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**Co Eco-Driving: Pilot Evaluation of Driving Behavior Changes
among U.S. Drivers**

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ABSTRACT

Among several strategies to reduce greenhouse gas emissions from motor vehicles, “eco-driving” is one that had not received much attention in the United States (U.S.) until recently. The core of eco-driving programs is to provide drivers with a variety of advice and feedback to minimize fuel consumption while driving. The advice and feedback can be provided through various means including website or brochure, class or training, and in-vehicle driving aids. This study evaluated how an on-board eco-driving device that provides instantaneous fuel economy feedback affects driving behaviors, and consequently fuel economy, of gasoline-engine vehicle drivers in the U.S. under real-world driving conditions. The results from 20 samples of drivers in Southern California show that on average the fuel economy on city streets improves by 6% while the fuel economy on highways improves by 1%. According to responses to the questionnaire at the end of the study period, this group of drivers is willing to adopt eco-driving practices in the near future (mean score of 7.4 out of 10). In fact, 40% of them have already practiced eco-driving, and that penetration rate could go up to 95% if the gasoline price increases to \$4.4 per gallon.

1. INTRODUCTION

In order to become energy independence and reduce greenhouse gas (GHG)—particularly carbon dioxide (CO₂)—emissions from transportation sector, policy makers are pushing for more efficient vehicles, the use of alternative, low carbon fuels, and the adoption of sustainable community strategies through integrated multimodal transportation and land use planning [California Energy Commission, 2005]. In addition, congestion relief and conservation programs are regarded as additional ways of reducing CO₂ from surface transportation [Barth and Boriboonsomsin, 2008].

“Eco-driving” is one of the conservation programs that can be very cost effective [International Energy Agency, 2008]. At the core of many eco-driving programs, a variety of advice is provided to drivers to minimize fuel consumption while driving. Specific advice include items such as shifting to a higher gear as soon as possible, maintaining steady speeds, anticipating traffic flow, accelerating and decelerating smoothly, keeping the vehicle in good maintenance (e.g. check tire pressure frequently), etc. Different eco-driving programs in Europe have been found to yield fuel economy improvements on the order of 5 to 15% [Onoda, 2009].

Most eco-driving research to date has been concentrated on providing eco-driving advice (by means of class or training) to drivers, and then measuring before and after differences. Alternatively, it is possible to provide various forms of eco-driving feedback to drivers. For instance, Figure 1 shows two types of feedback that aim at influencing drivers’ behaviors in a different way. The real-time indicator (the top path in Figure 1) will allow drivers to relate their driving style and other conditions (e.g. traffic congestion, road grade) to their vehicles’ fuel economy. With this type of instantaneous feedback, the drivers can adjust their driving behaviors accordingly to save fuel and reduce CO₂. On the other hand, the trip end summary (the bottom path in Figure 1) will allow drivers to learn about their actual costs of driving on a trip-by-trip basis. By allowing drivers to realize and monitor their driving costs, it may be possible that they change their travel behaviors in one way or another in an attempt to lower their travel costs or even eliminate unnecessary costs (i.e. trips). A similar concept of cost feedback has been reported to be successful in changing people’s electricity usage behaviors [Lohr, 2008].

This study is focused on the first type of feedback. This real-time feedback (i.e. instantaneous fuel economy reading) is already available in hybrid-electric vehicles (HEVs) and some high-end gasoline-engine vehicles. However, these vehicles represent a very small fraction of the current vehicle population in the U.S. On the other hand, several aftermarket devices are now available that can provide instantaneous fuel economy reading by accessing vehicle and engine data through the vehicle’s on-board diagnostic II (OBD-II) connection. These devices enable eco-driving feedback on a much larger fraction of U.S. vehicle population. Specifically, vehicles of model year 1996 and later can be equipped with such devices and the owners can receive instantaneous fuel economy reading that is specific to their vehicles.

The objective of this study is to evaluate how the availability of instantaneous fuel economy feedback affects driving behaviors, and consequently fuel economy, of gasoline-engine vehicle drivers in the U.S. The evaluation is performed under ‘real-world’ driving conditions.

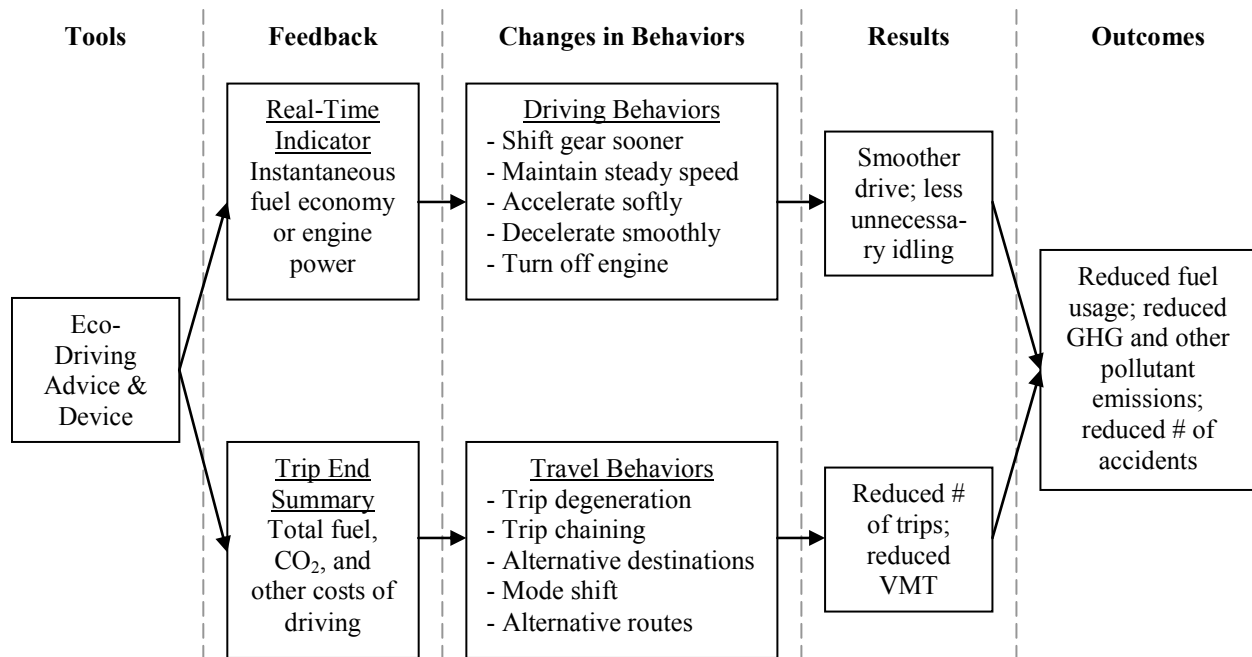


Figure 1. Reducing fuel use and GHG emissions through eco-driving feedback

2. METHODOLOGY

2.1. Eco-Driving Device

The eco-driving device used in this study is Eco-Way by Earthrise Technology. It consists of three components: 1) personal navigation device (PND), 2) OBD-II module, and 3) OBD-II cable. The OBD-II cable connects to the vehicle's OBD-II port, accessing messages from the controller area network (CAN) bus every 2 seconds. The cable also draws electrical power from the vehicle to supply the device. The OBD-II module is a firmware that decodes the received CAN messages. It also houses a GPS chip that is programmed to log the position (i.e. latitude and longitude) and speed of the vehicle. The data from the CAN bus and the GPS chip are synchronized before forwarding them to the PND. The OBD-II module has an optional general packet radio service (GPRS) modem that allows data to be transmitted wirelessly to a central server periodically. However, the Eco-Way units used in this study do not have the GPRS modem. All the data are stored on-board in the flash memory of the PND, which can be downloaded onto a personal computer.

The PND of Eco-Way serves as the input/output interface to the driver. It has several features and functionalities, but the only two that are used in this study are Eco:Drive and My Trips, as shown on the left and right of Figure 2, respectively. The Eco:Drive screen displays real-time fuel economy and CO₂ emission in a color scheme from red (poor) to green (good). The My Trips screen provides detained trip information, including start and end time, total travel time and distance, average and max speed, total fuel consumption and CO₂ emission, and maximum fuel rate and average fuel economy in miles per gallon (mpg).

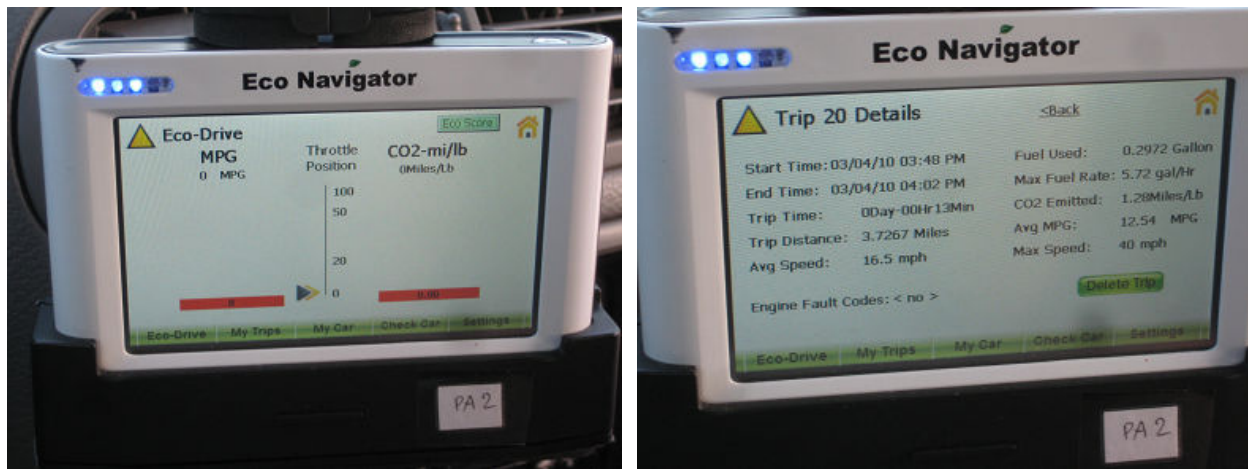


Figure 2. Eco-driving device used in this study

2.2. Data Collection

Driving data were collected from 23 self-selected samples of drivers in Southern California. These samples are a subset of those participating in a previous vehicle activity study conducted by the authors. In that study, GPS datalogger is used to collect vehicle usage of the participants on a second-by-second basis for a period of two weeks. Thus, this data can be used as a baseline for this eco-driving study (i.e. 'without' eco-driving device). To be eligible to participate, the vehicle must have a functioning OBD-II system; is not an alternative fuel vehicle (i.e. E85, natural gas); and is not already equipped with a similar instantaneous fuel economy feedback mechanism.

The qualified participants were briefed about the study objective and given a hand-out detailing eco-driving practices (<http://www.ecodrivingusa.com/#/ecodriving-practices/>). No formal class or training was provided. Then, the eco-driving device was installed on their vehicles, and instruction on how to use the device was given. The participants kept the device for two weeks while their driving data were being collected. At the end of the data collection period, the eco-driving device was retrieved and the participants were asked to complete a questionnaire about their eco-driving experience and attitude towards eco-driving. The questionnaire is provided in Appendix A.

Driving data from the 23 participating drivers were downloaded from the eco-driving device. Data from three drivers were incomplete or insufficient, and were excluded. The description of remaining 20 drivers and their vehicles as well as the fuel economy as rated by the U.S. Environmental Protection Agency (EPA) are listed in Table 1.

Table 1. Description of participating drivers and vehicles

Driver		Vehicle				EPA's Vehicle Fuel Economy		
No.	Gender	Make	Model	Year	Transmission	City	Highway	Combined*
1	F	Subaru	Impreza	2008	Automatic	20	22	21
2	M	Toyota	Sequoia	2005	Automatic	14	11	13
3	F	Nissan	Murano	2006	Automatic	18	16	17
4	F	Honda	CRV	2007	Automatic	20	22	22
5	M	Scion	tC	2005	Automatic	20	21	21
6	F	Toyota	Camry	2009	Automatic	21	19	21
7	M	Honda	Pilot	2007	Automatic	16	15	19
8	F	Lexus	RX330	2006	Automatic	17	16	19
9	F	Toyota	Sienna	2007	Automatic	17	18	19
10	M	Toyota	Tundra	2005	Automatic	14	11	12
11	F	GMC	Yukon XL	2007	Automatic	14	11	12
12	M	Toyota	Tundra	2005	Automatic	14	13	14
13	F	Ford	Expedition	2007	Automatic	12	12	12
14	M	Volvo	S60	2006	Automatic	19	22	22
15	M	Honda	Civic	2006	Manual	26	27	31
16	F	Toyota	Camry	2005	Automatic	21	22	21
17	F	Chevy	Silverado	2003	Automatic	14	13	14
18	F	Kia	Rio	2007	Manual	27	27	29
19	M	Chevy	Cobalt	2006	Automatic	21	23	22
20	M	Toyota	Solara	2002	Automatic	21	22	23

*EPA assumes 55% city driving and 45% highway driving.

2.3. Data Processing

The collected data, from both GPS data logger and eco-driving device, were processed as described below:

2.3.1. Quality Assurance

Several sources of error and data loss could be present during the data collection. For the GPS data loggers, the spatial configuration of GPS satellites, along with the number of satellites continuously in view and available to the receiver, has a major impact on data accuracy and completeness. For the eco-driving device, the embedded GPS chip is also subject to the same possibilities of error and data loss. In addition, the loose or unintended disconnection of the OBD-II cable could cause errors and missing values in the CAN data. In this step, several criteria were used to remove data records with errors and/or missing values. When appropriate, interpolation was performed to fill in data gaps.

2.3.2. Map Matching

Driving patterns on different roadway types are different. For example, driving on highways often involves cruising at higher speeds (e.g. 60-70 mph). On the other hand, driving on surface streets (i.e. arterials and local roads) experiences more frequent due to the presence of traffic signals and stop signs, and usually engages in longer duration of idle. These differences have significant impacts on vehicle fuel economy, which is the reason for the U.S. EPA to provide

separate vehicle fuel economy ratings for city versus highway driving in addition to the combined rating.

Therefore, it is of interest to analyze driving behaviors on different roadway types. There are several roadway classification schemes with varying number of roadway types. In this study, we use a roadway classification scheme with two roadway types—highway and city—analogue to the one used in the U.S. EPA’s vehicle fuel economy ratings. Note that our highway type does not include freeway ramps. Driving on freeway on-ramps has unique characteristics as drivers are advised to accelerate from a low speed to a freeway speed over a short distance to safely and smoothly merge into the mainline traffic. Eco-driving practices may not be applicable under this circumstance.

In this step, a two-pass map matching technique was applied to the driving data to determine a roadway type for each second-by-second driving record. The first pass was a standard point-to-line map matching where a GPS point (i.e. driving records) is assigned to a roadway link (in a digital roadway network database) with the minimum orthogonal distance from the point. In the second pass, a moving-average filter was applied to the previously matched roadway type to detect and correct unreasonable changes in roadway types, for instance, when the matched roadway type changes from city to highway for 30 seconds and then back to city, and vice versa. This usually occurs at freeway interchanges and overpasses/underpasses.

2.3.3. *Trip Detection*

To account for the impact of idling on vehicle fuel economy, it is necessary to differentiate between two types of idling activities—en route and trip start/end. En route idling activities are those occurred at traffic signals or due to traffic congestion. This type of idling is not driver’s own choice and should not be expected to be managed by the driver. On the other hand, idling at trip start/end is manageable by the driver and should be minimized.

Identifying the type of idling requires the collected second-by-second driving data to be segregated into trips. This was performed using a trip detection algorithm that identifies potential trip starts/ends over the course of driving. Potential trip starts/ends are the events where vehicle speed is lower than 5 mph for longer than 120 seconds. These criteria have been found to be effective in differentiating between intermediate stops at traffic signals and actual trip ends. Nevertheless, the potential trip starts/ends were verified visually in Google Earth.

2.4. **Normalization of Vehicle Fuel Economy**

It is important to recognize that there are a number of factors that could affect vehicle fuel economy in real-world. Roadway type, as discussed above, is one of them. Some of the other factors are discussed below:

- *Vehicle weight*: A vehicle carrying more weight requires more energy to run, thus directly affects its fuel economy.
- *Road grade*: Climbing a steep road grade requires higher power from the engine to overcome the added gravitational force. This can put the engine in a power enrichment mode, which reduces the vehicle fuel economy [Boriboonsomsin and Barth, 2009].

- *Weather conditions*: Weather conditions affect vehicle fuel economy, both directly and indirectly. For instance, headwind reduces vehicle fuel economy as the vehicle needs additional power from the engine to combat the wind drag. Hot weather induces the use of air conditioning, which places accessory load requirement on the engine.
- *Congestion level*: Stop-and-go movement in congested traffic wastes fuel. So, the vehicle fuel economy degrades significantly under this traffic condition [Barth and Boriboonsomsin, 2008].

In real-world experiment, it is impossible to control for all these factors during the driving periods with and without the eco-driving device. Therefore, it is necessary to normalize the vehicle fuel economy with and without the eco-driving device to nullify their effects to the maximum extent possible.

The normalization methodology used in this study is based on characterizing vehicle specific power (VSP) of individual vehicles. VSP has been shown to be a strong descriptor of vehicle fuel consumption and emissions [Jiménez-Palacios, 1999]. It is defined as the power per unit mass to overcome road grade, rolling & aerodynamic resistance, and inertial acceleration. For a typical light-duty vehicle, VSP (in kW/metric ton) can be calculated as:

$$\text{VSP} = v \cdot (1.1a + g \cdot \text{grade} + 0.132) + 0.000302 \cdot v^3$$

where v is vehicle speed (m/s); a is vehicle acceleration (m/s^2); g is gravitational acceleration (m/s^2); and grade is road grade (vertical rise divided by slope length).

Assuming that road grade is zero, VSP for each second of driving was calculated based on speed and acceleration alone. Then, the calculated VSP values were binned and the average fuel consumption as well as its 95% confidence interval for each VSP bin was computed. These are shown in Figure 3 for a 2007 Ford Expedition. The same type of plot for the rest of the participating vehicles is given in Appendix B.

In Figure 3, the confidence interval of the fuel rate for each VSP bin is an indication of the varying conditions under which fuel consumption were actually measured during the course of the study. Therefore, by taking the average fuel rates and assigning them to the second-by-second driving data based on their calculated VSP value essentially normalize the effects of road grade, weight, and rolling & drag forces.

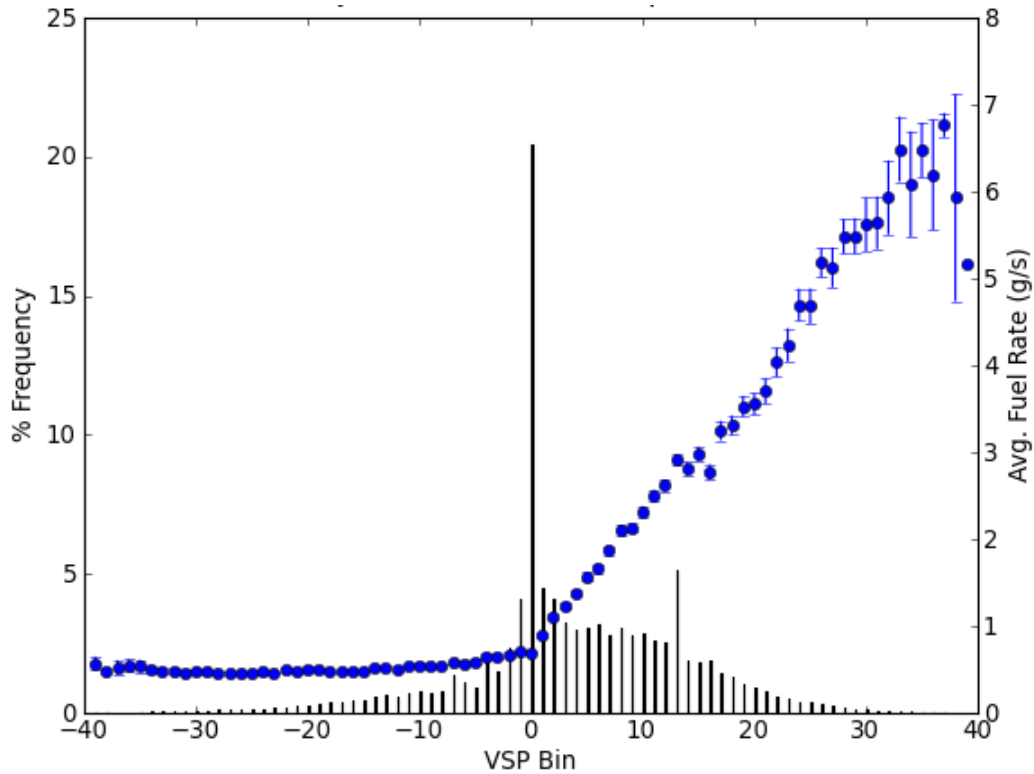


Figure 3. Fuel consumption by VSP bin of a 2007 Ford Expedition

3. RESULTS

3.1. Vehicle Fuel Economy

Table 2 shows the normalized fuel economy results without and with eco-driving device. The fuel economy is calculated separately for city and highway driving. According to the table, the change in fuel economy for individual drivers varies. For city driving, it ranges from -5% to +24%, with an average of 6%. For highway driving, the change ranges from -12% to +13%, with an average of 1%.

It should be noted that the normalized fuel economy values shown are a result of driving behaviors on the roads only. They do not include the effect of idling at trip starts/ends. If idling activities when the vehicles are equipped with the eco-driving device are reduced, then the overall change in fuel economy will move towards higher positive values.

Table 2. Comparison of vehicle fuel economy

Driver No.	Normalized City MPG			Normalized Highway MPG		
	Without	With	% Change	Without	With	% Change
1	22	21	0	33	33	-1
2	11	13	21	20	21	4
3	16	17	9	27	29	8
4	22	22	-1	30	30	1
5	21	21	-1	30	29	-3
6	19	21	7	36	32	-12
7	15	19	24	24	25	5
8	16	19	19	25	28	13
9	18	19	3	27	27	-1
10	11	12	5	17	17	2
11	11	12	7	20	20	0
12	13	14	5	20	20	0
13	12	12	-5	19	19	2
14	22	22	2	27	30	8
15	27	31	14	49	48	-4
16	22	21	-2	37	37	0
17	13	14	4	20	19	-4
18	27	29	6	50	49	-2
19	23	22	-3	38	37	-2
20	22	23	5	41	43	5

3.2. Questionnaire Responses

The responses to the questionnaire were transcribed into spreadsheet and analyzed. Some of the results are presented in Table 3. The first three questions ask about the eco-driving background of the participating drivers. Overall, this group of drivers knows about eco-driving practices moderately (mean score of 5.0), but they do not fully translate their knowledge into action (mean score of 4.2). Nevertheless, they indicated that they used the eco-driving device extensively during the period of the study (mean score of 9.4).

Table 3. Background, likelihood, and attitude towards eco-driving

Questions	Mean	S.D.
How much did you know about eco-driving practices before participating in this study?	5.0	2.8
How often did you drive in an eco-friendly way before participating in this study?	4.2	2.3
How often did you use the eco-driving device during the period of this study?	9.4	1.2
How likely will you adopt eco-driving practices in your driving habits in the near future?	7.4	1.9
How likely will you purchase an eco-driving device for use with your current vehicle?	3.9	2.6
How often will you use eco-driving feedback if it comes standard with your vehicle?	8.0	2.0
How important is fuel economy as a decision factor when you purchase your next vehicle?	8.3	1.3
How much do you believe in climate change and the needs to reduce carbon emissions?	7.3	2.7

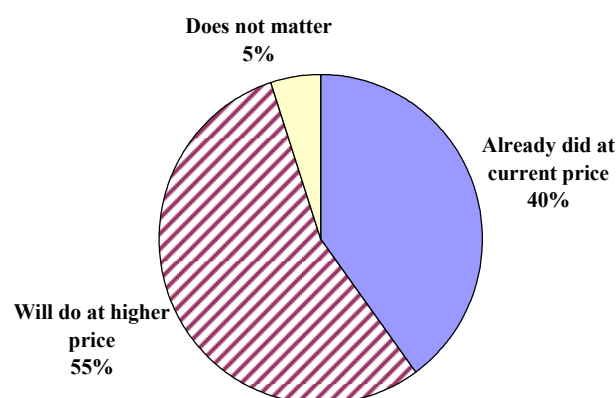
The next three questions ask about the likelihood of adopting eco-driving practices in the future. The results show that this group of drivers is quite willing to adopt eco-driving practices (mean score of 7.4), but is less willing to spend money on any sort of eco-driving device for use with

their current vehicle (mean score of 3.9). On the other hand, if eco-driving feedback is a standard feature in their vehicle, they will use it fairly often (mean score of 8.0).

The responses to the last two questions show that this group of drivers believes in the needs to reduce carbon emissions in order to address the climate change (mean score of 7.3). They will also seriously take into consideration the vehicle fuel economy when purchasing their next vehicle (mean score of 8.3).

When asked about the effect of fuel price on willingness to change driving behaviors, 40% responded that they had already changed their driving habits at the current price, which was \$3 per gallon for regular-graded gasoline at the time of study. On the other hand, the fuel price will not have any influence on how one driver drives (5%). For the remaining 55% of the drivers, the level of fuel price that would make them change their driving behaviors is averaged at \$4.4 per gallon. Similarly, the level of fuel price that would make 50% of the drivers drive less is averaged at \$4.5 per gallon.

“What is the fuel price that would make you seriously think about changing your driving habits to save fuel?”



“What is the fuel price that would make you seriously think about driving less to save fuel?”

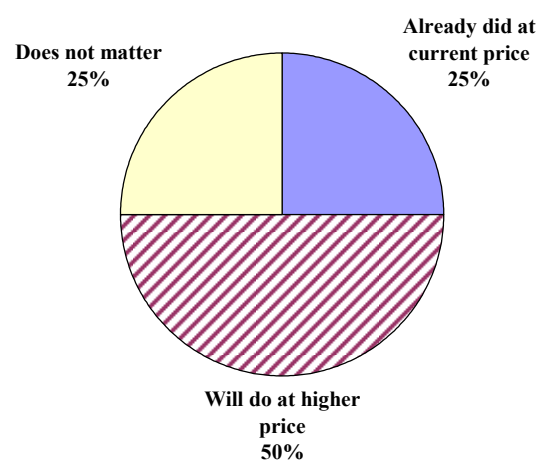


Figure 4. Effect of fuel price on willingness to change driving behaviors

4. CONCLUSIONS

Among several strategies to reduce greenhouse gas emissions from motor vehicles, “eco-driving” is one that had not received much attention in the United States (U.S.) until recently. The core of eco-driving programs is to provide drivers with a variety of advice and feedback to minimize fuel consumption while driving. The advice and feedback can be provided through various means including website or brochure, class or training, and in-vehicle driving aids. This study evaluated how an on-board eco-driving device that provides instantaneous fuel economy feedback affects driving behaviors, and consequently fuel economy, of gasoline-engine vehicle drivers in the U.S. under real-world driving conditions.

The results from 20 samples of drivers in Southern California show that on average the fuel economy on city streets improves by 6% while the fuel economy on highways improves by 1%. According to responses to the questionnaire at the end of the study period, this group of drivers is willing to adopt eco-driving practices in the near future (mean score of 7.4 out of 10). In fact, 40% of them have already practiced eco-driving, and that penetration rate could go up to 95% if the gasoline price increases to \$4.4 per gallon.

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1. How much did you know about Eco-Driving practices before participating in this study?
(Least) 1 2 3 4 5 6 7 8 9 10 (Most)

2. How often did you drive in an eco-friendly way before participating in this study?
(Least) 1 2 3 4 5 6 7 8 9 10 (Most)

3. How often did you use the Eco-Driving device when you drove during the period of this study?
(Least) 1 2 3 4 5 6 7 8 9 10 (Most)

4. Based on the Eco-Driving device, do you know the optimal speed for fuel efficiency of your vehicle?
☐ No, I do not. ☐ Yes, it is _____ mph

5. By using the Eco-Driving device, do you think your trip MPG has improved?
☐ No, it does not make any difference. ☐ Yes, my trip MPG has improved by _____%

6. How likely will you adopt Eco-Driving practices into your driving habits in the near future?
(Least) 1 2 3 4 5 6 7 8 9 10 (Most)

7. How likely will you purchase an Eco-Driving device for use with your current vehicle?
(Least) 1 2 3 4 5 6 7 8 9 10 (Most)

8. How often will you use Eco-Driving feedback if it comes standard with your vehicle?
(Least) 1 2 3 4 5 6 7 8 9 10 (Most)

9. What is the fuel price that would make you seriously think about changing your driving habits to save fuel?
☐ I already change at the current price. ☐ At \$_____ per gallon ☐ It will never matter to me

10. What is the fuel price that would make you seriously think about driving less to save fuel??
☐ I already drive less at the current price. ☐ At \$_____ per gallon ☐ It will never matter to me

11. Will you be willing to drive longer in travel time when making trips in order to save \$1 worth of fuel?
☐ No, I always want to get where I go ASAP. ☐ Yes, I can tolerate driving longer for _____ minutes

12. How important is fuel efficiency (i.e. MPG) as a decision factor when you purchase your next vehicle?
(Least) 1 2 3 4 5 6 7 8 9 10 (Most)

13. How much do you believe in the science of Climate Change and the needs to reduce carbon emissions?
(Least) 1 2 3 4 5 6 7 8 9 10 (Most)

Name _____ Date _____

THANK YOU FOR YOUR PARTICIPATION!!

Appendix B: Fuel Rate by VSP Bin

