, and blurred vision. We obtained the informed consent of all participants before the experiment.

3. Main Results.

3.1. **Experimental results.** We analyzed LF/HF, which is obtained from the power spectrum using Fast-Fourier-Transformed (FFT) R–R intervals. Here, LF is the intermediate-frequency component of the power spectrum and HF is the high-frequency component of the power spectrum. In this study, LF is defined as a range of the power spectrum from 0.05 to 0.15 Hz and HF is defined as a range of the power spectrum from 0.15 to 0.40 Hz. The ratio of LF to HF (LF/HF) is a useful indicator of tension or fatigue.

Frequency is usually analyzed by the autoregressive (AR) model, which is efficient for the analysis of short-time data because of a high spatial solution. However, in this study, we analyzed long-time data, and the frequency analysis results by the AR model and FFT showed a similar tendency [7]. Thus, we analyzed the R–R interval data and LF/HF data using FFT. LF/HF was z-transformed because its value is different for participants.

First, we confirmed whether the participants felt fatigued after going through "Jikaku-sho Shirabe" and "Hirou-bui Shirabe". From the results of the "Jikaku-sho Shirabe", the scores of some categories such as "can't think clearly", "yawning", "want to lie down", "getting sleepy" were found to be higher after the experiment (Table 1 upper). From the results of the "Hirou-bui Shirabe", the scores of some categories, such as "neck", "left elbow and forearm", "right upper arm", "left buttock and thigh", "right elbow and forearm" were also higher after the experiment (Table 1 lower). Thus, from the questionnaires, it was found that all participants felt fatigued.

We compared the average LF/HF values when participants were resting with their eyes closed with those when they were driving using a simulator. The results are shown in Figure 3 and Table 2. LF/HF values, which were not z-transformed when participants' eyes were closed, tend to be smaller than those when they were driving using a simulator. It was also found that the mental stress while driving tends to be higher. Next, the ratios of the z-transformed LF/HF value at 15 min (900 seconds) after the start of the drive to those at 5 min (300 seconds) intervals from 15 min after the start of the drive were calculated. The results are shown in Figure 4 and Table 3. Here, from the driver model of Arakawa et al. [8], drivers tend to be in an "excessive state" just after the start of driving and thus the values tend to be high. Thus, the data before the first 15 min of driving were omitted because drivers were in an "excessive state" and as a result, the LF/HF values were high. Therefore, we started analyzing LF/HF 15 min after the start of the drive.

From Figure 4 and Table 3, the z-transformed LF/HF values of participants B and C tend to increase with time, although they are dispersed.

From the results of the "Jikaku-sho Shirabe" for participant A, the scores of "yawning" and "drowsy" before the experiment were already high (see Table 1), and thus it was

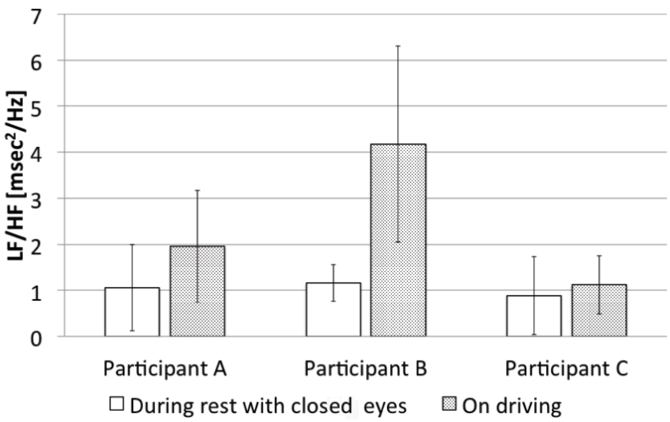

Figure 3. LF/HF values of all participants when at rest with eyes closed and when driving

Table 1. Results of the "Hirou-bui Shirabe" before and after the experiment. ("+" means that the scores after the experiment are higher than those before the experiment)

Symptom	Participant A		Participant B		Participant C	
	Before	After	Before	After	Before	After
Head feels heavy	1	1	1	2(+)	1	1
Nervous	1	1	1	1	1	1
Eyes become dry	1	1	2	2	1	3(+)
Feel bad	1	1	1	1	1	1
Uncomfortable	1	1	1	1	2	2
Have headache	1	1	2	2	1	1
Have sore eyes	1	1	3	3	1	2(+)
Have stiff shoulders	1	2(+)	2	2	1	1
Feel out of it	1	3(+)	1	3(+)	1	1
Yawning	3	5(+)	1	2(+)	1	1
Have sore arms and/or fingers	1	1	1	1	1	1
Feel dizzy	1	1	1	1	1	1
Getting sleepy	5	5	1	4(+)	1	1
Poor motivation	1	2(+)	1	1	1	1
Feel uneasiness	1	1	1	1	1	1
Blurred	1	1	1	1	1	1
General maraise	1	1	1	1	1	1
Depressed	1	1	1	1	1	1
Languid arms	1	1	1	2(+)	1	1
Can't think clearly	2	3(+)	1	1	1	1
Want to lie down	1	4(+)	1	2(+)	1	1
Tired eyes	3	1	3	3	1	3(+)
Have a backache	1	1	1	2(+)	1	4(+)
Get bleary	4	5(+)	1	2(+)	1	3(+)
Feel heave in legs	1	1	1	2(+)	1	1

Fatigue	Participant A		Participant B		Participant C	
	Before	After	Before	After	Before	After
Neck	1	2	0	1(+)	0	0
Left shoulder	1	1	1	1	0	0
Back	0	1	0	0	0	0
Left upper arm	0	1	0	1(+)	0	0
Left elbow/foerarm	0	1	0	1(+)	0	0
Waist	0	0	1	2(+)	0	0
Left arm/wrist	0	0	0	0	0	0
Left buttock/thigh	0	0	0	1(+)	0	2(+)
Left knee/crus	0	0	0	1(+)	0	0
Left leg/ankle	0	0	1	1	0	0
Right shoulder	1	1	1	1	1	0
Right upper arm	0	1(+)	0	1(+)	0	0
Right elbow/forearm	0	1(+)	0	1(+)	0	0
Right arm/wrist	0	0	0	0	0	0
Right buttock/thigh	0	0	0	1(+)	0	0
Right knee/crus	0	0	0	1(+)	0	0
Right leg/ankle	0	0	1	2(+)	0	0

Table 2. LF/HF values for all participants when at rest with eyes closed and when driving

	During rest with closed eyes	On driving
Participant A	1.05 ± 0.94	1.95 ± 1.21
Participant B	1.16 ± 0.40	4.18 ± 2.13
Participant C	0.89 ± 0.85	1.12 ± 0.64

※mean ± 1S.D., unit: msec^2/Hz

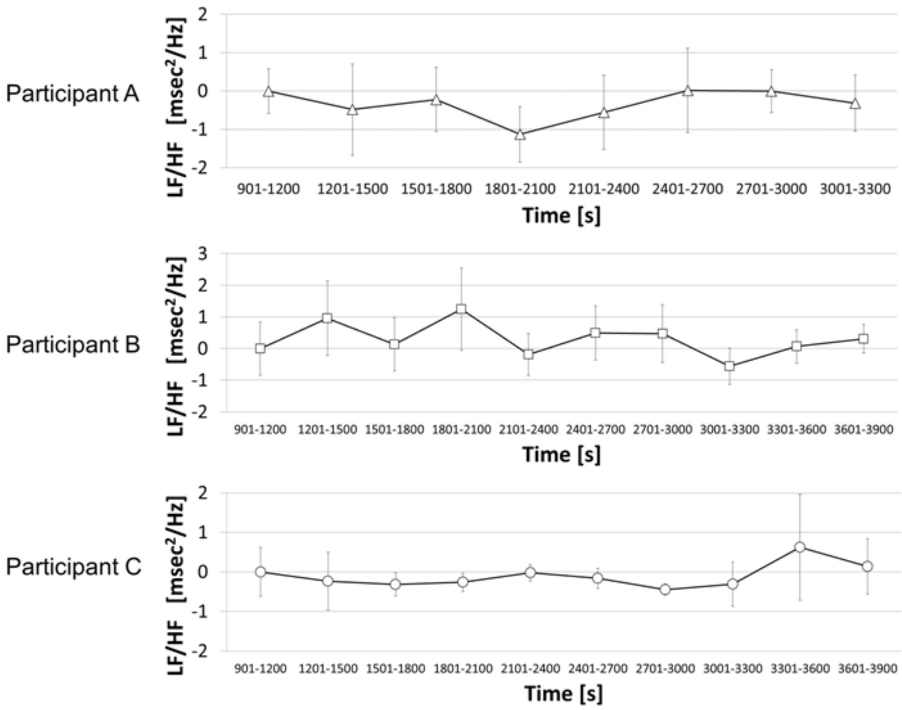

Figure 4. The ratios of the z-transformed LF/HF value at 15 min after the start of the drive to those at 5 min intervals from 15 min after the start of the drive

Table 3. The ratios of the z-transformed LF/HF value at 15 min after the start of the drive to those at 5 min intervals from 15 min after the start of the drive

Time	Participant A	Participant B	Participant C
900-1201	0.00 ± 0.58	0.00 ± 0.84	0.00 ± 0.62
1201-1500	-0.48 ± 1.20	0.96 ± 1.18	-0.23 ± 0.73
1501-1800	-0.22 ± 0.83	0.13 ± 0.84	-0.32 ± 0.30
1801-2100	-1.13 ± 0.72	1.24 ± 1.30	-0.26 ± 0.23
2100-2401	-0.56 ± 0.98	-0.18 ± 0.66	-0.02 ± 0.21
2401-2700	0.02 ± 1.10	0.50 ± 0.86	-0.16 ± 0.26
2701-3000	0.00 ± 0.56	0.47 ± 0.92	-0.44 ± 0.14
3001-3300	-0.31 ± 0.73	-0.56 ± 0.57	-0.31 ± 0.56
3301-3600	–	0.07 ± 0.53	0.63 ± 1.39
3601-3900	–	0.31 ± 0.45	0.14 ± 0.70

※mean ± 1S.D., unit: msec^2/Hz

clear that participant A was drowsy before the experiment. Therefore, it is suggested that participant A was already in a fatigued state and his or her LF/HF values did not increase during the experiment.

3.2. **Trial estimation of fatigued state.** An easy method for estimating the fatigued state is to determine the LF/HF value threshold. The driver is considered to be in a fatigued state when his or her LF/HF value exceeds the threshold. For example, an LF/HF value threshold is determined as 1.5 and the driver is considered to be in a fatigued state when the value exceeds 1.5. It should be noted that we determined an LF/HF value threshold based on matching the result of estimation and participant's feeling roughly. The results of all participants (shown in Figure 5) elucidate that the participants' fatigued state was approximately detected and there is consistency based on the introspective report on driving. However, this method does not consider the differences in each driver's characteristics and lacks versatility. Thus, it is necessary to improve the detection algorithm. For example, it may be possible to detect by applying machine learning or artificial intelligence with high accuracy. Further discussion about this is required.

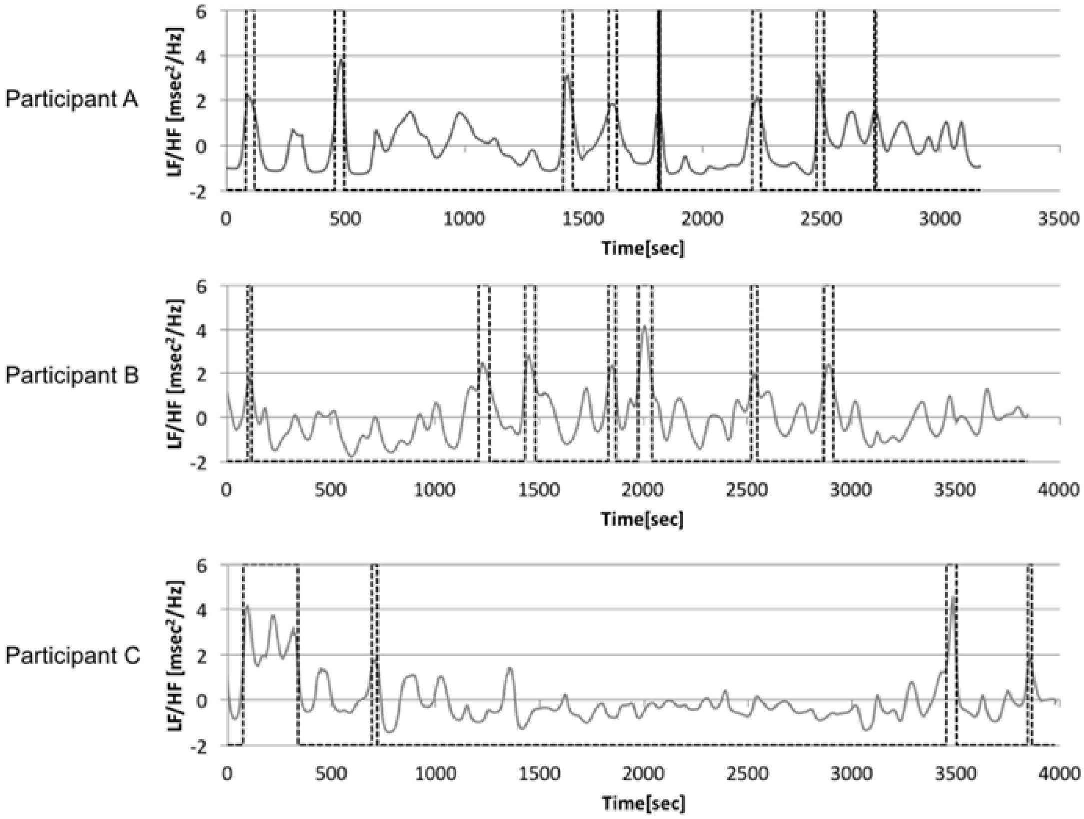

FIGURE 5. The timing of judging as fatigue in the case that the value of LF/HF exceeds 1.5

4. **Conclusions.** From this experiment, it was found that the fatigue state can be detected by LF/HF. However, the total driving time of all participants was approximately one hour, and it is unclear whether they entered a fatigued state. In addition, there were only three participants, so it seems to be insufficient for reliable results. In the future, thus, we will recruit more participants and will have them drive for a longer duration to obtain the LF/HF data by which a driver's fatigued state can be more clearly evaluated. In addition to that, we will improve the detection algorithm by applying machine learning or artificial intelligence in order to detect driver's fatigued state with high accuracy.

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