Steer-by-Wire System for Ultra-Compact Electric Vehicle
—Functional Evaluation of Vehicle Handling Preference by Cornering on the Street—

by

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Abstract

Nowadays, the need for producing ultra-compact electric vehicles has been increasing, especially in the current Japan automobile industry, as a way of traveling and transportation for elderly people. Our research group has studied an active seat suspension (ASS) for ultra-compact electric vehicles, and a high-value added driver's seat that enables feedback control of the vibration by estimating the psychological state of the driver during driving on the basis of biological signals and other parameters. We aim to design and manufacture a steer-by-wire system (SBWS) to control the driver's seat when the driver's entire body is on the ASS system, in other words, neither the driver's arms nor legs are in contact with the chassis. In addition, we aim to develop an intelligent seat that can provide an optimal driving environment in accordance with changing conditions by monitoring of the driver's physical condition by the system, on the basis of various biological signals. Unlike the system in which tires are steered via a rack-and-pinion mechanism as in conventional vehicles, the SBWS enables tires to be steered through control using electrical signals. This paper considers the experimental operation feeling of right or left turns at low speeds which is more practical for running. In addition, aiming at acquisition of more reliable basic data, it was carried out with 95 subjects, and multivariate analysis of the data in a running experiment was conducted.

Keywords: Steer-by-wire steering, Operation, Subjective view evaluation, Questionnaire form

1. Introduction

For the last two or three years, ultra-compact electric vehicles have been increasingly demanded because of environmental issues and the aging of society [1,2]. The authors have studied an active seat suspension (ASS) for ultra-compact electric vehicles, and a high-value added driver's seat that enables feedback control of the vibration by estimating the psychological state of the driver during driving on the basis of biological signals and other parameters [3-6].

We expect that electric vehicles with a "skateboard-shaped" chassis that are directly driven by in-wheel motors will become the mainstream in the future [7]. General Motors released the concept car "AUTOnomy" in 2001 and proposed the skateboard-shaped running system that needs no engine room by placing motors inside the four wheels, and combining the motors with a by-wire steering system [8]. Such a technology has a significant impact on the shape of the cabin. For example, a car design with a custom cowl is possible because driver's seat and other seats can be freely placed.

In addition, more space can be easily secured in the car, improving the added value of electric vehicles that are primarily for short-distance travel. Figure 1 shows intelligent seat completely independent of car body. We aim to design and manufacture a steer-by-wire system (SBWS) to control the driver's seat when the driver's entire body is on the ASS system, in other words, neither the driver's arms nor legs are in contact with the chassis. In addition, we aim to develop an intelligent seat that can provide an optimal driving environment in accordance with changing conditions by monitoring of the driver's physical condition by the system on the basis of various biological signals [9].

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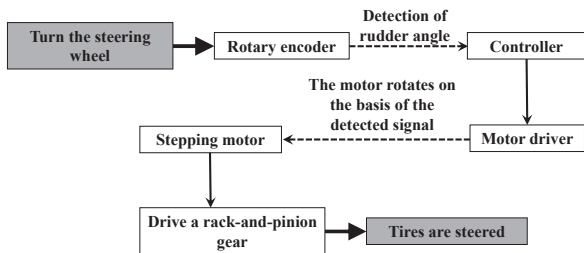Fig. 1   Intelligent seat completely independent of car body

Fig. 2   Block diagram of control system

Fig. 3   Control system of steer-by-wire

Fig. 4   Photograph of experimental vehicle

In the previous paper, the SBWS was mounted in the ultra-compact electric vehicle. It served as verification of the mounted equipment, and subjectivity evaluation about the operativity at the time of slalom running was performed [10]. However, verification practical as an everyday transportation device is not yet performed. Therefore, since this paper considered experimental operation feeling of right or left turns at low speeds which is more practical for running. In this paper, aiming at acquisition of more reliable basic data, it was carried out with 95 subjects, and multivariate analysis of the data in a running experiment was conducted. However, it was 30 subjects in the last paper.

2. Experimental setup

2.1 *Outline of SBWS*

Figure 2 shows a block diagram of the control system of SBWS that was implemented by Takebayashi *et al* [11]. The angle of rotation of the steering wheel is detected by an encoder. Unlike the system in which tires are steered via rack-and-pinion mechanism and column shaft as in conventional vehicles, the SBWS enables tires to be steered through control using electrical signals.

2.2 *Experimental setup*

The SBWS with a device to control the reaction force of the steering wheel (reaction-force device) were installed in Friendly Eco[10, 12] because it has a structure similar t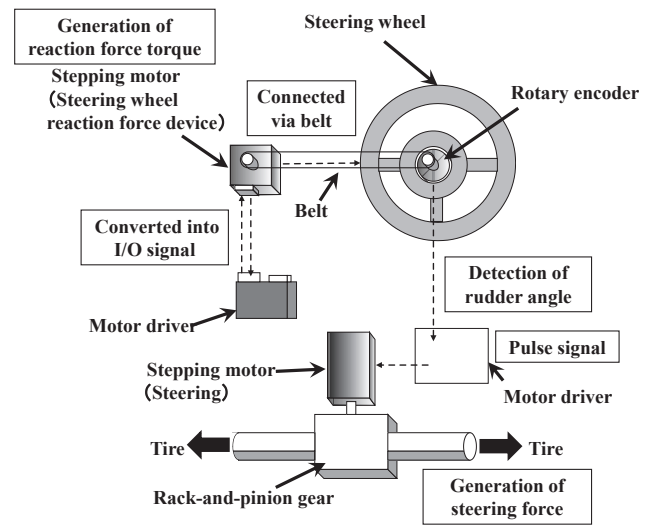o the skateboard-shaped chassis, wh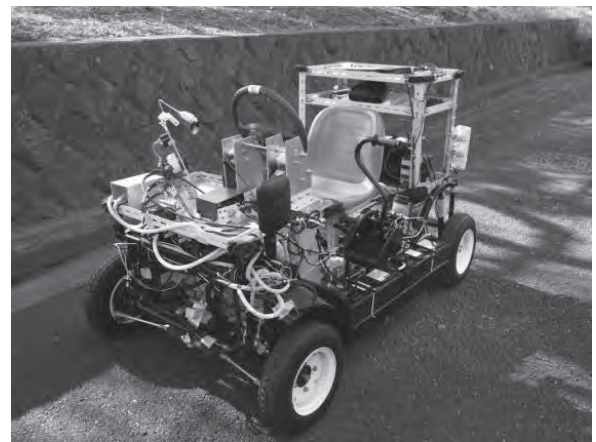ich is expected to become mainstream in the future. It was manufactured by Takeoka Jidosha Kogei and modified for experimental use. The vehicle has a flat frame to allow a person on a power-operated wheelchair to get in and out of the vehicle. In addition, it adopted a rack-and-pinion steering mechanism; thus, its steering system was modified so that the steer angle was detected using a rotary encoder and the detected angle was inputted as an electrical signal into the stepping motor used for steering via a wire to drive the rack-and-pinion gear. Figure 3 shows the schematic of the control system, and Fig. 4 shows a photograph of the modified experimental vehicle. The seat of the original electric wheelchair was exchanged with the seat of other ultra-compact electric vehicle. The stepping motors were used for the actuators of the SBWS and the reaction force device. The specifications of the stepping motor are shown in Table 1. Figures 5(a) and 5(b) show the photographs of the stepping motor for steering that directly drove the rack-and-pinion mechanism and the stepping motor

Table 1　Specifications of the stepping motor

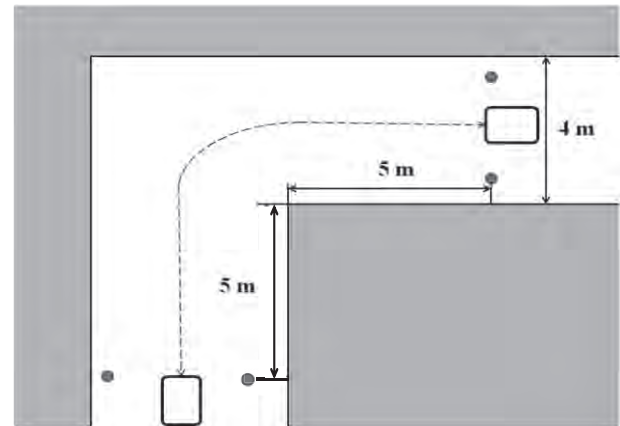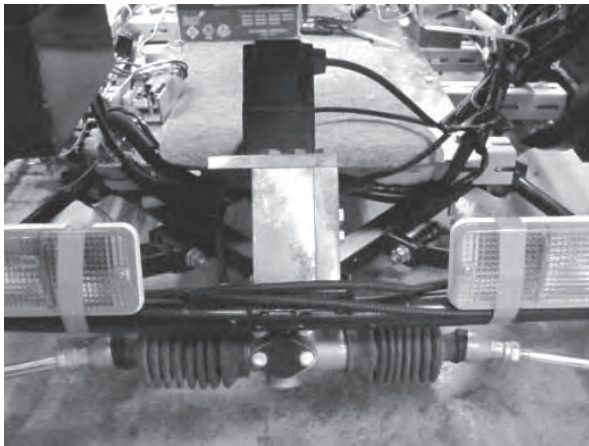|		CRK566APB-N10 (ORIENTAL MOTOR)	
SBWS	Frame size	60 mm	
	Mass	1.5 kg	
	Rated current	1.4 A/Phase	
	Basic step angle	0.072 °	
	Rated torque	5 N·m	
	Maximum torque	11 N·m	
Reaction-force device	AR66SMKD-T10 (ORIENTAL MOTOR)		
	Frame size	60 mm	
	Mass	1.53kg	
	Allowable torque	3 N·m	
	Resolution setting	0.036 °/step	
	Rated torque	3 N·m	
	Permissible speed range	0～180 r/min	

Fig. 6　Layout of test course

(a) Stepping motor for steering
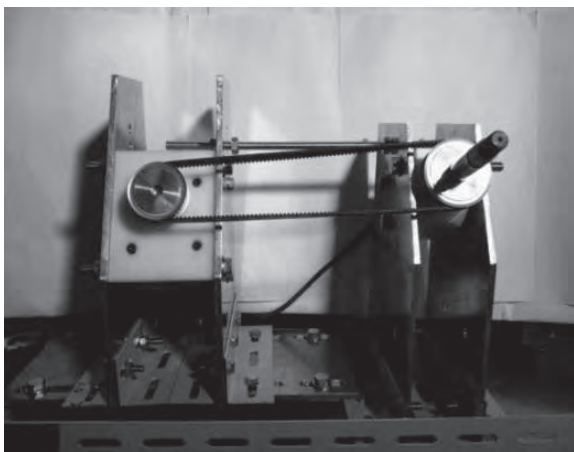
(b) Rotary encoder and stepping motor for steering wheel reaction force device

Fig. 5　Devices in steer-by-wire-system

3. Experimental method

3.1 *Experimental protocol*

　　The test course was a paved flat road on which the experimental vehicle was driven along corner course (Fig. 6) in the Shonan Campus of Tokai University. The subjects were asked beforehand to drive the experimental vehicle as if they were driving a conventional passenger vehicle.

　　To determine the difference of the operational feel perceived by subjects caused by the change in the reaction force of the steering wheel and the characteristics of the subjects, a driving experiment was carried out and the two questionnaire surveys explained in §3.2 were conducted before the driving experiment. (After that, the driver who participated in the experiment is referred to as the subject.) Before the driving experiment, subjects were asked to answer a preliminary questionnaire and to undergo a psychological test to check their driving aptitude [13] (hereafter, driving aptitude test). In the driving experiment, subjects drove an experimental vehicle with one of the three levels of reaction force. The level of the reaction force was not disclosed to the subjects so that the subjects evaluated the reaction force only from the operational feel. Three levels of the reaction force of the steering wheel could be set in the experimental vehicle as follows: reaction force with a motor output of 4.6 Nm (medium), which was equivalent to that during the mechanical fastening in the state of rest before the modification of the vehicle, and reaction forces with motor outputs of 3 Nm (low) and 6 Nm (high). In addition, the steering reaction force is changed by the variation speed of vehicle in a non-assistance's vehicle, such as power steering. However, due to constant speed of the vehicle, steering reaction force for each driving was constant in this experiment.

for the reaction force device, respectively. As shown in Fig. 5(b), the force of the stepping motor of the reaction force device is transmitted to the steering wheel via a belt.

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Table 2 Principal component score coefficient matrix
(operativity in left turn course)

	1st principal components	2nd principal components
Low reaction force	0.278	0.856
Medium reaction force	0.639	0.049
High reaction force	0.548	-0.491

Fig. 7 Dendrogram

Each subject drove the experimental vehicle 6 times for each reaction force. Thus, right turn and left turn for low, medium and high reaction force were examined respectively. They were asked to answer the questionnaire on subjective evaluation on every test time. This questionnaire consisted of four items, i.e., stability, operability, strength of reaction force, and overall evaluation, on a scale of five levels, with "5" being "very good" or "too strong" and 1 being "very bad" or "too weak".

The total number of subjects was 95 undergraduate or graduate students of Tokai University who have a driver's license. We obtained approval from the Ethics Committee for Research on Human Subjects of Tokai University. We also explained to the subject about the contents of the research and obtained signed consent (using a form approved by the Committee) from the subject who participated in this research.

3.2 *Driving aptitude test*

The subjects were asked to answer a preliminary questionnaire and took a driving aptitude test before the driving experiment.

The items in the preliminary questionnaire included the number of years since getting a driver's license, how often they drove, the purpose of driving, and the presence of fellow passengers.

The driving aptitude test was similar to the aptitude test in the driver's license examination. There were 75 items in the driving aptitude test, such as "I often sound the horn during driving" and "I am always depressed during driving". Subjects were asked to answer these questions on a scale of five levels, i.e., "strongly disagree", "disagree", "neutral", "agree", and "strongly agree". From the results of the driving aptitude test, the scores of the aptitude in terms of 6 categories were obtained. The results of the driving aptitude test were used to examine the relationship between the driving aptitude and the tendency of the operational feel of subjects. The subject with high scores had a stronger tendency in each category. The median of the score is used as a reference to evaluate the tendency of the subject. The subjects with a high score of aggressiveness tend to drive tough, those with a high score of weak mindedness change
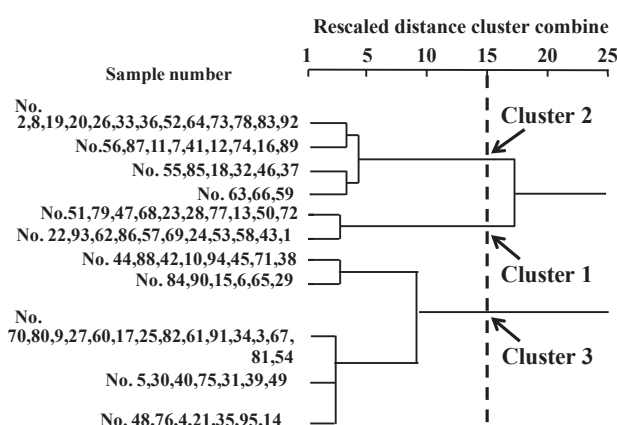
their driving style depending on their mood, those with a high score of impulsiveness drive without careful consideration, those with a high score of vanity drive ostentatiously, and those with a high score of hypersensitivity drive under tremendous stress or nervousness, and those with a high score of selfishness tend to prioritize their own vehicle over others.

4. Experimental results and discussion

4.1 *Principal component analysis*

In order to consider the tendency of operativity among the results obtained by questionnaire on subjective evaluation, the principal component analysis was conducted in SPSS.

The analysis result of the left turning by which the characteristic tendency was confirmed in the result is shown. Table 2 is the principal component score of the operativity in left turn. This research targeted even the 2nd principal components which have competent tendency. From Table 2, the principal component score coefficient has medium reaction force (4.6 Nm) and high reaction force (6 Nm) with the 1st principal components. From this, it is shown that the 1st principal components are an ingredient by which the operativity of medium and high reaction force is favor. Moreover, with the 2nd principal components, it turns out similarly that it is an ingredient which favor the operativity of low reaction force.

4.2 *Cluster analysis*

Next, cluster analysis was conducted in order to use the principal component score calculated with §4.1 and to carry out the group division of the favoring each subjects' reaction force. Figure 7 shows the dendrogram (tree diagram) obtained from the result of cluster analysis. With this paper, the number of clusters was arbitrary and the difference couldbe determined as they are divided and compared with three clusters in the clear dashed line portion of Fig. 7.
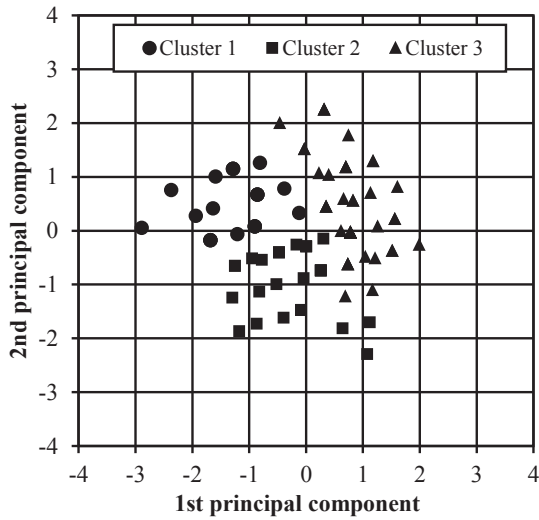
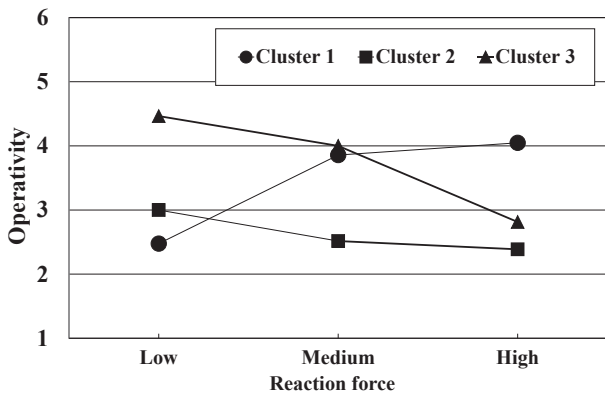Fig. 8   Principal component score distribution
(turn left course)

Table 3   Evaluation criteria of the driving aptitude test

	Aggressiveness	Weak mindedness	Impulsiveness	Vanity	Hypersensitivity	Selfishness
Average	18	25	14	15	22	15
Standard deviation	6	6	4	4	5	4
Top	21	28	16	17	25	17
Bottom	15	21	12	13	20	13
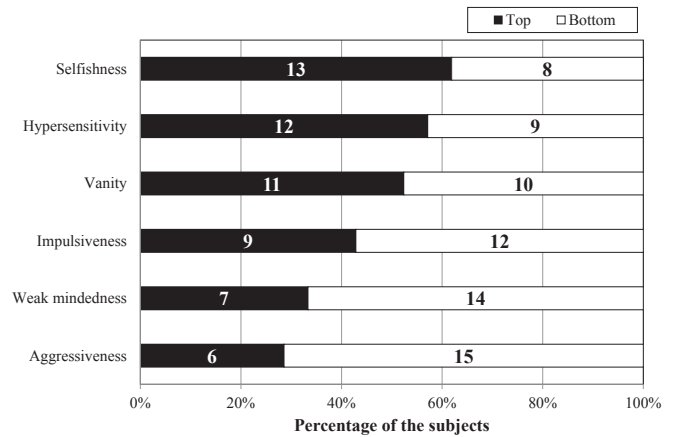
Fig. 10   Trend of driving aptitude of cluster 1
(turn left course, N=21)

Fig. 9   Operability average points in each cluster
(turn left course)

4.3 Subjective evaluation of the reaction force and the driving aptitude test

The tendency of favor of reaction force and the relation of the driving aptitude test for each cluster are confirmed. Therefore, it classified into top and bottom about the score of the driving aptitude test, and the tendency was confirmed by each cluster. The method of a classification is as follows. Top is more than "average value＋0.5×standard deviation" value. Bottom is below "average value－0.5×standard deviation" value [14]. In addition, the score of top and bottom in 6 driving aptitude are shown in Table 3.

The tendency of the operation aptitude of cluster 1 which the tendency characterized is shown in Fig. 10. This graph arranged the tendency of top and bottom in six driving aptitude in each cluster. From Fig. 10, since top of aggressiveness is 6 persons and bottom is 15 persons, cluster 1 is comfirmed to have much number of aggressiveness for bottom. Therefore, the subjects with a low score of the aggressiveness in the operation aptitude confirmed to have more tendency which favors medium and high reaction force.

5. Conclusion

In this study, SBWS was mounted in the ultra-compact electric vehicle and the operation feeling of the right and left

The scatter chart of the principal component score of operativity evaluation of each cluster is shown in Fig. 8. A horizontal axis is the 1st principal component score and vertical axis is the 2nd principal component score. Since the value in the 1st principal component score of a cluster 1 are positive and the 2nd principal component score are negative, it turns out that medium and high reaction force are favored. Moreover, since the 1st and 2nd principal component score of a cluster 2 are negative values, it is thought that there is a tendency to disfvor all the reaction force. Furthermore, it is thought that it favors low reaction force since the 2nd principal component score of a cluster 3 are positive values. As for the result of a tree diagram (Fig. 8) as well as the necessary and sufficient condition for Fig. 9, cluster 1 favors medium and high reaction force. Moreover, cluster 2 disfavored all reaction force and cluster 3 has a tendency which favors low and medium reaction force.

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turn in a low speed was verified experimentally as an everyday transportation device. In addition, aiming at acquisition of reliable basic data, the multivariate analysis was conducted from the subjectivity assessment data of the large-scale driving experiment by 95 subjects. As a result, the tendency by each factor has been comfrmed from comparison which used driving aptitude diagnosis and subjectivity evaluation questionnaire about the operation in the weight of reaction force.

A future examination is due to grasp favor of a subject's operation as prior information from the basic data obtained in this paper, and to control reaction force using the information on the living body signal of real time.

References

1) The Ministry of Land, Infrastructure, Transport and Tourism: The Guideline Towards Ultra-Compact Mobility Introduction (2012).

2) M. Kamata, N.Fhjii, T. Akiyama: Study on Human Friendly Vehicle Usable for Elderly People -1st Report, Investigation on Physical Characteristics and Life Style of Elderly People, and Discussion of User Needs for Vehicle Design-, Trans. Jpn. Soc. Mech. Eng. C **68** (2002) No.665, 220-227, (in Japanese).

3) H. Kato, Y. Oshinoya, S. Hasegawa: Active Control of Ultra-Compact Vehicle Seat With Voice Coil Motor -Examination of the Control Performances during Driving on a Bad Road-," J.Magn. Soc. Jpn., **37**, No.3-1, 95-101 (2013), (in Japanese).

4) H. Kato, K. Nakashima, Q. Lan, S Hasegawa, Y. Oshinoya: Active Seat Suspension for a Small Vehicle -Effect of Weight Change on Vibration Suppression Performance-, ICEE, CD-ROM (2012).

5) H. Kato, S. Hasegawa, Y. Oshinoya: Ride Comfort Evaluation of Active Seat Suspension for

6) H. Kato, M. Ishida, S. Hasegawa, Y. Oshinoya: Active Seat Suspension for Ultra-Compact Electric Vehicle -Fundamental Consideration on a Method for Switching Control Using Heart Rate Variability, Proc. Schl. Eng. Tokai Univ., Ser. E **38** (2013) 75-82.

7) Lawrence D. Burns, J. Byron McCormick, Christopher E. Borroni-Bord, NIKKEI SCIENCE, January 2003, 32-33, (in Japanese).

8) General Motors Corp, Vehicle having a movable driving position, United States Patent No.US6, 991, 060B2 (2006).

9) M. Koga, Y. Oshinoya: Development of the Intelligent Sheet of Electric Vehicle -Proposal of a Fundamental Plan-, Magnetodynamics Conference **18** (2009) 367-368, (in Japanese).

10) H. Kato, Y. Oshinoya, S. Hasegawa: Steer-by-Wire System for an Ultra-Compact Electric Vehicle -Fundamental Considerations on Changing the Reaction Force of the Steering Wheel-, Proc. Schl. Eng. Tokai Univ., Ser. E **38** (2013) 66-74.

11) A. Takebayashi, H. Sakamoto: Development of a Small-Sized Electric Vehicle Have Driving Control Mechanism by Steer-by-Wwire, Proc. of Jpn. Soc. Mech. Eng. **45** (2007) 377-378, (in Japanese).

12) Friendly Eco (Takeoka Jidosya Kogei): http://www.takeoka -m.co.jp/friendly.html, (in Japanese).

13) Driving aptitude test: http://car.sinritest.com/, (in Japanese).

14) M. Ishibashi, S. Doi: Effect of Introversion-Extraversion and Mental Task Load on Mental Fatigue, The Japanese journal of ergonomics **45** (2009) No.1 19-28, (in Japanese).