Proposal of An Eco-Driving Assist System Adaptive to Driver's Skill

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***Abstract*— The purpose of the present study is to develop an eco-driving assist system that is adaptive to a driver's skill and to demonstrate its effectiveness. The eco-driving assist system consists of a visual indicator illustrating the eco-driving. In the proposed adaptive system, the resolution of the indicator and the threshold of eco-driving are changed to adapt to the driver's skill. The proposed eco-driving system was installed in a driving simulator. Changes in driving behavior and the corresponding eco-driving scores, measured over five days, were investigated. As a comparison, experiments were conducted on a system without any level changes (a non-adaptive system) and on one without any assist system. In the results, eco-driving scores were higher with the assist systems than without them. The score with the adaptive system increased through the trial days, while no clear tendency was found with the non-adaptive system.**

I. Introduction

According to the background of global efforts to reduce CO2 emissions and increase of awareness regarding the fuel efficiency of automobiles, improvements in the practical fuel economy of automobiles are being realized. Current areas of effort include improvement of the engine itself and reduction of the weight of automobile bodies using lightweight materials. A route guidance method for reducing fuel consumption has been developed [1]. A vehicle control method to improve fuel efficiency has also been developed [2]. Furthermore, it is well-known that the driver's operation strongly affects fuel economy [3], [4]. Eco-driving systems have been developed and widely used in commercial automobiles in recent years to increase fuel economy by encouraging eco-driving with a state-of-the-art human machine interface. Note that Eco-driving means ecological and economical driving by means of high fuel efficiency in this paper.

An eco-driving assist system indicates the eco-driving status of the driver via visual and/or auditory information, etc., to improve fuel economy. It has been demonstrated that the use of such systems improves fuel economy. For example, Hiraoka et al. demonstrated that displaying the instantaneous fuel consumption and providing instruction on the key features of eco-driving improves the fuel economy [5]. Van der Voort et al. developed an eco-driving system that enhances the driver's operation both tactically and strategically [6]. Tomiyama et al. investigated the effect of the modality of the eco-driving status display method on the fuel economy and driving behavior [7]. Yoshimura et al. evaluated the annoyance level when using an assist system [8]. In addition, Sakaguchi proposed haptic pedal feedback as an eco-driving assist [9]. All of the above-mentioned research studies deal with only the short-term effectiveness of the system. The long-term effectiveness of an eco-driving assist system is very important for the sustainability of eco-driving. In pioneering research into the long-term evaluation of such a system, Hiraoka et al. demonstrated that the instantaneous fuel economy meter has the effect of reducing fuel consumption as well as providing instruction in the eco-driving approach through long-term experiments lasting six months [10].

It is thought that repeated use of these systems leads to boredom and results in low efficacy of increasing the fuel economy. The boredom and low motivation stem from saturation of the efficiency due to skill increase. The current study supposes that the efficacy of the system can be maintained by maintaining the task difficulty adaptive to the user's eco-driving skill because such a system may produce motivated use of the system for a long time, even in a skilled user. Therefore, the current study proposes an eco-driving assist system that controls the resolution of the eco-driving level and the threshold of the eco-driving judgment according to the user's current score for maintaining fuel efficiency.

In this paper, we first propose an eco-driving assist system adaptive to the user's skill. We then investigate the effectiveness of the system by driving simulator experiments to compare using a conventional (non-adaptive) system condition and without using such a system.

II. Eco-driving Assist Systems

A. Conventional (non-adaptive) Eco-driving Assist System

Figure 1 illustrates human machine interface (HMI) of a typical conventional eco-driving assist system. The HMI of the eco-driving assist system is located at the bottom of the instrument panel (Fig. 1). Figure 2 illustrates the details of the HMI. The score for eco-driving is simply calculated from the instantaneous operation of the acceleration pedal. The blue bar represents the throttle ratio defined in Eq. (1).

$$\Theta = \frac{\theta}{\theta_{max}(v)} \tag{1}$$

Manuscript received May 2, 2011.

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where, θ denotes the percentage of throttle-pedal opening. The nonlinear function $\theta_{max}(v)$ denotes the throttle-opening position that realizes the maximum efficiency of the engine at the given vehicle velocity. In the present paper, we identify this function from measurements taken in a real sedan car. Thus, the effective acceleration can be realized with $\Theta=1$ when the driver wants to increase velocity. This implies that $\Theta>1$ can be judged as excessive acceleration. Namely, $\Theta \le 1$ is preferable for any situations. Therefore, the variable Θ was introduced as the status of eco-driving. Then, the instantaneous throttle operation is judged as eco-driving if $\Theta \le 1$, where $\Theta=1$ represents the threshold of eco- and non-eco-driving.

The HMI in Fig.2 was designed based on this idea. The blue bar extends to the right end of the left rectangular area at $\Theta=1$. Conversely, the bar retracts to the left when the throttle ratio Θ is lower. The bar extends beyond the thick vertical bar and the right non-eco-driving indicator blinks when $\Theta>1$, that is, when the system judges that the current driving is non-eco-driving. The Eco indicator on the left side is turned on when eco-driving and extinguishes when non-eco-driving. This system is referred to as a non-adaptive system because the threshold and resolution are not changed based on the driver.

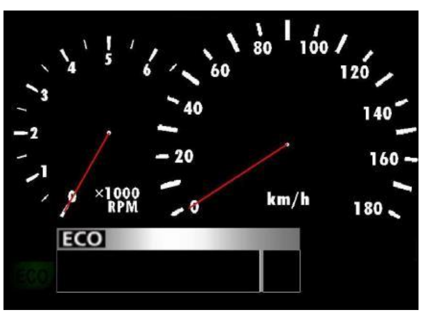


Fig. 1. Instrument Panel Interface Design of the Driving Simulator. The HMI for eco-driving is seen at the bottom of the panel.

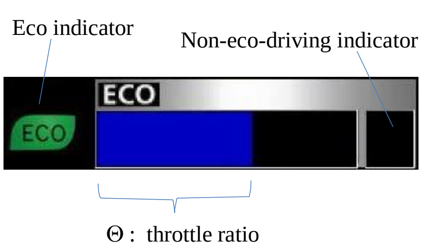


Fig. 2. HMI of Non-adaptive Eco-driving Assist System. The “ECO” mark at the left side illuminates when the system judges that the current driving is eco-driving. The blue bar denotes the throttle ratio, which is a representative variable of the eco-driving score. The blue bar extends beyond the vertical line and enters the non-eco-driving indicator area when non-eco-driving.

B. Proposed (Adaptive) Eco-driving Assist System

Basic idea.

The purpose of the current study is to develop an eco-driving assist system that can be used continuously and that will continue to improve fuel efficiency. For this purpose, we propose a new eco-driving assist interface that controls the difficulty of eco-driving by changing the HMI according to the driver's skill.

The HMI features associated with the driver's operation for eco-driving are as follows: 1) on/off state of the ECO indicator, 2) blinking/off state of the non-eco-driving indicator, and 3) length of the throttle ratio bar. Items 1) (Eco indicator) and 2) (non-eco-driving indicator) have the same meaning. It is easy to recognize them at a glance. Item 3) (throttle ratio bar) has an analogous meaning that can be used as rich information to modify driving operation so as to improve fuel efficiency, even within the eco-driving status. Thus, the resolution of the bar is important in providing feedback to the driver, as is the threshold; that is, a higher resolution is valuable for a driver with higher skill.

Therefore, we propose to change the threshold for judging eco-driving according to the driver's skill without changing length of the bar during marginal eco-driving status. The resolution of the displayed score is then changed according to the setting of the threshold. For a skilled driver, a decrease in the threshold increases the resolution of the score bar. This feature enables skilled drivers to improve further by setting a new level with a lower threshold and higher resolution. This new challenge is expected to maintain motivation for improving eco-driving and to realize continuous improvement of fuel economy. In this study, we utilize the percentage of runs with non-eco-driving to evaluate the skill. This is because the eco/non-eco information is basic for drivers, and we supposed that this information is well-linked to pedal operation for eco-driving. In addition, the threshold change is made via settings at five levels because this is understood by the drivers better than a continuous change.

HMI.

Figure 3 presents an overview of the HMI of the proposed adaptive eco-driving assist system. As seen in the figure, an indicator representing the current level setting is located on the right side of the HMI for eco-driving, the same as in the non-adaptive system in Fig. 2. There are five level settings, namely very easy, easy, normal, hard, and very hard. The hard setting employs the same algorithm as the non-adaptive system. Based on trial and error, we employed three easier levels (normal, easy, and very easy) and one harder level (very hard). For an adaptive eco-driving assist system, the throttle ratio is defined as in Eq. (2).

$$\Theta = \frac{\theta}{\alpha\,\theta_{max}(v)} \tag{2}$$

where, α denotes a coefficient to change the level settings, defined in Eq. (3).

$$\alpha = \begin{cases} 0.90 & \text{(very hard)} \\ 1.00 & \text{(hard)} \\ 1.15 & \text{(normal)} \\ 1.25 & \text{(easy)} \\ 1.50 & \text{(very easy)} \end{cases} \tag{3}$$

Variables θ and $\theta_{max}(\cdot)$ are defined the same as in the non-adaptive system. In addition, Θ=1 denotes the boundary between eco- and non-eco-driving for all level settings, with the bar reaching the right end of the left rectangle of the HMI.

Fig. 3. Instrument Panel Interface Design of the Driving Simulator with Adaptive Assist System. The right hand side of the eco-driving indicator denotes the current level setting.

As examples, Fig.4 demonstrates the differences in the indicator appearance at the very easy, normal, and very hard levels with the same driving status, to illustrate the differences in their algorithms. As seen in the figure, the harder level setting has a longer bar, representing a lower threshold.

(a) Very easy level

(b) Normal level

(c) Very hard level

Fig. 4. HMI of the Adaptive Eco-driving Assist System. Examples of Differences in the Indicator in Very Easy, Normal, and Very Hard Settings with the Same Driving Status

Method of updating level setting

We propose a method for updating the level setting appropriately according to the evaluated driving behavior. From the viewpoint of practical use, the updating algorithm might evaluate the driving skill from the driving behavior over a certain travel distance or time, or a certain number of trips. In this paper, the updating algorithm utilizes the percentage of acceleration scenes that include non-eco-driving status, which is called non-eco-driving percentage, for skill evaluation. The details of the updating criteria are given in Table I, as determined by trial and error. For example, let us consider that we are at the normal level now. If 80% of the trials include non-eco-driving on a given day, then the level setting will be changed to hard for the next day.

TABLE I
Updating Method of Level Settings by Non-eco-driving Percentage

%

	-3	-2	-1	No change	+1	+2
Very easy	-	-	-	40-100	5-39	0-4
Easy	-	-	60-100	30-59	5-29	0-4
Normal		90-100	70-89	30-69	10-29	0-9
Hard	90-100	70-89	50-69	20-49	0-19	-
Very hard	70-90	50-69	20-49	0-19	-	-

III. Experiments

A. Experiment Setup

Figure 5 illustrates the driving simulator (DS) used in the experiments. A real sedan car's cockpit is used as the DS's cockpit. There are three 100-inch screens with a field of view of 137 degrees. The distance from the driver's eye to the center of the screen is 2.5m.

Fig. 5. Fixed-base Driving Simulator Developed by Kagawa University.

Fig. 6. A Scene of Driving Course in the Experiments.

Figure 6 is an example of the driving scene used in the experiments with the DS. The test track is an urban road 1200m in length, with two lanes for each direction, as seen in Figs. 6 and 7. The driver was instructed to follow a lead vehicle with a 20m gap between two vehicles. The lead vehicle's velocity was changed gradually between 15 and 55km/h. Its frequency was three times per minute. In the experiment sessions, many vehicles were assigned to cause traffic congestion in the other lane in the same direction in order to prevent the participant from changing lanes, as seen in Figs. 6 and 7.

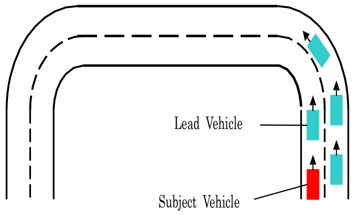


Fig. 7. Test Track for the Experiments.

B. *Experiment Design*

There are three system conditions: adaptive system, non-adaptive system, and no system. In the no-system condition, the driver had no interface to help promote eco-driving. The system condition was a between-subject factor. The day of driving (from day 1 to day 5) was a within-subject factor. Thus, the overall experiment design was a 3x5 mixed design. Specifically, five participants were assigned to each system condition. The participants drove the test track six times per day. Each participant experienced a total of five days of driving. The experiment interval for each participant was less than or equal to two days. During a given day the level setting was not changed, but it was changed at the beginning of the next day if the criteria given by Table I required it.

C. *Procedure*

On the first day of the experiments, each participant experienced the trials to get used to driving the DS and using the system. The participant then learned the methods of eco-driving, such as mild acceleration and not making unnecessary changes in the throttle position. In the adaptive system condition, the participant experienced the normal setting on the first day.

On each experiment day, the participant drove a few trials to get used to the DS, and then the participant drove the experiment track six times in recorded sessions. Each trial included four chances to accelerate the subject vehicle. Thus, there were a total of 24 scenes involving acceleration on any one day. The updating algorithm calculated the number of scenes that did not include non-eco-driving and the percentage of such trials in the total accelerations scenes was calculated. The level setting was changed at the beginning of the next day if necessary, based on the scores for the 24 scenes obtained using the updating criteria in Table I. After all of the sessions for the day, the participant was requested to evaluate the workload using the Japanese version of NASA-TLX [11].

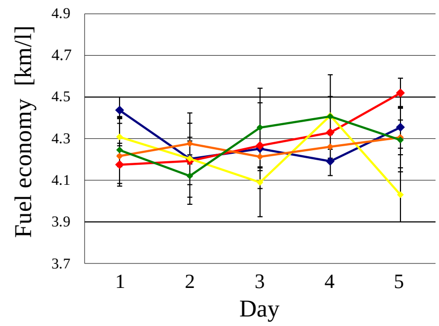
D. *Participants*

Fifteen healthy individuals with driver's licenses, 14 males and 1 female from 21 to 24yrs of age, gave informed consent to participate in the experiments. The participants were explained that they could stop the experiments at any time and for any reason. The fifteen participants were divided into three groups at random, and the members of each group were assigned to each system condition.

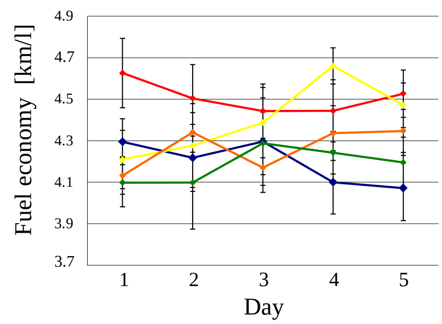
IV. Results

A. *Fuel Consumption*

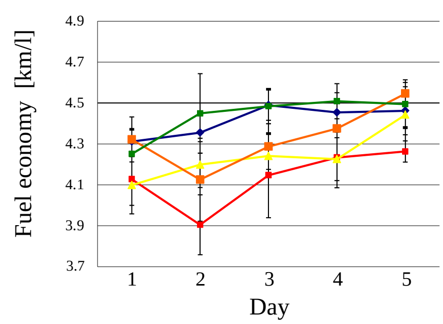
The present paper estimates fuel consumption from state variables related to the vehicle and its operation according to [12]. Figure 8 plots the transition of mean fuel economy over the five days for each participant: each line denotes the result of one participant. A clear tendency cannot be seen in (a) the no-system condition or (b) the non-adaptive system condition, while an increase in fuel economy can be seen in (c) the adaptive system condition.



(a) No-system condition



(b) Non-adaptive system condition



(c) Adaptive system condition

Fig. 8. Fuel Economy Results

A mixed-design ANOVA with day and system factors revealed that the main effect of the day condition was significant ($F(4,48)=3.617$, $p=0.012$) while the main effect of the system condition was not significant ($F(2, 12)=0.284$, $p=0.757$). The interaction between these conditions was also not significant ($F(8, 48)=0.906$, $p=0.519$). In addition, a Kruskal-Wallis test applied to the first day indicated that the main effect of the system condition was not significant ($p=0.526$). Furthermore, a Kruskal-Wallis test of the differences between the fuel economy on the fifth day and that on the first day revealed that the main effect of the system condition was significant (p=0.002). A Mann-Whitney U test with Bonferroni correction used as a post-hoc test revealed that no significant difference was found between the no system condition and the non-adaptive system condition (U=421.0, $n1$=$n2$=30, p=0.668), while significant differences were found between the no system condition and the adaptive system condition (U=220.0, $n1$=$n3$=30, p=0.001) and between the non-adaptive and adaptive systems (U=269.0, $n1$=$n2$=30, p=0.007). Specifically, the improved fuel economy with the adaptive system exceeded that with no system and with the non-adaptive system. It should be noted that the fuel economy obtained in the experiments was lower than that seen in real mid-sedans because the experimental scenario included frequent acceleration and deceleration of subject vehicle.

B. Pedal Operation

Figure 9 illustrates the transition in the mean of 95-percentile throttle opening over five days as an index to represent a change in driving operation. The throttle-opening in the no-system condition was greater than those in the other two conditions with eco-driving assist systems. In addition, the error bar representing the standard deviation (SD) in the no-system condition was larger than those in the other two conditions. These observations demonstrate a clear tendency in which an eco-driving system reduced and stabilized pedal operation.

A mixed-design ANOVA including the day and system factors revealed that the main effects of both the day and system conditions were significant (F(4,348)=10.921, p=0.000, F(2,87)=113.8, p=0.000) while the interaction between these conditions was not significant (F(8, 348)=1.434, p=0.1891).

A post-hoc test using the Bonferroni method indicated that throttle-opening with no system employed significantly exceeded that with the non-adaptive system (p=0.000) and with the adaptive system (p=0.000) employed, while there was no significant difference between the non-adaptive and adaptive systems (p=1.0).

Furthermore, a Kruskal-Wallis test of the differences between the 95-percentile throttle-opening on the fifth day and that on the first day revealed that the main effect of the system condition was significant (p=0.02). A Mann-Whitney U test with Bonferroni correction used as a post-hoc test revealed no significant difference between the no system condition and the non-adaptive system condition (U=326.0, $n1$=$n2$=30, p=0.067), or between the non-adaptive and adaptive systems (U=436.5, $n1$=$n2$=30, p=0.842), while significant differences were found between the no-system and the adaptive system conditions (U=252.5, $n1$=$n3$=30, p=0.003).

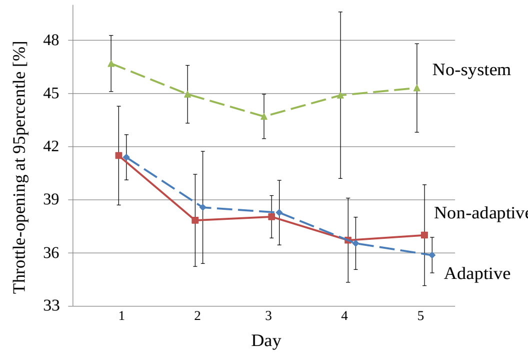


Fig. 9. Transition of throttle-opening at 95-percentile.

C. WWL Score

Figure 10 shows the transitions of the Weighted Workload (WWL) score on the NASA TLX, representing the estimated total amount of workload exerted on the participant [13]. WWL scores in the no-system and non-adaptive system conditions can be seen to decrease on experiment days. In contrast, WWL in the adaptive system condition did not change so much with experiment day even though it was not statistically significant, as mentioned in the next paragraph. This implies that the apparent workload was maintained by changing the level setting in the adaptive system while the actual workload decreased with the non-adaptive system and no system.

A mixed-design ANOVA with day and system factors revealed that the main effect of the day condition and the interaction between the two factors were not significant (F(4,48)=2.02, p=0.106) , (F(8,48)=0.997, p=0.451), while the main effect of the system condition was marginally significant (F(2, 12)=3.218, p=0.076). A post-hoc test using the Bonferroni method revealed a marginally significant difference between the non-adaptive and adaptive system conditions (p=0.76).

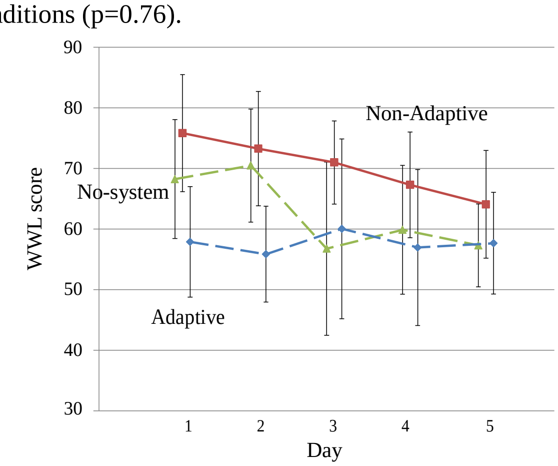


Fig. 10. Transition of WWL Scores.

D. Transition of level setting

Figure 11 illustrates the transition of the eco-driving level setting for the five experiment days for each participant. After beginning from normal, the level setting tends to increase, even though some up and down movement can be seen. In addition, no trial employed the easy or very easy levels.

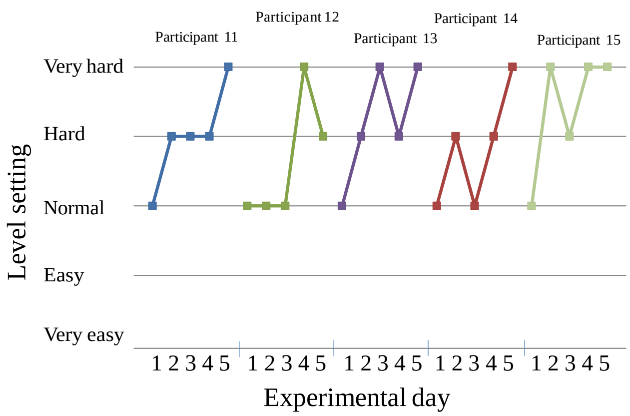


Fig. 11. Transition of Level Setting.

E. Discussion

The increase in fuel economy on the fifth day from the first day with the adaptive system was significantly greater than with the other two system conditions. This demonstrates the effect on fuel efficiency of continuous use of the adaptive system. From the pedal-operation results, the decrease in the throttle-opening on the fifth day compared with the first day with the adaptive system was significantly greater than with the other two conditions. From results, the adaptive system increased the fuel efficiency by effectively reducing the throttle-opening. From the viewpoint of workload, the WWL score with the adaptive system was not significantly changed through the five experiment days, while the WWL scores seemed to decrease with the other two system conditions. Still, the level settings were increased for all participants. These results imply that the workload was maintained at a moderate level by changing the level settings while workload imposed by the non-adaptive system was reduced due to participants' increased skill.

Hiraoka et al. [10] demonstrated an increase in fuel efficiency when an instantaneous fuel-economy meter was displayed throughout long-term experiments using a driving simulator. The paper pointed out that self-determination [14] is important as a motivation toward continuous eco-driving from a psychological viewpoint. Namely, the user determines to use the instantaneous fuel-economy meter by their selves and in their own way. Such self-determination contributed continuous use of the device. In the present study, the level setting was introduced in an effort to stimulate continuous use. This is thought to be related to self-efficacy or competence [15], that is, the participants could recognize the increase of their skills by change of the level setting and maintain the moderate challenge to the eco-driving with the update level. This is also an important factor in building motivation toward continuous use of the HMI.

V. Conclusion

The present study proposed an eco-driving assist system that changes a level setting adaptive to the driver's growing skill in continuous effective use of such a system. Driving-simulator experiments demonstrated an increase in fuel economy associated with a decrease in pedal operations,
as well as preventing decreased workload, which might lead to low motivation or boredom during the five experiment days.

The effectiveness of the system should be investigated with longer experiments, since the current study ran for only five days. In particular, the saturation effect should be investigated. In addition, the potential effects of other modalities in the HMI, such as auditory or haptic information, should be investigated, since the present study dealt only with visual information. Finally, the effects of such a system should be further investigated by considering the effects of normal driving behavior connected with safe driving as an important future research topic.

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DOI:10.1109/ITSC.2011.6083034

Publication Year: 2011

Date of Conference: 5-7 Oct. 2011

Publisher: IEEE

Published in: Intelligent Transportation Systems (ITSC), 2011 14th International IEEE Conference on

Page(s): 1880 - 1885

Type: author version