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Research article

The eco-driving effect of electric vehicles compared to conventional gasoline vehicles

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Abstract: Eco-driving is attractive to the public, not only users of internal-combustion-engine vehicles (ICEVs) including hybrid electric vehicles (HEVs) but also users of electric vehicles (EVs) have interest in eco-driving. In this context, a quantitative evaluation of eco-driving effect of EVs was conducted using a chassis dynamometer (C/D) with an "eco-driving test mode." This mode comprised four speed patterns selected from fifty-two real-world driving datasets collected during an eco-driving test-ride event. The four patterns had the same travel distance (5.2 km), but showed varying eco-driving achievement levels. Three ICEVs, one HEV and two EVs were tested using a C/D. Good linear relationships were found between the eco-driving achievement level and electric or fuel consumption rate of all vehicles. The reduction of CO_2 emissions was also estimated. The CO_2-reduction rates of the four conventional (including hybrid) vehicles were 10.9%–12.6%, while those of two types of EVs were 11.7%–18.4%. These results indicate that the eco-driving tips for conventional vehicles are effective to not only ICEVs and HEVs but also EVs. Furthermore, EVs have a higher potential of eco-driving effect than ICEVs and HEVs if EVs could maintain high energy conversion efficiency at low load range. This study is intended to support the importance of the dissemination of tools like the intelligent speed adaptation (ISA) to obey the regulation speed in real time. In the future, also in the development and dissemination of automated driving systems, the viewpoint of achieving the traveling purpose with less kinetic energy would be important.

Keywords: eco-driving; BEV; HEV; energy consumption; chassis dynamometer

1. Introduction

In Europe, eco-driving has become a popular measure for coping with global warming issues in the transport sector. For example, "ecodrive.org" listed five "Golden Rules of Eco-driving": 1. Anticipate traffic flow; 2. Maintain a steady speed at low RPM; 3. Shift up early; 4. Check tire pressures frequently at least once a month and before driving at high speed; and 5. Consider any extra energy required costs fuel and money [1]. In Japan, "10 Recommendations for Eco-driving" are listed in [2] and [3]. They are mostly consistent with those listed above except for "Press the accelerator gently when accelerating," which is strongly recommended. The correspondence between eco-driving tips in Europe and in Japan is shown in Table 1. Differences in the lists arose from differences in the predominant transmission types of passenger vehicles. Manual transmissions are mainstream in Europe, while automatic transmissions are preferred in Japan. The instructions to "shift up early at low RPM" (in Europe) and "go easy on the acceleration pedal" (in Japan) are both intended to improve the engine's energy-conversion efficiency. There are many reports on the effectiveness of eco-driving as a results of drivers' spontaneous behavior change; ecodrive.org showed that eco-driving saves 5%–15% of fuel-consumption over the long term [1]. Lovejoy et al. [4] reviewed previous studies in the U.S. concerning eco-driving and reported that it reduced fuel consumption by 10%–31%. Kato and Kobayashi [5] reviewed many reports [5,6,7] in Japan and reported a saving of 10%–20% from eco-driving. Kato and Kobayashi [5] also reported that eco-driving in a test-ride event reduced fuel consumption by 11.6%, and its major effect was to decrease the kinetic running energy due to observation of the speed limit and the maintenance of a constant speed. EV users' interest in eco-driving stems from maximizing the travel distance per charge of their EVs [8]. However, discussions and quantitative evaluations of whether eco-driving methods for ICEVs are valid for EVs are rare. Therefore, this study conducted comparative measurements of the effects of eco-driving for ICEVs and EVs using a chassis dynamometer (C/D), which could provide a constant test environment in a room at a laboratory.

Table 1. The correspondence between eco-driving tips in Europe and in Japan.

"five Golden Rules of Eco-driving" in Europe	"10 Recommendations for Eco-driving" in Japan
1. Anticipate traffic flow	- Release the accelerator earlier when decelerating
2. Maintain a steady speed at low RPM	- Reduce acceleration and deceleration while keeping enough distance between cars
3. Shift up early	-
4. Check tire pressures frequently at least once a month and before driving at high speed	- Check the pressure of the tires as the first step toward better maintenance
5. Consider any extra energy required costs fuel and money	- Use air conditioners appropriately - Avoid unnecessary idling - Avoid traffic jams; leave home with time to spare - Take out unnecessary loads - Be aware of your fuel consumption
-	- Press the accelerator gently when accelerating - Do not block traffic when parking

2. Test Method

The method for evaluating reduction of fuel consumption and CO_2 emissions through eco-driving which the same subjects drive twice (once as usual and once eco-driving) along a test route on a public road is conventionally and mainly used. Even when comparing several vehicle models, it is not impossible to verify the difference in effect between vehicles or to perform the actual running test on public roads. However, it may be difficult to evaluate the eco-driving effect because the subjects might not be the same, conditions such as weather, road conditions are not kept constant and these factors may also affect fuel consumption. In this study, operation with the intention of eco-driving for a variety of vehicles was evaluated using a C/D facility capable of performing the test under constant conditions. The test method had three steps, as shown in Figure 1. Firstly, we created an eco-driving test mode from the results if a real running test that was conducted using a gasoline-powered passenger car. Then, these tests were performed for a plurality of models, including gasoline and electric vehicles, using a C/D facility.

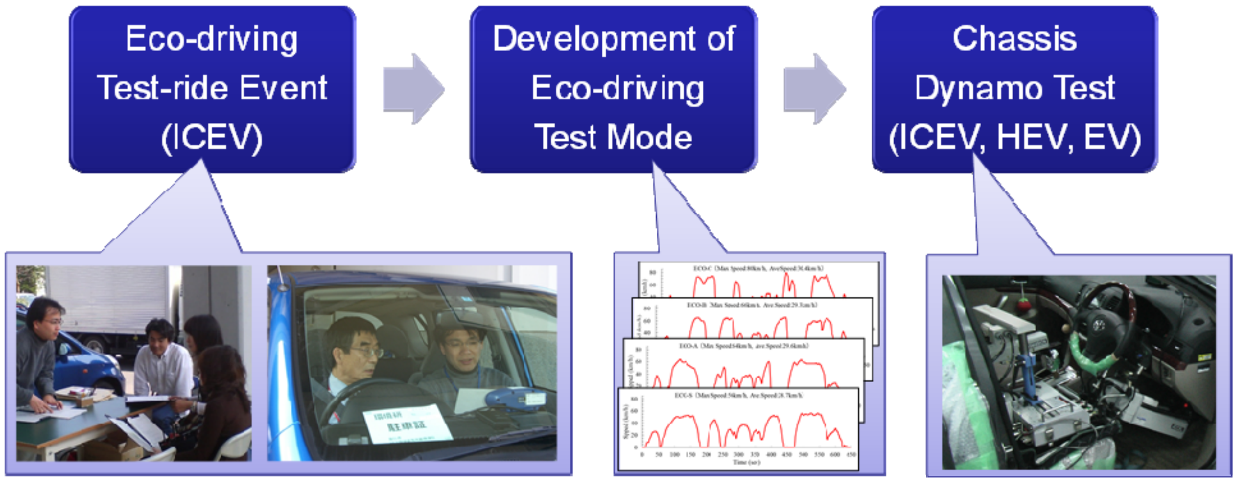


Figure 1. Flow of the test method.

2.1. Eco-driving Test-ride Event

To obtain the data concerning eco-driving achievement level, an eco-driving test-ride event was conducted [5]. Twenty six test subjects drove vehicles along a test route which was mainly on a public road in Tsukuba-city, Japan. The subjects were thirteen females and thirteen males who were non-professional drivers working for the National Institute for Environmental Studies (NIES) in Japan. Their ages were between 20 and 65 years old. They mainly commuted by car. The test route was 5.2 km long, comprising a 3.7-km arterial road with a speed limit of 60km/h, a 0.9-km community road with a speed limit of 40km/h, and a 0.6-km private road in the NIES with a speed limit of 20 km/h. Speed exceeding the limit by 10 km/h or more were commonly observed on the arterial road. The test route imitated typical commuter routes in Japanese local cities. The vehicle used in this event was Japan's best-selling passenger car, which is equipped with a gasoline-powered, 1,300 cc displacement engine and a continuously variable transmission (CVT). The equipment used to collect data from driving was an "eco-manager" developed by the Environmental Restoration and

Conservation Agency (ERCA) in Japan. It was linked to the vehicle's engine control unit (ECU) and logged data concerning vehicle speed, fuel consumption, and so on with a 1-second collection interval. Each subject drove the passenger car twice; once as normal, and then immediately after in eco-driving. Before the second trip, an instructor gave subjects guidance pertaining to the three eco-driving tips listed in Table 2. The only tips related to driving operation were selected from 10 eco-driving tips. However, the manual idling stop while waiting at signals was prohibited because of safety considerations. Furthermore, the use of air conditioner was also prohibited in order to unify the accessory-usage conditions.

Table 2. Three eco-driving tips given to subjects.

1. Observe the speed limit and maintain a constant speed
2. Release the accelerator earlier when decelerating
3. Press the accelerator gently when accelerating

The average fuel consumption rates during normal driving and during eco-driving were 60.4 and 53.4 cc/km, respectively. As a result of a paired t-test, it was confirmed that fuel consumption during eco-driving was less than that during normal driving at a significance level of 99%. The average fuel and CO_2-reduction rates were 11.6%. Gasoline consumption [cc/km] and CO_2 emissions [g/km] were proportional since only the CO_2 emissions of the tank-to-wheel were considered in this study. Therefore, the reduction rates of fuel consumption and CO_2 emissions were calculated using formula (1). We call the reduction rates the eco-driving effects:

$$RR = \frac{FC_0 - FC_1}{FC_0} \times 100, \tag{1}$$

where RR is the reduction rate of fuel consumption and CO_2 emissions [%], FC_0 is fuel consumption during normal driving [cc/km], and FC_1 is fuel consumption during eco-driving [cc/km].

2.2. Development of the Eco-driving Test Mode

2.2.1. Indicator for Eco-driving

To objectively express the eco-driving achievement level, the kinetic running energy [J] was used as an indicator. This energy was calculated using formulas (2) through (9) (Kato et al. [9]):

$$E = \frac{\sum_{t=0,P>0}^{T} P(t) \cdot \Delta t}{1000 \times D}; \tag{2}$$

$$P(t) = R(t) \cdot V(t); \tag{3}$$

$$R(t) = R_r + R_l(t) + R_a(t); \tag{4}$$

$$R_r = \mu \cdot M \cdot g; \tag{5}$$

$$R_l(t) = \rho \cdot C_d \cdot S \cdot V(t)^2 / 2\,; \tag{6}$$

$$R_a(t) = (M + \delta \cdot M) \cdot \alpha(t)\,; \tag{7}$$

$$D = \frac{\sum_{t=0}^{T} V(t)}{1000}\,; \tag{8}$$

$$\alpha(t) = \frac{V(t) - V(t - \Delta t)}{\Delta t}\,; \tag{9}$$

where T is the travel time [sec], D is the travel distance [km], $P(t)$ is the power required to propel the vehicle [W], $R(t)$ is the running resistance [N], $V(t)$ is the vehicle speed [m/s], R_r is the rolling frictional resistance, $R_l(t)$ is the air resistance, $R_a(t)$ is the acceleration resistance, μ is the coefficient of friction [-], M is the vehicle mass including two passengers [kg], g is the gravitational constant [9.8 m/s^2], ρ is the air density at standard ambient temperature and pressure [1.169 kg/m^3], C_d is the coefficient of air resistance [-], S is the frontal projected area [m^2], δM is the equivalent mass of the rotating parts [kg] and $\alpha(t)$ is the acceleration [m/s^2]. The calculation step, Δt, is one second for all formulas except for formulas (5). The vehicle speed data obtained by the "eco-manager" was used as $V(t)$. The vehicle specification used for the calculation are shown in Table 3. Due to lack of road-inclination data, gradient resistance is not taken into account.

Table 3. Vehicle specifications used for the calculation.

parameter	value
μ [-]	0.013
M [kg]	1,110
C_d [-]	0.35
S [m^2]	2.16
δM [kg]	38

Figure 2 shows the relationship between kinetic running energy and fuel-consumption rate for all fifty-two driving datasets. The orange and green points correspond to normal driving and eco-driving, respectively. A good correlation was found between the two quantities. By adopting eco-driving, kinetic running energy and fuel consumption were on average reduced by 15.5% and 11.6%, respectively.

2.2.2. Selection of Speed Patterns

To express the relationship between the kinetic running energy and fuel (or electric) consumption rate, four speed patterns were selected from the fifty-two collected in the eco-driving test-ride event (the four red circles in Figure 2). To determine suitable speed patterns, characteristics such as the equality of the running energy's interval and the similarity of stopping frequencies and intersections at which stopping took place were taken into account. Most trips had 5–6 stops. Trips were classified into groups based on the intersections at which they stopped. The most appropriate trip group was selected based on the variation of the kinetic running energy and by matching the regression line. We called the set of four speed patterns the "eco-driving test mode," and named the speed patterns "ECO-S," "ECO-A," "ECO-B," and "ECO-C" in increasing order of kinetic running energy. "ECO-S" has the lowest kinetic running energy. Table 4 shows the specifications of each eco-driving test mode. The speed patterns of these modes are shown in Figure 3.

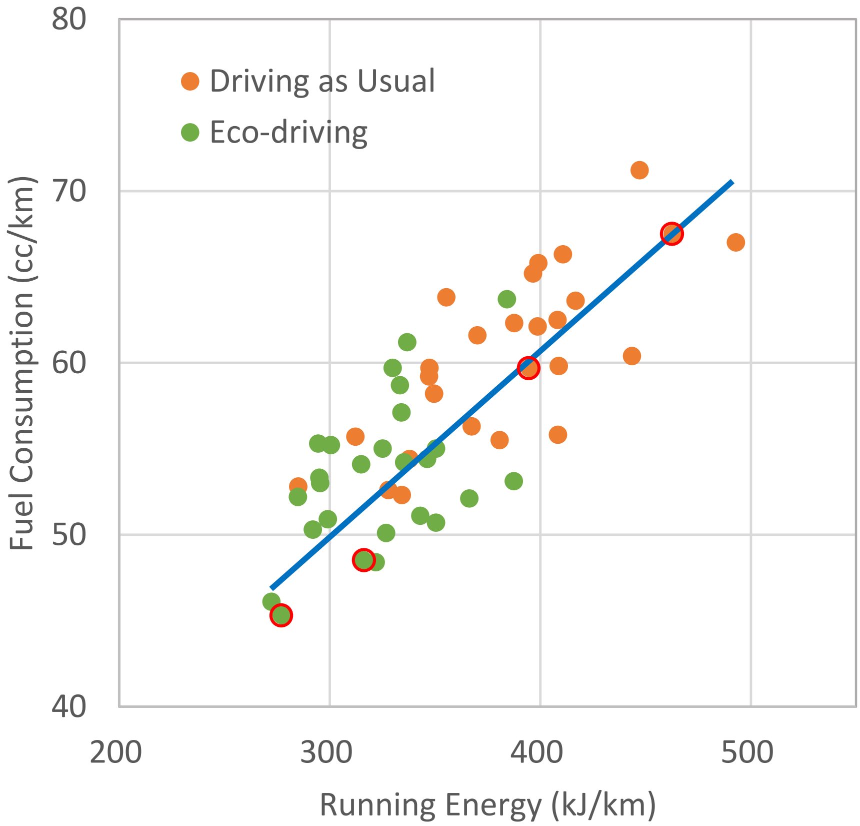


Figure 2. Relationship between kinetic running energy and fuel-consumption rate in the eco-driving test-ride event (real-world driving data).

Table 4. Specifications of eco-driving test mode.

		ECO-S	ECO-A	ECO-B	ECO-C
Travel Time (sec)		648	628	627	612
Max Speed (km/h)		56	64	66	80
Stopping Frequency		5	5	6	5
Running Energy (kJ/km)		277	316	395	463
Fuel Consumption (cc/km)		45.3	48.5	59.7	67.5
Time Share	**Idle**	14%	20%	26%	28%
	Cruise	40%	35%	29%	20%
	Acceleration	23%	24%	26%	24%
	Deceleration	23%	20%	18%	29%

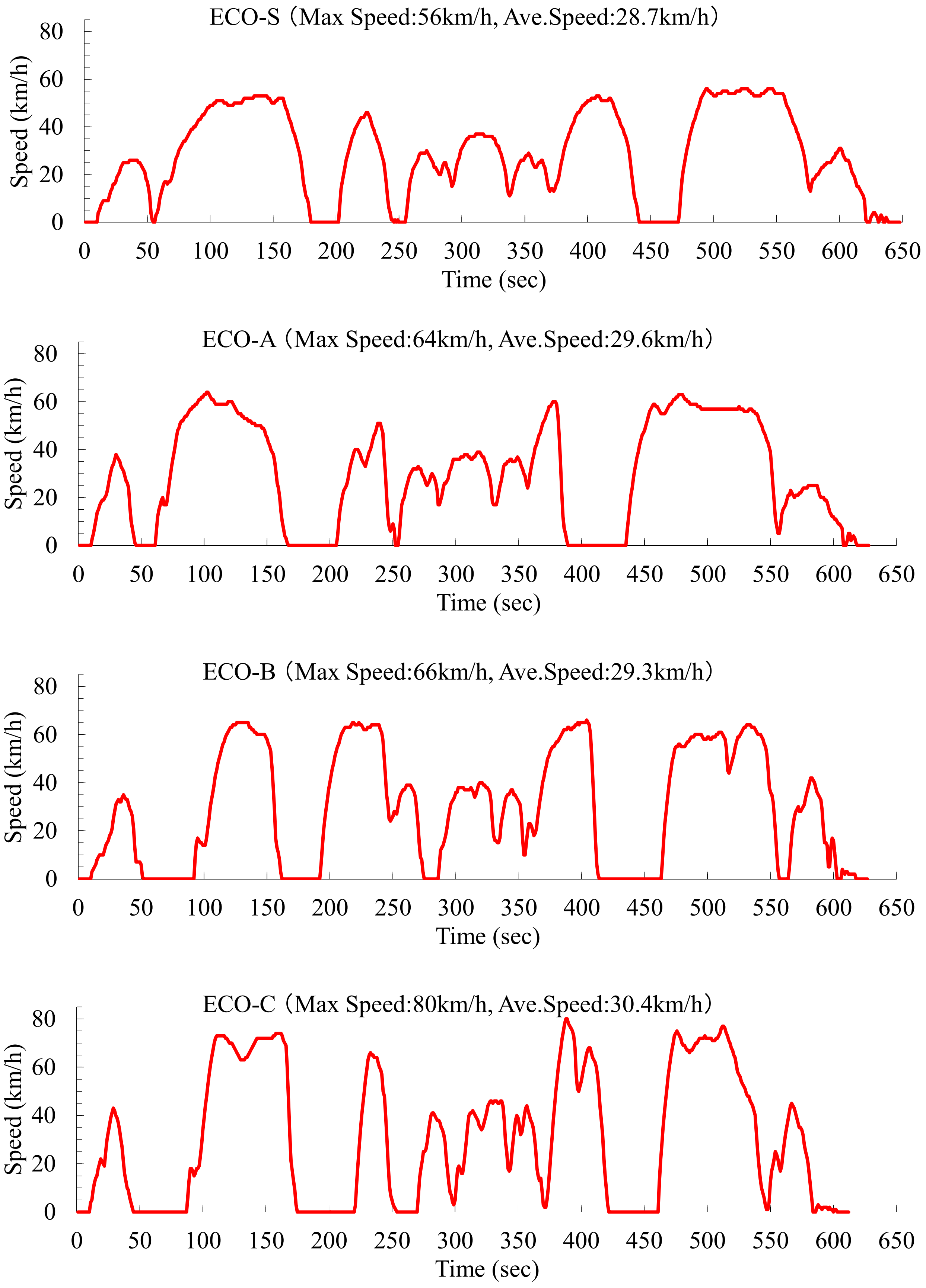


Figure 3. Four speed patterns constituting the "eco-driving test mode."

2.3. Chassis-dynamometer Test

It is not practical to perform running tests targeting a variety of vehicles in the real world due to time constraints, economic constraints, difficulties maintaining similar environmental conditions and subject attributes, and so on. A C/D can test a variety of vehicles under the same conditions. In this study, three ICEVs, one HEV, and two EVs were tested using a C/D with an eco-driving test mode. Table 5 shows the specifications of each vehicle. The 660 cc ICEV and both EVs were small passenger cars categorized as "kei-cars"—a Japanese unique super-minivehicle segment. A kei-car is less than or equal to 3.40 m in length, 1.48 m in width and 2.0 m in height. Their engine displacement is 660 cc or less, and the self-regulated maximum power of the engine or motor is 47 kW or less. About one-third of car ownership in Japan is of kei-cars. One EV had front-wheel drive (called "EV type A" in this paper), and the other had rear-wheel drive (called "EV type B"). EV type A is not commercially available. Some views of the C/D test are shown in Figure 4.

Table 5. Specifications of tested vehicles.

	Vehicle Type	Engine Displacement	Transmission	Weight (nt.)
660cc CVT	ICEV	1,800 cc	CVT	770 kg
1,300cc CVT		1,300 cc	CVT	1,000 kg
1,800cc 4AT		660 cc	4 AT	1,170 kg
1,500cc HEV	HEV	1,500 cc	e-CVT	1,260 kg
EV Type A	EV	-	-	1,030 kg
EV Type B		-	-	1,070 kg

Figure 4. View of chassis-dynamometer test.

3. Results and Discussion

3.1. Confirmation of Reproducibility

In order to confirm its reproducibility, the eco-driving effect in the test-ride event was compared to the results of the C/D test for the same vehicle, the 1,300 cc CVT. Figure 5 shows the relevant test results. The four circular markers in this figure represent the fuel-consumption rates of ECO-S, ECO-A, ECO-B and ECO-C. A good linear relationship between the kinetic running energy and fuel-consumption rate was found. Using this linear-regression equation, the eco-driving effect was estimated. The origin and end point of the arrow in this figure were the average kinetic running energy for "normal driving" and "eco-driving," respectively, over all twenty-six subjects. The fuel consumption rate was decreased from 51.5 to 45.2 cc/km. Therefore, the eco-driving effect estimated by the C/D test was 12.2%. Considering that the eco-driving effect in the test-ride event was 11.6%, it is considered to be highly reproducible with an error of less than 5%.

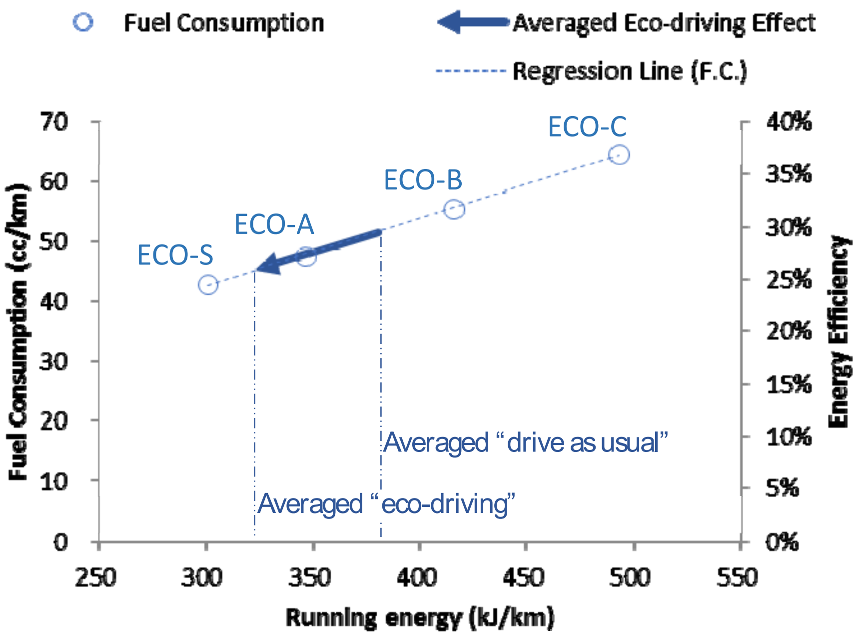


Figure 5. Test results of 1300 cc CVT.

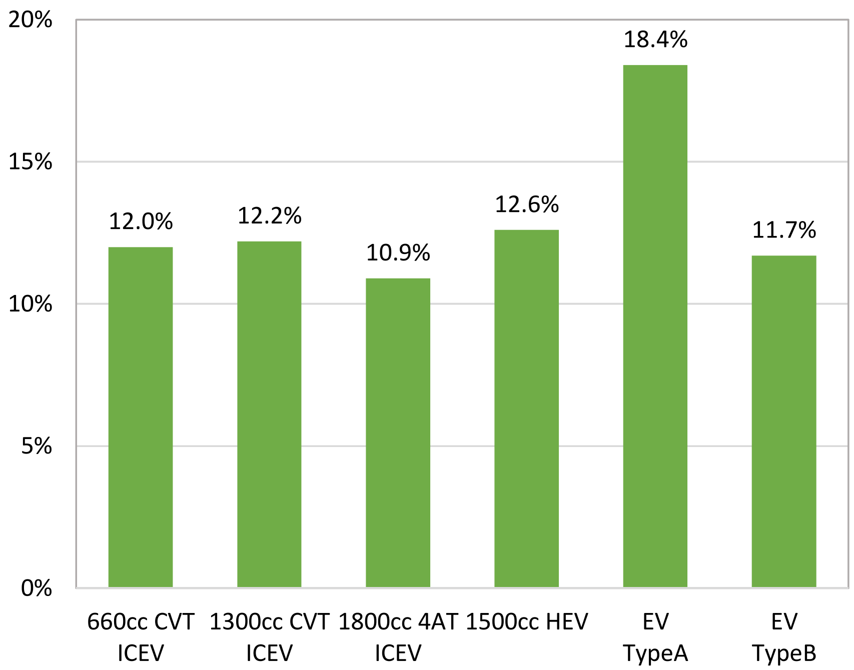


Figure 6. Estimated eco-driving effect.

3.2. Estimation of Eco-driving Effect

The eco-driving effects of the five other vehicles besides the 1,300 cc CVT were also estimated using the same way as previously mentioned at *3.1. Confirmation of Reproducibility*. Figure 6 shows the estimated eco-driving effects of all six vehicles. The eco-driving effects of 660 cc CTV, 1,300 cc CVT, 1,800 cc 4AT, 1,500 cc HEV, EV type A, and EV type B were 12.0%, 12.2%, 10.9%, 12.6%, 18.4% and 11.7%, respectively. The results indicate that the eco-driving tips for ICEVs were effective not only for ICEVs (including HEVs), but also for EVs.

3.3. Energy Conversion Efficiency

EV type A had a larger eco-driving effect than the other vehicles. To determine the reason for this, the energy-conversion efficiency, H [%], was calculated using formulas (10) and (11):

For ICEVs and a HEV,

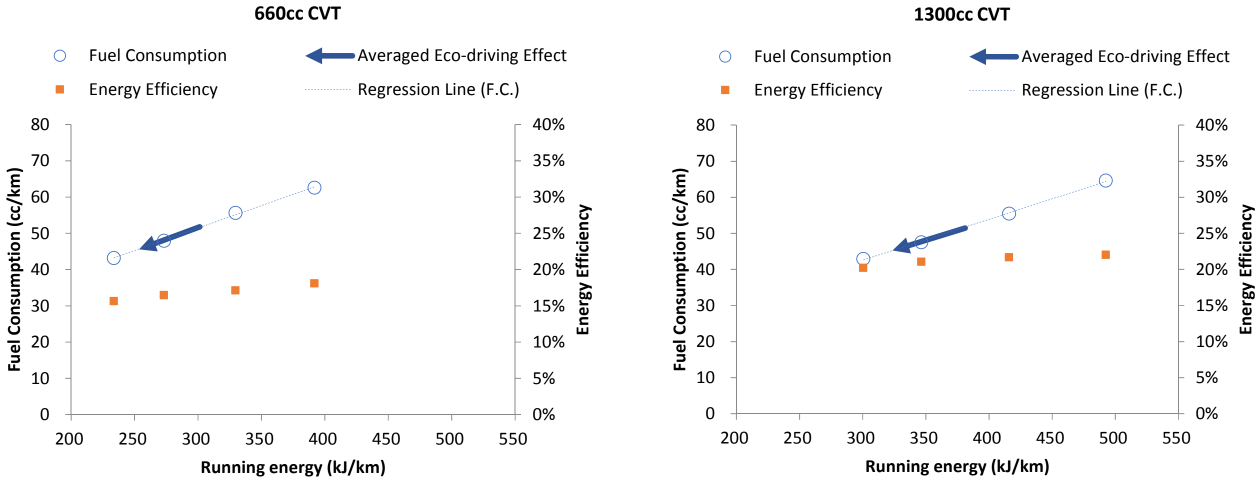
$$H = \frac{E}{FC \times 34.6} \times 100 \, . \tag{10}$$

For EVs,

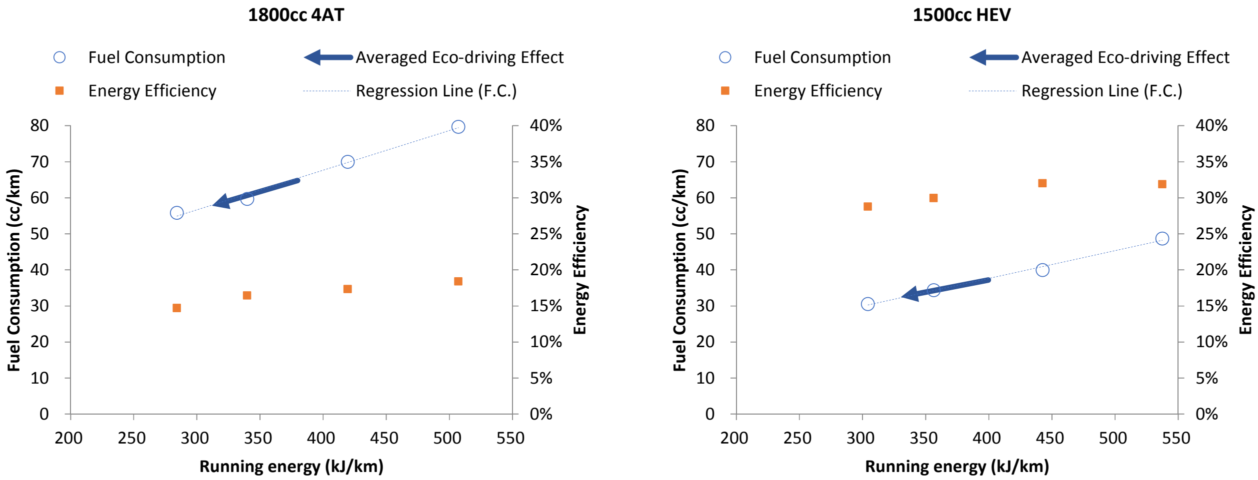
$$H = \frac{E}{EC \times 3{,}600} \times 100 \, , \tag{11}$$

where E is the kinetic running energy [kJ/km], FC is the fuel-consumption rate [cc/km], and EC is the electric-consumption rate [kWh/km].

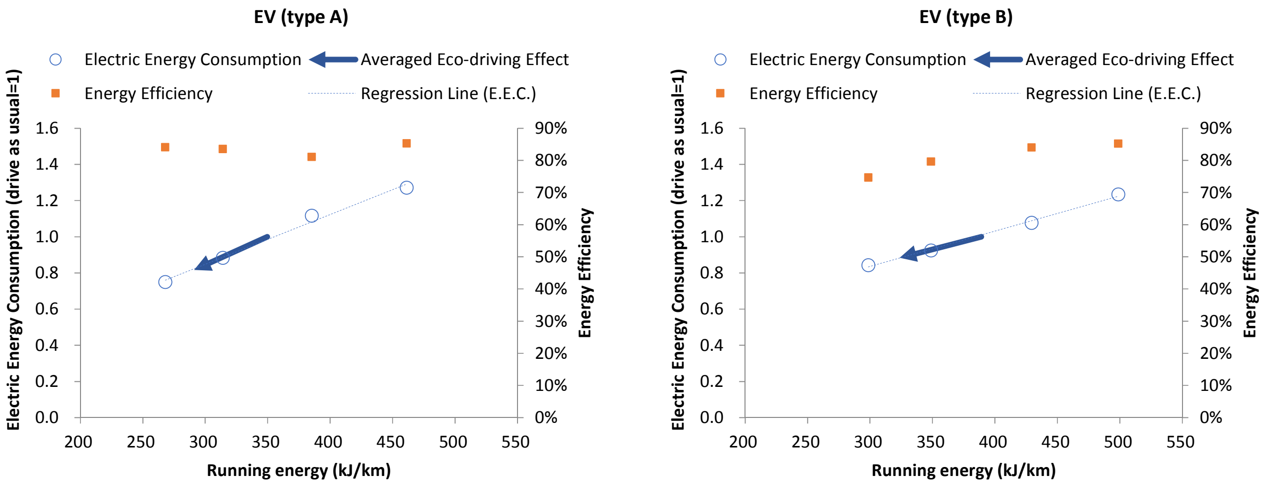
Figure 7 shows the test results for the energy-conversion efficiencies of all vehicles. From the viewpoint of differences in energy efficiency due to the type of vehicle, the averaged efficiency of 660 cc CTV, 1,300 cc CVT, 1,800 cc 4AT, 1,500 cc HEV, EV type A, and EV type B were 16.8%, 21.3%, 16.7%, 30.7%, 83.5%, and 80.8% respectively. It can be concluded that the hybrid system increased the utilization efficiency of thermal energy by 9.4–14.0%, and it is well known that the motors of EVs can convert electrical energy into kinetic energy with high efficiency. On the other hand, from the viewpoint of the differences in energy efficiency due to eco-driving achievement level, the energy-conversion efficiency tended to decrease with low kinetic running energy, except for the EV type A. This vehicle maintained high energy efficiency over a wide range of kinetic running energies. This result indicates that EVs have higher potential eco-driving effects than ICEVs if they maintain high energy-conversion efficiencies at low load range, because ICEV engines have a characteristically low energy-conversion efficiency at low load range. We believe that the EV type B had a lower energy efficiency in this condition because the regenerative energy during deceleration of a rear-wheel-drive vehicle is less than that of a front-wheel-drive vehicle.



(a) internal conbusion engine vehicles



(a) internal conbusion engine vehicles



(b) electric vehicles

Figure 7. Test results of all vehicles with respect to energy conversion efficiency.

4. Conclusions

Comparative measurements of the eco-driving effect between ICEVs and EVs were conducted using a C/D with an eco-driving test mode that we developed. Eco-driving effects and energy-conversion efficiencies were examined. The eco-driving effects of 660 cc CVT, 1,300 cc CVT, 1,800 cc 4AT, 1,500 cc HEV, EV type A, and EV type B vehicles were 12.0%, 12.2%, 10.9%, 12.6%, 18.4% and 11.7% respectively. These results indicate that eco-driving with low kinetic running energy by "observing the speed limit" and "maintaining a constant speed" is effective not only for ICEVs (including HEVs), but also for EVs. While, the averaged energy-conversion efficiency of 660 cc CTV, 1,300 cc CVT, 1,800 cc 4AT, 1,500 cc HEV, EV type A, and EV type B were 16.8%, 21.3%, 16.7%, 30.7%, 83.5%, and 80.8% respectively. Electric vehicles have high energy-conversion efficiencies because they use a motor to convert electrical energy into kinetic energy. From the viewpoint of the differences in energy efficiency due to eco-driving achievement level, the energy-conversion efficiency of tested vehicles tended to decrease with low kinetic running energy, except for the EV type A which had the largest eco-driving effect. These results indicate that EVs have a higher potential of eco-driving effect than a gasoline-powered vehicle if EVs could maintain high energy-conversion efficiency at low load range. EVs have begun to be more widely adopted, and various power trains will coexist on public roads. It is preferable for the same eco-driving method to be used by both electric and gasoline-powered vehicles to create a smooth and safe traffic flow. At present, it remains the responsibility of the driver to observe the speed limit and maintain a constant speed. Therefore, this study is intended to support the dissemination of tools like intelligent speed adaptation (ISA) to obey speed regulations in real time. In the future, as well as the development and dissemination of automated driving systems, traveling with less kinetic energy will be important. The future steps of this study are as follows: it is necessary to extend the evaluation target of electric vehicles. The eco-driving test mode developed in this study assumed a Japanese local city with an upgraded arterial road. If the road conditions are different (frequent road congestion, etc.), it will be necessary to create a new test mode in order to evaluate them.

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Conflict of Interest

All authors declare no conflict of interest in this paper.

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