Evaluation on sleepiness under long term exposure of car interior noise while driving a small diesel truck
-A model for sleepiness by physical and physiological metrics-

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ABSTRACT
In order to see the effect of long term exposure of car interior noise under driving of small diesel truck on sleepiness, evaluation of sleepiness was conducted every 5 minutes for an hour experiment. During the subjective evaluation of sleepiness, simultaneous measurements of seat vibrations below 20Hz as well as above 20 Hz and physiological values such as heart beat rate and brain waves were conducted. After the experiment, the relations between the sleepiness and physical and physiological metrics such as heart beat fluctuation, brain waves and skin resistance were tested for the sleepiness model. As a result, positive contributions of physiological values and positive and negative contributions of seat vibration were observed for sleepiness. The region of the opposite contribution to sleepiness in terms of vibration components is located 20 Hz. Below 20Hz, the contribution is positive and above 20 Hz, that is negative. A tendency of the time history of the variation of subjective evaluations were averaged over 10 subjects for analysis..

Keywords: Sound, Insulation, Effect of Vibration on driver, Sleepiness, Sound Quality: 49.1, 63.7

1. INTRODUCTION
The dose of the driver of a truck running on a highway will be the cause of the severe traffic accident related to the life of the driver and that of the other vehicles near the truck. So, we have to prevent the dose of the driver for inventing the method to awaken the driver. The authors of this paper used the recorded signals of an interior noise and seat/floor vibrations recorded at a constant speed of 100km/h driving on a highway for the durations of approximately one hour as the stimuli for the jury subjects inside the sound proof room sitting on a driving simulator and tested the effect of the variations of vibration levels to the sleepiness (1, 2). In these experiments, small vibration transducers fixed on rear side of the subject’s seat and the seat below were used to reproduce the vibration signal. For this reason, the vibration signal reproduced was above 20Hz. So far, we found the reduction of vibration signal within 40Hz and 50Hz increased sleepiness and the brain wave and the low frequency content of the fluctuation of heart beat signal of the subjects significantly related to the sleepiness.

In real driving, the prominent components of the seat vibration were below 20Hz, so we have to study effect of low frequency content below 20Hz. This time, we introduced the vibration exciter capable of reproducing vibration signal below 20Hz and fixed this under the subject seat and to study the effect of vibration signal below 20Hz to the sleepiness. The recorded signals during the experiment were the same as our previous one such as heat beat, brain waves and skin resistance in order to see the effect of physiological response to the sleepiness.

2. EXPERIMENT
The physiological responses such as brain wave, electrocardiogram and skin resistance were recorded during the long term experiment as well as the continuous category judgment of sleepiness of seven categories at every 4 minutes by the subject.

2.1 Experimental Procedures
The experimental set up is shown in Figure-1 and the subject was requested to sit on the driving
simulator set inside the sound proof room.

2.1.1 Reproduction of interior noise and seat vibration
Seat vibrations above 20 Hz were reproduced by the each 4 transducers set under and behind the subject’s seat and the vibration signal below 20Hz was reproduced by the vibration exciter set under the driver seat. Car interior noise recorded simultaneously with the vibration signals was reproduced by a speaker set in front of the subject. In figure-2, the definition of the directions of seat vibrations was shown. The vertical of the vibration signal to the bottom seat surface and back seat surface were defined as Fz and Bz. In Figures 3 and 4, the original and reproduced vibration signals in Bz and Fz directions were shown. The reproduction of vibration signal in Fz direction was pretty good and coincided with the original one but that of Bz direction did not coincide with the original signal in the frequency region below 20Hz. The reproduction signal related to the original one was defined as the medium level and vibration signals related to the half and twice power of the original were defined as low and high vibration levels.

![Figure-2 Directions of the component of the seat vibrations](image)

![Figure-3 Spectrum of seat vibration(Bz)](image)  ![Figure-4 Spectrum of seat vibration(Fz)](image)
2.1.2 Duration of Experiment

The duration of experiment per vibration condition was set to 64 minutes. The experiment starts with the 4 minutes silent time interval and within this timing, subjects were asked to close their eyes and sit still. After this timing, 60 minutes exposure of car interior noise and seat vibration was exposed to the subjects.

2.1.3 Evaluation of sleepiness

The evaluation of sleepiness was conducted every 4 minutes in 4 minutes after the exposures of interior noise and seat vibration begun. Total of 15 times of the sleepiness evaluations were conducted during the one session. The scores of sleepiness are in seven categories ranging from not sleepy at all to very sleepy. The subject was asked to his impression on sleepiness by hitting the respective numeric score key on the PC key board while watching the PC display where the relation between the numeric score and sleepiness impression was shown.

2.1.4 Visual recognition work

While the interior noise and seat vibration were presented to the subject and when the subject was not asked to evaluate sleepiness, the subject was asked to watch the PC screen where the different single digit was continuously displayed time to time. And when the odd number of the single digit repeatedly displayed three times then the subject asked to click a mouse connected with the PC. This work had similarity with car driving so the subject was asked to do this job for simulating the task of driving while he had nothing to do during the experiment.

2.1.5 Subject

The subjects participated in this experiment were total of 10 aged between 22 to 24 years old with normal hearing.

2.1.6 Car interior noise

Car interior noise used for the experiment was recorded sound on a highway during 100Km/h driving and the sound pressure level at the ear position of the subject was 73.8 dBA.

2.1.7 Condition for vibration signal

The conditions of vibration signal were 4 conditions namely, high, medium, low levels and without vibration. Each experiment was continued 64 minutes including the silent 4 minutes on the top.

2.1.8 Data measured during the experimental session

The data collected during the experiment were physiological responses, signal of vibration and the evaluation of sleepiness by the subject. The physiological responses were brain wave, heat beat rate, electrocardiogram, skin resistance and the blood flow volume.

- **Brain wave (EEG)**: signal recorded at the Fz position under the international 10-2 method.
- **Heat beat rate (ECG)**: measured by the 3 poles method by the chest lead.
- **Skin resistance (SRR)**: measured by left hand two fingers under alternative current condition. The fingers used were index and ring fingers on the left hand.
- **Pulse wave (PPG)**: measured by the infrared penetration sensor set at the earlobe.
- **Blood flow**: measured by the Laser Doppler sensor set at the left hand
- **Seat vibration signals**: after obtaining the seat vibration level spectrum, then each 10 Hz band level was integrated starting from 0 to 100Hz.

The weighted according to BS681 was also calculated.

2.2 Result of Sleepiness Evaluation

In Figure-5, the result of sleepiness evaluation averaged over 10 subjects with respect time is shown. The sleepiness monotonously increased with time up to 40 minutes under all vibration levels. After 40 minutes, sleepiness begun to decrease its rate of increase or to seize to increase. The tendency of sleepiness after 40 minutes showed that sleepiness became less sleepy than before. According to our previous study, sleepiness monotonously increased with time within 30 to 40 minutes from the beginning and then it showed some decrease. The result obtained this time was closely related our previous result (2). With respect to the effect of the conditions of vibration exposure, the time histories of the evaluations related well with the high vibration level and without vibration and the results located below with the other two conditions. In case of medium vibration level, sleepiness stayed unchanged after 40 minutes and the absolute values of sleepiness was the highest among the four conditions. This medium vibration level condition was closely related to the real seat vibration condition under real driving.
3 RELATION BETWEEN SLEEPINESS AND PHYSIOLOGICAL RESPONSES

The data within 40 minutes from the beginning, we could see monotonously increase of sleepiness over 4 vibration conditions. Within this time period, sleepiness of 10 evaluations for each of 4 vibration conditions were normalized with their own standard deviations as well as the same treatment for the physiological responses. Then the relations between the sleepiness and physiological responses were examined.

3.1 Relation between Brain wave and Sleepiness

Among various brainwave components, the relations between α wave (the component within 8~13Hz) and β wave (the component within 1~25Hz) were compared with sleepiness.

3.1.1 α wave (peak) and Sleepiness

In Figure-6, the relation between α wave (peak) and sleepiness was shown. We could see tendency that sleepiness increased with the increase of α wave (peak) component.

3.1.2 α/β ratio (peak) and Sleepiness

In Figure-7, variation of sleepiness with α / β ratio (peak) was shown. Sleepiness increased with time with the increase of α / β ratio. The tendency of increase of sleepiness with the increase of α / β ratio was more clearly observed than with the α wave alone.

3.2 Relation between Fluctuation of Heat beat and Sleepiness

In this section, the relation between heart beat fluctuation components LF (0.05~0.15Hz) and HF (0.15~0.45Hz) were compared with sleepiness.

3.2.1 LF/HF (peak value) and Sleepiness

Figure-8 shows the relation between LF/HF and sleepiness. The tendency of the increase of sleepiness with increase of LF/HF was observed. The index LF/HF has the meaning that it increases...
with the increase of mental tension. This result that sleepiness increased with the increase of LF/HF means that the subject on the experimental task tried to cope with his sleepiness even under the condition that he felt sleepy due to the experimenter’s instruction for not to sleep when subject felt sleepiness. This tendency was consistently observed in our previous studies (1, 2).

3.2.2 LF/(LF+HF) (peak value) and Sleepiness

Figure-9 shows the relation between LF/(LF+HF) and sleepiness. As like the relation between LF/HF and sleepiness, sleepiness increased with the increase of LF/(LF+HF) due to the fact the this index is also has the meaning that it related to the mental tension.

3.3 Relation between Skin resistance (SRR) and Sleepiness

In order to see the relation between skin resistance and sleepiness, the data at each time was divided by the SRR peak, difference value between the peak and minimum and standard deviation within the 4 minutes timing before the experimental session.

3.3.1 SRR divided by the Peak value (4minutes before the session) and Sleepiness

Figure-10 shows the relation between the SRR divided by the peak value within the 4 minutes before the session starts and sleepiness. From this figure, high correlation was observed between SRR divided by the peak 4 minutes before the session starts and sleepiness.

3.3.2 SRR divided by the difference between the peak and minimum (4 minutes before the session)

Figure-11 shows the relation between SRR divided by the difference between the peak and minimum 4 minutes before the session and sleepiness. The relation between this value and sleepiness again showed good relation.

3.3.3 SRR divided by the standard deviation for whole experimental time and Sleepiness

Figure-12 shows the relation between SRR divided by the standard deviation for whole session and sleepiness. As like the other previous results, sleepiness increased with the increase of SRR that is divided by the standard deviation.
3.4 Relation between Pulse Wave Transmission Time (PWTT) and Sleepiness
The pulse wave transmission time calculated by the time difference of electrocardiogram (ECG) and pulse wave measured at earlobe (PPG) and sleepiness without the treatment of normalization is shown in Figure-13. We could see the tendency that sleepiness increases with the increase of pulse wave transmission time, namely, if sleepiness increases there is a tendency for the drop of blood pressure and this could be easy to understand.

3.5 Relation between Blood Flow and Sleepiness
The relation between the raw data of blood flow and sleepiness is shown in Figure-14. The tendency including whole 4 vibration conditions showed that if blood flow increased then sleepiness decreased and subjects became awaken. But in case of medium vibration level alone, the tendency is opposite, namely, if blood flow increased then sleepiness increased.

3.6 Relation between vibration component normal to the seat back Bz and Sleepiness
Compared with seat vibration of the normal component with seat surface, we could observed higher correlation between the sleepiness and normalize component to the seat back Bz. Here the results of the two opposites were discussed with their tendencies.

3.6.1 Bz (10~20 Hz) component and Sleepiness
Figure-15 shows the relation between Bz (10~20Hz) weighted with BS6841 and sleepiness. With this figure, we could see that sleepiness increases with the increase of the weighted Bz component.

3.6.2 Bz (20~30 Hz) component and Sleepiness
Figure-16 shows the relation between the weighted Bz (20~30 Hz) with the BS6841 and sleepiness. Although the correlation is poor compared with the previous result with Bz (10~20 Hz), the tendency with increase of weighted Bz (20~30 Hz) is opposite with the weighted Bz (10~20 Hz). Namely, if the weighted Bz (20~30 Hz) increases then sleepiness decreases.

Our previous results were due to the capability of reproducing vibration signal beyond 20 Hz and
with this condition, the relation between the sleepiness and Bz component showed negative correlation and these results coincided with the present result. The result obtained this time showed that Bz component below 20 Hz contributes to the increase of sleepiness and the one above 20 Hz contributes to the decrease of sleepiness, namely, sleepiness becomes shallower with the increase of this component.

![Figure-15 Bz (10~20 Hz) and Sleepiness](image)

![Figure-16 Bz (20~30 Hz) and Sleepiness](image)

4. MULTIPLE REGRESSION ANALYSIS OF SLEEPINESS

In order to see the contribution of physiological responses and vibration components to Sleepiness, multiple regression analysis was conducted using physiological responses and vibration levels as the explanatory variables and sleepiness as the observatory variable.

For the model construction, physiological responses and vibration levels are normalized using the their standard deviations as the explanatory variables. The reason why we have processed the raw data as like this is due to the fact that data range differ by the vibration conditions and in order to match the different range into more close deviation.

The model of two explanatory variables with the multiple correlation coefficient $R=0.956$ is shown in equation (1) and the explanatory variables are Bz (10~20 Hz) and $\alpha$ wave (peak). Test of variance for partial regression coefficients is shown in Table 1.

![Table 1 Test of variance for partial regression coefficients: model 1](image)

(Sleepiness)$=0.576** \times \text{Bz(10~20 Hz)} + 0.190** \times \alpha \text{ wave (peak)} - 1.02 \quad \ldots \ldots \ (1)$

With this model, multiple correlation coefficient $R=0.956$ and the contribution of vibration component normal to the seat back is positive and that of $\alpha$ wave (peak) is also positive and these are well coincide with the previous correlation analysis. The relation between the evaluation and estimation by this model is shown in Figure-17.
The model of 3 explanatory variables are shown in Table 2 and equation (2) with the multiple correlation coefficient $R=0.965$.

\[
\text{sleepiness} = 0.589^{**} \times \text{Bz} (10^{-20} \text{ Hz}) + 0.147^{**} \times \alpha\text{ wave (peak)} + 0.105^* \times \text{LF/HF} - 1.17 \tag{2}
\]

With the addition of the 3rd variable, namely, LF/HF, the multiple correlation does not increase much. But the contribution of each three variables to the sleepiness is clear to understand according to the correlation analysis conducted before. The evaluation and the estimation by the model (2) is shown in Figure-18.

5. CONCLUSIONS

Under the utilization of driving simulator capable of reproducing vibration signal below 20 Hz components, we have studied how the seat vibration contributes to the sleepiness evaluation as well as the physiological responses. As a result, following conclusions have been obtained.

1. The evaluation of sleepiness significantly related with the Values of $\alpha$ brain wave (peak), $\alpha/\beta$ ratio, fluctuations of heart beat such as LF/HF and LF/(LF+HF), peak value and difference between the peak and minimum of skin resistance and pulse wave transmission time, blood flow and those were defined as the physiological response values.

2. With respect to the seat vibration component, we could find positive correlation below 20Hz components and negative correlation beyond 20Hz.

3. When multiple regression model for sleepiness is studied, the pretreatment of the explanatory variables for normalization with utilization of standard deviation of each variable is useful. For
this treatment, we could easily understand the model to see the contribution of each variable to sleepiness.

4. The explanatory variables for sleepiness are vibration components below 20Hz of the normal component to the seat back, peak value of $\alpha$ brain wave and ratio of heart beat fluctuation component LF/HF.

REFERENCES


