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Psychological and Physiological Effects of Active Seat Suspension on Ride Comfort of Small Vehicles

by

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Abstract

In this study, the moods of drivers were estimated using physiological information; fluctuations in heart rate were measured by an electrocardiogram to measure autonomic nervous activity. We estimated the level of relaxation of drivers during driving by comparing the sympathetic nervous and parasympathetic nervous activities of drivers when they are driving cars with and without an active seat suspension. A frequency analysis of the nervous activities was carried out using a real-time system that analyzes fluctuations in heart rate. The moods of the drivers were also examined using a questionnaire to evaluate the correlation between the moods of drivers during driving estimated on the basis of electrocardiographic measurements and those estimated on the basis of responses to the questionnaire. Furthermore, their correlation was also examined by conducting a questionnaire survey with a five-point scale with three as a reference value to examine the subjective ride comfort of drivers in cars with and without an active seat suspension.

Keywords: Active seat suspension, Riding comfort, Electric vehicle, Heart rate variability

1. Introduction

In Japan, the elderly population has been increasing and it has become increasingly important to ensure self-supported daily and social lives for the elderly. To this end, improving the availability and safety of transportation for the elderly has become increasingly important. Kamata *et al.* have reported a series of studies on transportation devices that can be easily used by the elderly,[1,2] and they concluded that small vehicles are more suitable transportation devices for the elderly.

Unlike conventional automobiles, such small vehicles may frequently travel on roads of poor condition, such as narrow and unpaved roads. These roads have bumps and many small obstacles, and therefore, the ride comfort of the vehicles is expected to deteriorate. To solve this problem, researchers in our laboratory have proposed an active seat suspension that can be installed in small electric automobiles. We have previously examined the control performance of the system and verified the practicality of the system. Most studies have not focused on the psychological and physiological effects of active seat suspension on ride comfort of small vehicle. Therefore, we carried out traveling experiments on an indoor road on which hard rubber obstacles were placed, discussed the practicality of our active seat suspension, focusing on ride comfort,[3-5] evaluated the ride comfort by sensory tests, and examined the psychological factors that affect the ride comfort.[6-9]

In this study, focusing on the moods of drivers as psychological factors affecting ride comfort, we examined physiological information in terms of biological reactions as well as psychological information. In an outdoor experiment, the fluctuation in heart rate was measured as a biological reaction to monitor autonomic nerve activity. In addition, the relationships among ride comfort, mood of the driver, and physiological effects were discussed on the basis of psychological information during driving acquired through a questionnaire survey.[10-12]

2. Experiment

2.1 *Driving course and experimental method*

Fig. 1 shows the small electric automobile used in our experiment. Considering the actual conditions of driving,

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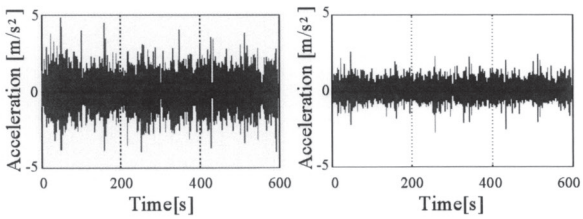
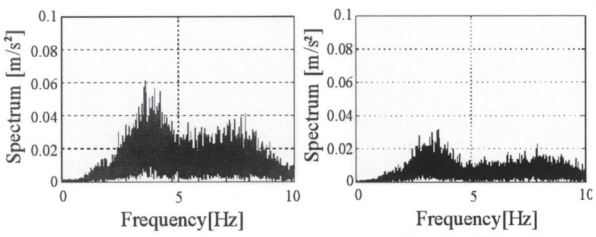
Fig. 1 Photograph of electric vehicle

Fig. 2 Surface of test road for outdoor experiment



(a) Vehicle A (b) Vehicle B

Fig. 3 Time histories of seat acceleration for outdoor experiment



(a) Vehicle A (b) Vehicle B

Fig. 4 Spectrum of seat acceleration for outdoor experiment

we carried out an outdoor driving experiment considering long-time driving on an actual driving course. The stone path in the Shonan Campus of Tokai University, shown in Fig. 2, was used as the driving course. It is a straight path with a rough surface paved with 300-600 mm quadrangular stones. In the driving experiment, the vehicles traveled straight at a speed of approximately 8 km/h, whereby vibrations with random frequencies were input to the vehicles as disturbance.

Two test vehicles were prepared: one is an uncontrolled vehicle, with fixed floor and seat surfaces so that the relative displacement between them is unchanged (Vehicle A), and the other is a controlled vehicle, in which the voltage

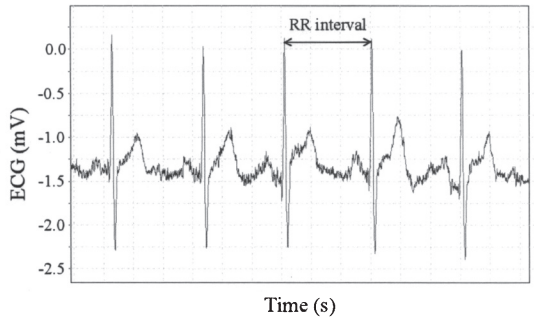


Fig. 5 Myocardial potential

supplied to the voice coil motor is controlled (Vehicle B). The seat acceleration was experimentally compared between the two vehicles. The Vehicle B is controlled by adjusting the voltage supplied to the voice coil motor using an optimal controller and a disturbance cancellation controller along with an optimal controller.

2.2 *Vibration acceleration and vibration spectrum of test vehicles*

Figs. 3 and 4 show the measured result of seat acceleration in the outdoor experiment. Figs. 3(a) and 3(b) show the time histories of the seat acceleration of Vehicles A and B during driving, respectively. The abscissa indicates the driving time, and the ordinate indicates the seat acceleration. When the standard deviation of the seat acceleration of Vehicle A is assumed to be 100%, the vibration of Vehicle B is suppressed by approximately 40%.

Figs. 4(a) and 4(b) show the power spectral density of the seat acceleration for Vehicles A and B, respectively. The abscissa indicates the frequency, and the ordinate indicates the power spectral density. Compared with the vibration acceleration of Vehicle A, that of Vehicle B is suppressed in the frequency range of 4-8 Hz, which significantly affects ride comfort.

3. Analysis of fluctuation in heart rate

3.1 *Index of autonomic nerve activity*

An electrocardiogram, which provides information on biological reactions, was obtained as an evaluation index in the outdoor driving experiment, instead of conducting a questionnaire survey that gives psychological information. Fig. 5 shows the results. The abscissa indicates time, and the ordinate indicates myocardial potential. The duration from the occurrence of one R wave to that of the next R wave is referred to as the R-R interval. The fluctuation in the R-R interval is called heart rate fluctuation[13], from which changes in mood and changes in autonomic nerve activity can be detected. Thus, ride comfort is analyzed on the basis of the changes in biological reactions during driving determined

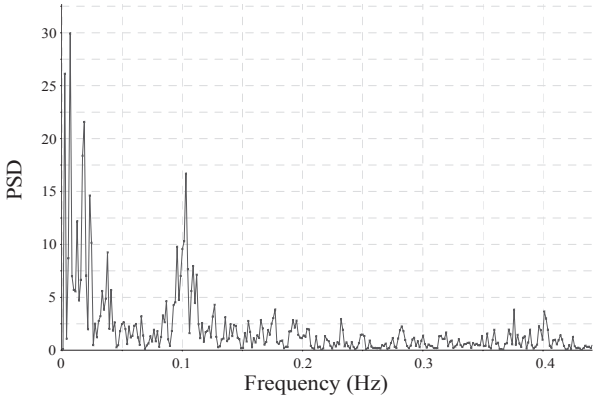


Fig. 6 PSD of myocardial potential

using such physiological information.

Autonomic nerves are composed of sympathetic and parasympathetic nerves. The activity of sympathetic nerves increases upon receipt of an external stress, whereas that of parasympathetic nerves is related to resting functions. The balance between the opposing actions of these two types of nerves determines whether the physical and mental states are active or resting.

To assume the heart rate fluctuation to be an autonomic index, the heart rate fluctuation shown in Fig. 6 is examined by analysis of the frequency element. The abscissa indicates the frequency element, and the ordinate indicates power spectrum density of the frequency element of the heartbeat fluctuation. The frequency element obtained from the heart rate fluctuation of the electrocardiogram is analyzed as the low-frequency (0.04-0.15Hz) and the high-frequency (0.15-0.4Hz). The high-frequency (HF) is an index of parasympathetic nerve stimulation. And low-frequency/high-frequency (LF/HF) ratio is considered to be an index of sympathetic nerve stimulation.

3.2 *Experimental evaluation of ride comfort on the basis of biological information*

In the experimental evaluation of ride comfort, autonomic nerve activities are examined on the basis of heart rate fluctuation during driving of the test vehicles, as explained in § 2. The relationship between ride comfort and mood during driving is determined.

The experiment was carried out following the procedure shown in Fig. 7. For both Vehicles A and B, time changes of HF and LF/HF components during a 5 min rest period before driving and a 10 min period during driving were measured. In addition, to determine the moods of the drivers during driving, a questionnaire survey, profile of mood state (POMS), was carried out after they drove each vehicle (Vehicles A and B), and an additional questionnaire survey about ride comfort was also conducted for the people who

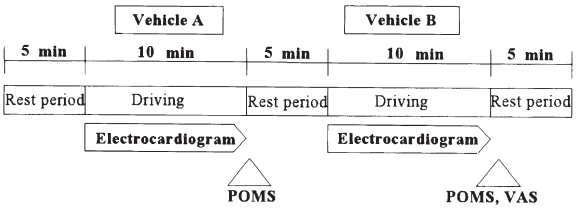


Fig. 7 Experimental protocol for outdoor experiment

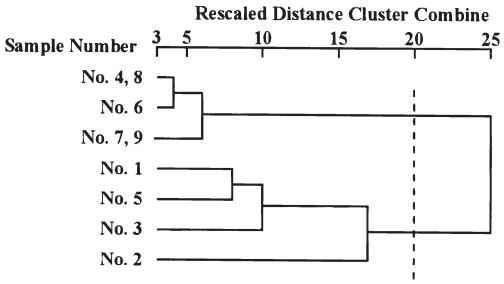


Fig. 8 Dendrogram

drove Vehicle B. These surveys were conducted as group surveys for 9 graduate and undergraduate students with an average age of 22.2 (SD, 0.8) years.

4. Questionnaire survey

4.1 *POMS*

We have made a survey of the moods of the drivers by the POMS[13]. This questionnaire survey can measure the psychological mood scale of T-A (Tension-Anxiety), D (Depression), A-H (Anger-Hostility), V(Vigor), F (Fatigue) and C (Confusion). We analyzed the factor which had influences on ride comfort by the T-score that normalized each psychological mood scales.

4.2 *VAS*

The VAS (Visual analog scale)[14] is the method how subjective evaluation is possible. Four values, fatigue, tension, rolling and the subjective evaluation of the ride comfort, were measured by the VAS. We use these scores for analysis for the values of the subjective evaluation.

5. Results and considerations

5.1 *Grouping of subjective evaluation*

To discuss the subjective evaluation of ride comfort, which is affected by the seat suspension, the individual differences in the VAS subjective evaluation were examined and compared. Cluster analysis[15] was used to in the outdoor experiment. Fig. 8 is a dendrogram divided as a

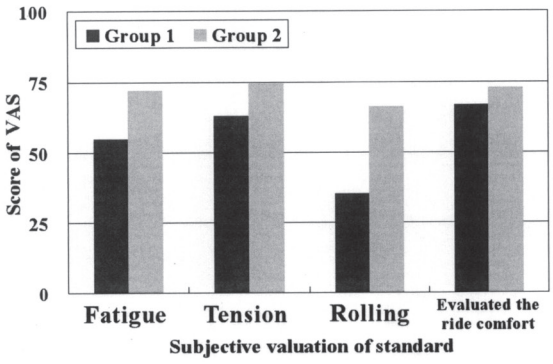


Fig. 9 Score of VAS vs. mood standard

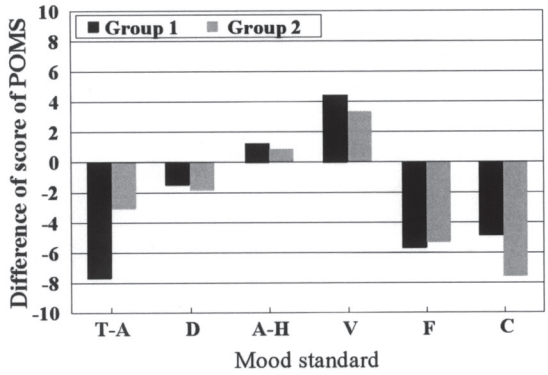


Fig. 10 Difference of score vs. mood standard for outdoor experiment

result of the cluster analysis. By cluster analysis, the subjects can be classified according to the differences in their subjective evaluation of Vehicle B with respect to Vehicle A. The data were classified into two clearly distinct groups. Furthermore, the data were standardized so that the standard deviation of the subjective evaluation value for each subject is 1 for use in the analysis.

5.2 *Relationship between ride comfort and subjective evaluation*

Fig. 9 shows the values of the subjective evaluation classified into two groups. The abscissa and ordinate indicate the scale and score of the subjective evaluation, respectively. As shown in Fig. 9, both groups evaluated the ride comfort of Vehicle B to be higher than that of Vehicle A, and experienced less fatigue and tension. The subjects in Group 1 gave a relatively low rolling score in the subjective evaluation (significance level, $p<0.05$), indicating that they felt greater rolling in Vehicle B than in Vehicle A. However, the subjects in Group 2 gave a high rolling score in the subjective evaluation ($p<0.05$), indicating that they felt that the rolling of Vehicle B is suppressed.

5.3 *Relationship between ride comfort and mood*

Fig. 10 shows the difference in the POMS scores obtained after driving for each group. The abscissa

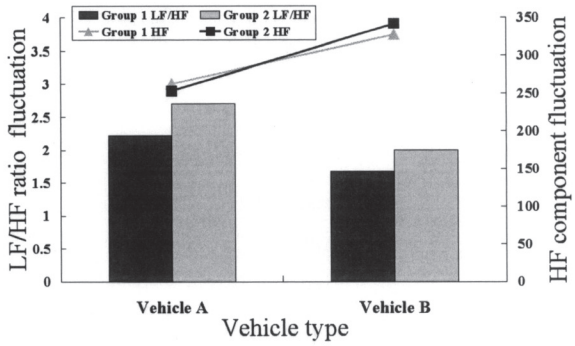


Fig. 11 Results of heart rate variability analysis

indicates the psychological mood scale, and the ordinate indicates the value obtained by subtracting the POMS score after driving Vehicle A from that after driving Vehicle B. In Fig. 10, T-A during driving of Vehicle B is found to be lower than that during driving of Vehicle A ($p<0.05$) for Group 1. It is also confirmed that F and C are lower when driving Vehicle B than when driving Vehicle A ($p<0.05$) for both Groups 1 and 2. Namely, the tension and fatigue on the mood scales decrease while driving the vehicle with suppressed vibration acceleration; in particular, those who felt increased rolling experienced less tension and anxiety.

5.4 *Relationship between ride comfort and heart rate fluctuation*

Fig. 11 shows the experimental results of heart rate fluctuation classified into two groups. The abscissa indicates the type of vehicle, and the ordinates on the left and right indicate the LF/HF components (bar graph) and HF components (line graph) for a driving time of 10 min, respectively. As shown in Fig. 11, the HF components are higher and LF/HF components are lower when driving Vehicle B than when driving Vehicle A ($p<0.05$) for both groups. Therefore, the HF components suppress the sympathetic nerve activities when driving Vehicle B with a vibration acceleration lower than that of Vehicle A, confirming that the parasympathetic nerve activities become dominant.

6. Conclusions

In the outdoor driving experiment, moods were used as the factors that affect ride comfort. In addition, the frequency components of heart rate fluctuation were analyzed to discuss ride comfort while also considering physiological information obtained during driving.

As a result, we succeeded in analyzing the effect of mood on ride comfort by grouping the subjects according to the personal preference regarding ride comfort. In the subjective evaluation and psychological evaluation using

POMS scores, the tension and fatigue felt by the drivers driving the vehicle with suppressed vibration acceleration tended to decrease. For psychological effects, it was confirmed that tension and confusion tend to be alleviated during driving of the vehicle with suppressed vibration acceleration.

For physiological effects, the analysis of frequency components revealed that the parasympathetic nerve activities become dominant upon suppressing vibration acceleration. Therefore, tension and fatigue during driving can be measured by analyzing heart rate fluctuation, and the results confirmed that the relaxed state was induced by the suppression of vibration acceleration.

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