World Electric Vehicle Journal

MDPI

*Article*

# Speed Change Pattern Optimization for Improving the Electricity Consumption of an Electric Bus and Its Verification Using an Actual Vehicle

**Yiyuan Fang [1,*], Wei-hsiang Yang [1], Yushi Kamiya [1], Takehito Imai [2], Shigeru Ueki [2] and Masayuki Kobayashi [2]**

[1] Faculty of Science and Engineering, Waseda University, Tokyo 169-8555, Japan
[2] Organization for the Promotion of Low Emission Vehicles, Tokyo 160-0004, Japan
* Correspondence: fyy@aoni.waseda.jp

**Abstract:** In this study, we focused on the eco-driving of electric vehicles (EVs). The target vehicle is an electric bus developed by our research team. Using the parameters of the bus and speed pattern optimization algorithm, we derived the EV's eco-driving speed pattern. Compared to the eco-driving of internal combustion engine vehicles (ICVs), we found several different characteristics. We verified these characteristics with actual vehicle driving test data of the target bus, and the results confirmed its rationality. The EV's eco-driving method can improve electricity consumption by about 10–20% under the same average speed.

**Keywords:** energy consumption; efficiency; EV (electric vehicle); simulation; optimization

check for updates

**Citation:** Fang, Y.; Yang, W.-h.; Kamiya, Y.; Imai, T.; Ueki, S.; Kobayashi, M. Speed Change Pattern Optimization for Improving the Electricity Consumption of an Electric Bus and Its Verification Using an Actual Vehicle. *World Electr. Veh. J.* **2024**, *15*, 16. https://doi.org/10.3390/wevj15010016

Academic Editors: Joeri Van Mierlo and Genevieve Cullen

Received: 28 November 2023
Revised: 22 December 2023
Accepted: 2 January 2024
Published: 4 January 2024



## 1. Introduction

The energy efficiency of the transportation sector has become a key factor to reduce greenhouse gas emissions and fuel consumption in response to the negative impacts of global warming [1–3]. As a method of energy conservation and environmental sustainability, eco-driving has attracted considerable research interest over the past two decades [4–6]. Eco-driving is an emerging research field, and its definition is not yet strictly defined. However, it generally refers to the practice of driving vehicles in a way that improves fuel economy [7–9].

Many studies have shown that eco-driving is a low-cost, high-efficiency method of energy conservation and emission reduction [1,10,11]. Eco-driving has been widely discussed and applied worldwide due to the aforementioned advantages. German scholars were the first to focus on this field in 2001. As of 2020, scholars from the United States and China have contributed the most publications in this field (total papers—percentage: 178—23% (US), 117—15% (China)) [4,12,13]. Numerous studies from around the world have shown the enormous potential of eco-driving in energy conservation, emission reduction, and other aspects [14–16]. Eco-driving has also been summarized into some specific and easy-to-implement principles that are promoted worldwide. In European countries including England, Germany, Italy, and Finland, eco-driving methods such as the golden rules of eco-driving have been regarded as part of the driving license examination [4,17]. In Japan, the 10 recommendations for eco-driving promoted by government departments such as the ministry of the environment are well-known to the public [18].

Many popular eco-driving principles, including gentle acceleration and quick shifting up, are usually based on ICVs [19,20]. With the popularization of EVs, research on EV eco-driving becomes more and more important. Many researchers study eco-driving as an optimization problem. For example, a study conducted by Mensing et al. shows that using optimization techniques at a fixed distance and time to adjust the driver's operations significantly improves the energy efficiency of the ICV [21]. This fixed distance and time method is convenient to clarify the energy consumption improvement effect of eco-driving under the same driving conditions, so we also adopted it in our research. However, the power system characteristics of EVs and ICVs are different, and the applicability of EVs needs further verification. And a study conducted by Sundström et al. introduces a generic dynamic programming function for Matlab [22], which can be used in vehicle power consumption optimization problems. Referring to this research, we built a speed change pattern optimization simulator by combining our developed accuracy-proven vehicle simulator with an optimization algorithm and used it to develop EV eco-driving. In addition, an eco-driving optimization study often focuses on algorithms and lacks the verification of actual vehicle experiments [23,24]. In this regard, after deriving the optimal EV eco-driving, we verified its characteristics using the driving test data of a small electric bus that was developed by our research team.

The purpose of this study is to explore eco-driving strategies that are applicable to EVs. Currently, many eco-driving views for cars are based on ICVs. Are they still applicable to EVs, which have undergone significant changes in their powertrain systems and are rapidly becoming popular [25]? We want to find out what kind of driving strategies will improve the electricity consumption of EVs. For this purpose, we selected a self-developed electric bus as the object vehicle, constructed a simulator that can accurately calculate the power consumption of the vehicle during operation, and combined it with an optimization method to derive the EV eco-driving speed change pattern, which is the speed change pattern that results in the best electricity consumption under the set conditions. After investigating it, we obtained some eco-driving strategies that are applicable to EVs and discovered the differences between them and the eco-driving strategies that are applicable to ICVs. Then, we verified the correctness of these eco-driving strategies through the experimental driving data of the object vehicle and investigated the reasons why these eco-driving strategies can improve the electricity consumption.

## 2. Target Vehicle and Simulator

### *2.1. Target Vehicle and Simulation Conditions*

In this study, the target vehicle is a small electric bus, the Waseda Electric Bus-3Advanced (WEB-3A). This vehicle was created by converting a small diesel bus using Hino Motors into a remodeled small electric bus with standard specifications. Table 1 summarizes the basic specifications.

**Table 1.** Basic specifications of WEB-3A.

| | **Base Diesel Bus** | **WEB-3A** |
|---|---|---|
| Manufacturer/Type | Hino/Poncho (BDG-HX6JLAE) | |
| Capacity | 31 persons | |
| Curb/Gross weight [kg] | 5710/7415 | 5990/7695 |
| Engine or Motor | 132 kW Engine | 145 kW/400 Nm (PMSM) |
| Transmission | 5 speed AT | Fixed |
| Battery [kWh]/[V] | None | 40/331 (TOSHIBA "SCiB™") |
| Exterior photograph | None |  |

Since we focused on the aforementioned street bus in this study, we optimized the speed change pattern, in which "driving distance" and "average speed" are fixed from start to stop, while considering the distance between bus stops and the schedule [26,27]. Our purpose was to cover a total distance of 400 m in three intervals (acceleration, coasting, and deceleration) at an average speed of 30 km/h. In addition, we also focused on the double travel distance when stops were skipped (800 m total with an average speed of 30 km/h). In this study, we assumed that there would be no impact from traffic lights or congestion.

*2.2. Vehicle Driving Energy Calculation Simulator and the Speed Change Pattern Optimization Method*

Figure 1 shows the schematic of the backward simulator used to calculate the driving energy of WEB-3A. The power consumed by the battery is obtained by inputting the vehicle's speed. The vehicle simulator was constructed using methods that are commonly used in electric vehicle simulations. It can simulate the power consumption of a vehicle during operation by using information on the vehicle's speed and road gradient. The vehicle simulation considers the driving resistance of the vehicle (acceleration resistance, air resistance, rolling resistance, and slope resistance), the transmission efficiency and the motor/inverter efficiency during driving and regeneration (transmission efficiency is a constant value, while motor/inverter efficiency comes from the efficiency map), and the power consumption of the vehicle's auxiliary equipment.

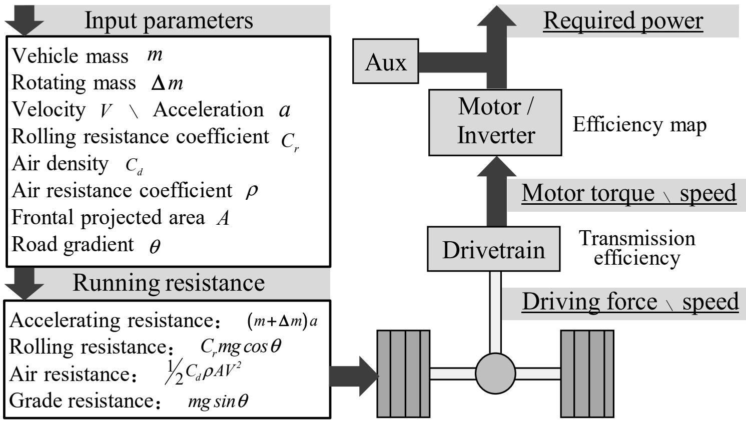



**Figure 1.** Image of vehicle running energy calculation simulator.

The vehicle simulator constructed using the above method can achieve high-precision calculation of instantaneous electricity consumption and comprehensive electricity consumption for the entire journey. Figure 2 shows the comparison between the actual measured motor power and the simulated calculated motor power of the object vehicle on a certain route (which is described in detail in Section 4). It can be seen that the simulation results are highly consistent with the measured values, and the comprehensive electricity consumption error of the simulation is within 5%.

We optimized the drive of 400 m (or 800 m) with an average speed of 30 km/h, as mentioned above. First, we define a cost function to search for the speed change pattern that consumes least energy, as shown in Equation (1).

$$C = \int_{t_{start}}^{t_{end}} P(j)\mathrm{d}t \quad (1)$$

Here, $C$ [kWh] is the consumed energy, $t$ [s] is time, $P$ [kW] is consumed power, and $j$ [m/s$^3$] is the jerk (control variable).

Figure 3 shows a schematic of the optimization method used in this study (dynamic programming) ($x$ [m] represents position, $v$ [m/s] represents speed, and $a$ [m/s$^2$] represents acceleration). The following are the constraints and convergence conditions: (a) maximum jerk of $\pm$1 m/s$^3$, (b) maximum acceleration (deceleration) of $\pm$0.2 G, (c) starting (stopping) speed of 0 km/h, and (d) maximum speed of 60 km/h.

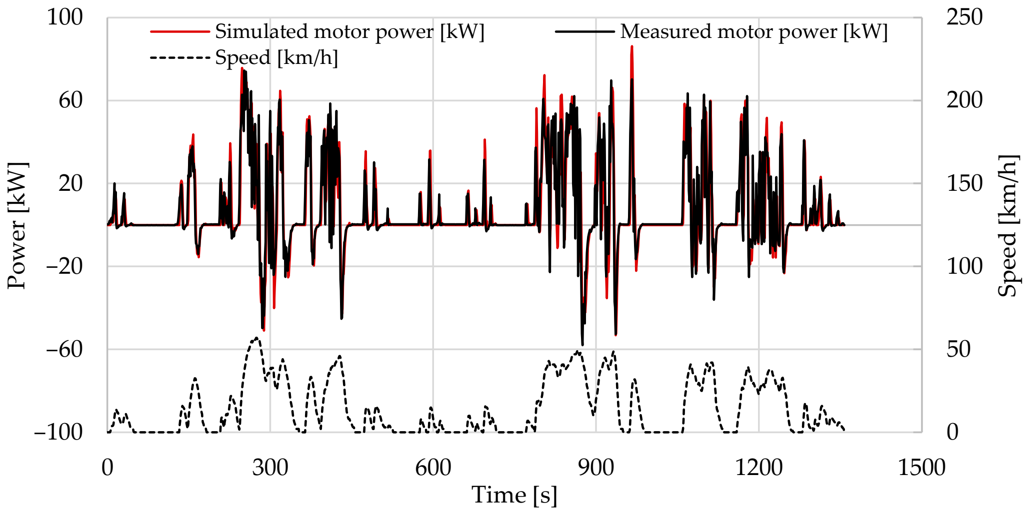



**Figure 2.** Comparison of simulated and measured motor power consumption.

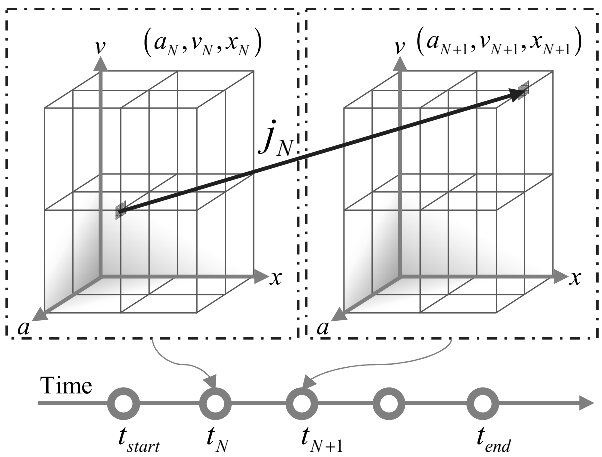



**Figure 3.** Image of dynamic programming.

The speed change pattern is optimized by incorporating the proposed optimization method into the vehicle's driving energy calculation simulator. Calculations are performed in the following order: (a) determine the relationship among acceleration, speed, position, and time as state variables and jerk as the control variable, (b) input the state variables of each tiny time period into the vehicle simulator to calculate the battery electricity consumption, and (c) search for the combination that minimizes the cost function.

## 3. Investigation and Trial Calculation of the Electricity Consumption Optimization Speed Change Pattern

### *3.1. Derivation of the Electricity Consumption Optimization Speed Change Pattern*

In this section, we summarize the optimization of the speed change pattern for various conditions.

The vehicle loss conditions are listed in Table 2. In addition, we investigate the use of "coasting", which has gained attention recently for improving the electricity consumption of electric vehicles. In most cases, coasting is not advantageous in terms of fuel efficiency or safety in internal combustion vehicles; thus, it is not employed in regular driving. However, it is widely employed in trains as an eco-driving method. In some cases, coasting has been implemented in electric vehicles. For example, some EVs using a one-pedal accelerator in the neutral range of pedal opening, to account for the driver's unintentional fine operation, set a dead zone to keep the output of the motor at 0 Nm, so that the vehicle maintains coasting [28], while others maintain coasting by releasing the accelerator pedal [29]. Coasting is possible by reducing the motor torque to 0 Nm while the inverter is operating [30] or disconnecting the inverter from the motor [31]. In the current study, we employed the latter "inverter off coasting control (with coasting control)". Finally, as the second analytical condition, we employed "without coasting control".

**Table 2.** List of various data used for vehicle loss calculation.

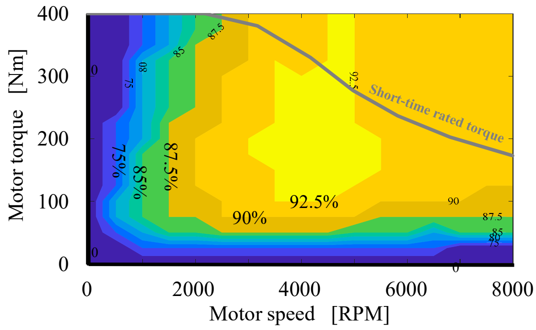
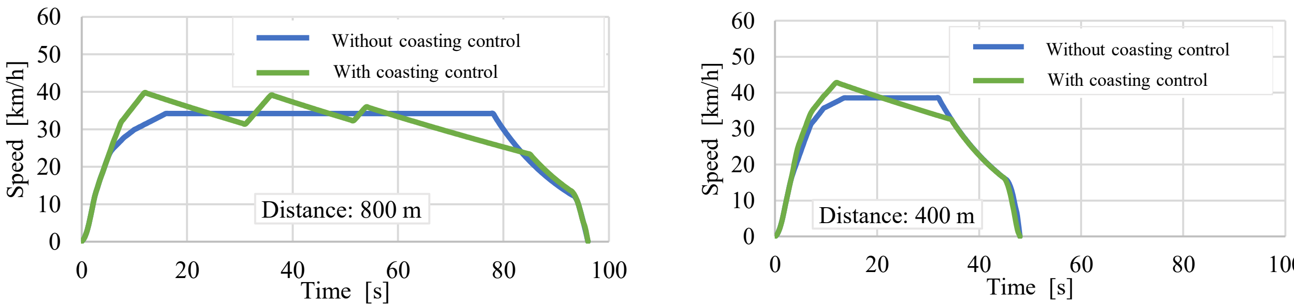
| Transmission Efficiency | Auxiliary Equipment Consumption Power | Motor/Inverter Efficiency (Using Efficiency Map Data) |
|---|---|---|
| 98% | 1.5 kW |  |

Figure 4 illustrates the simulator's speed change pattern optimization result. The following section summarizes the details of "with coasting control (Co)" and "without coasting control (W/O Co)".



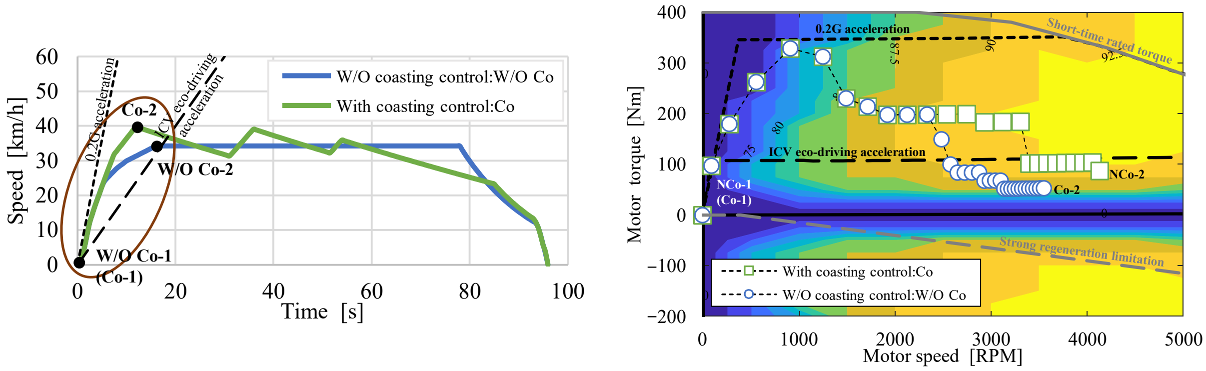

(a) (b)

**Figure 4.** Optimized speed change patterns in different settings: (**a**) distance: 800 m, time: 96 s, average speed: 30 km/h; (**b**) distance: 400 m, time: 48 s, average speed: 30 km/h.

*3.2. Discussion on the Details of the Derived Electricity Consumption Optimization Speed Change Pattern*

This section examines the results of the "with coasting control (inverter OFF coasting control)" and "without coasting control" settings, which are derived in the previous section. For detailed discussions, driving is divided into three parts: acceleration, cruising, and deceleration. Due to space constraints, we only present the discussion on the 800 m drive.

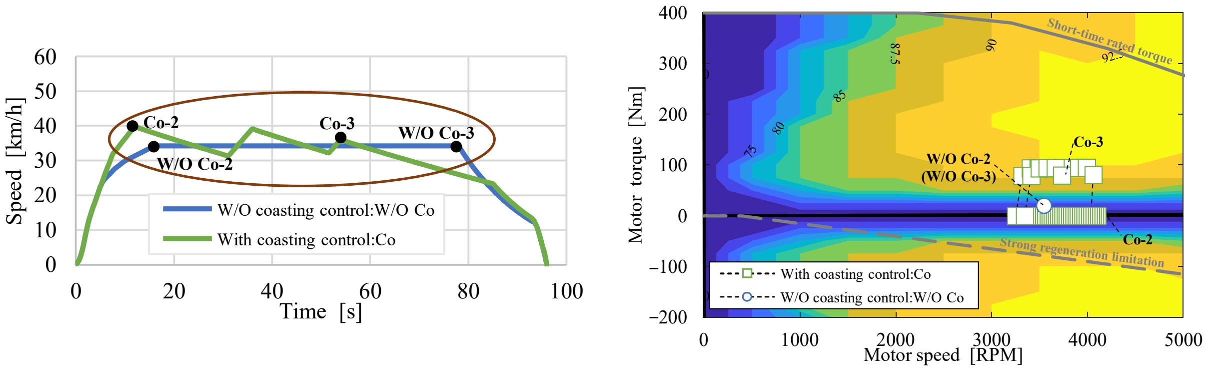
First, we consider the acceleration interval. Figure 5 illustrates the details of the acceleration interval in optimized speed change patterns. Both types of controls "should accelerate strongly" compared to the typical internal combustion engine vehicle's eco-driving acceleration pattern [19,20]. In particular, the vehicle starts near the maximum allowable acceleration (0.2 G) based on the optimization calculation, then eases slightly, but remains close to full acceleration. This strong acceleration can reduce the cruising speed under the situation of fixed driving distance and time, thereby reducing the energy that is required for acceleration and the air resistance loss of the entire driving trip. When performing similar acceleration, for an internal combustion engine vehicle, the engine must be revved high while the gear remains low, leading to poor fuel efficiency. However, the motor is resistant to load changes while maintaining good efficiency across a wide range of operating points. Therefore, strong acceleration is not a major issue in terms of electricity consumption. We can see this from the motor operating points of Figure 5, which demonstrate that good efficiency is maintained. For a diesel bus, if the bus “accelerates slowly” while leaving a bus stop, it may disrupt traffic flow and potentially cause accidents. Thus, there is a safety concern. However, with an electric bus, while passenger comfort is important, relatively strong acceleration to merge safely into the traffic does not cause a major issue in terms of electricity consumption.




(**a**) (**b**)

**Figure 5.** Details of acceleration interval in optimized speed patterns (distance: 800 m): (**a**) speed—time profile; (**b**) motor torque—speed profile.

Next, we consider the cruising interval. Figure 6 shows the details of the cruising interval in optimized speed change patterns. “With coasting control” is “repetition of acceleration and coasting”, while “without coasting control” is “constant speed driving”, which is also recommended for heavy internal combustion engine vehicles as well. From the motor operating points of Figure 6, in some cases, a repetition of acceleration and coasting may be preferable to a constant speed of driving in the cruising interval (depending on the loss when the motor operating point is at 0 Nm). This conclusion is similar to the “coasting-powering operation” being recommended for trains.




(**a**) (**b**)

**Figure 6.** Details of cruising interval in optimized speed patterns (distance: 800 m): (**a**) speed—time profile; (**b**) motor torque—speed profile.

Finally, considering the deceleration interval, Figure 7 shows the details of the deceleration interval in optimized speed change patterns. Both types of coasting controls were described as “deceleration while maintaining the maximum regeneration”. To maximize regenerative energy recovery, this is a speed change along the vehicle-set regenerative braking line (the break line in the motor's operating points of Figure 7). Energy dissipation due to mechanical braking in the same interval can be prevented, thereby contributing substantially to improved efficiency. Note that when using "with coasting control", coasting deceleration has advantages over regenerative deceleration in energy saving and is therefore preferred. Afterwards, it is switched to regenerative deceleration for a stronger deceleration. After nearly reaching the minimum regenerative speed, it decelerates or stops using mechanical braking. This operation is comparable to that of a diesel bus.

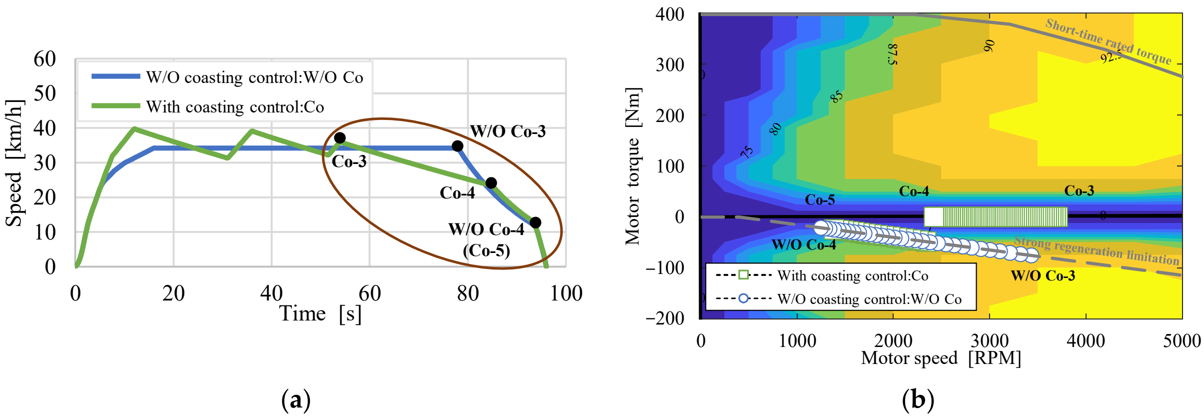



**Figure 7.** Details of deceleration interval in optimized speed patterns (distance: 800 m): (**a**) speed—time profile; (**b**) motor torque—speed profile.

### 3.3. Calculation of the Improvements in Electricity Consumption with the Derived Electricity Consumption Optimization Speed Change Pattern

In this section we compare the electricity consumption when the target vehicle, WEB-3A, is driven with the various electricity consumption optimization speed change patterns. Figure 8 summarizes the speed change patterns. We specifically used the electricity consumption during (a) the cruising zero style (constant acceleration interval and constant deceleration interval without cruising) as the reference and compared this value to the (b) ICV eco-driving speed change pattern for diesel buses and the optimization speed change pattern when the two types of coasting control mentioned above were used ((c) without coasting control and (d) with coasting control). The (b) ICV eco-driving is based on relevant reference studies [19,20]. The three internal combustion engine vehicle's eco-driving principles were considered as follows: (i) limiting acceleration: ICV eco-driving uses a smaller acceleration of approximately 0.06 G to limit the acceleration based on gentle acceleration and a quick shift up; (ii) constant speed cruising: ICV eco-driving uses cruise control to reduce unnecessary acceleration and deceleration and to maintain a constant speed while cruising; (iii) engine braking: ICV eco-driving simulates the engine braking of diesel buses by using a smaller deceleration when slowing down.

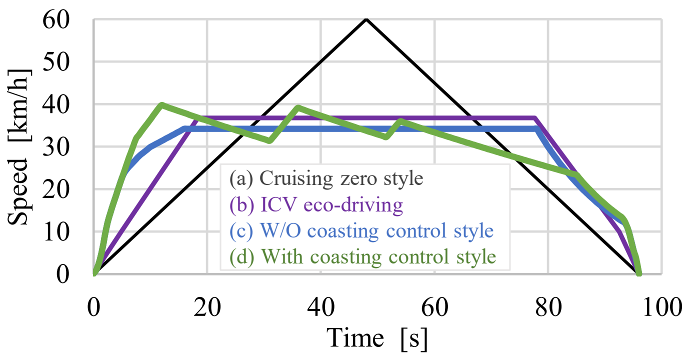



**Figure 8.** Various speed change patterns in different settings.

Table 3 compares the electricity consumption derived from the vehicle driving energy calculation simulator. We can quantitatively see that driving with the electricity consumption optimization speed change pattern derived in this study improves electricity consumption.

**Table 3.** Electricity consumption comparison of various speed change patterns in different settings.

| | Electricity Consumption | |
|---|---|---|
| | **[kWh/km]** | **[%]** |
| (a) Cruising zero style | 0.408 | (Benchmark) |
| (b) ICV eco-driving | 0.382 | −6.2% |
| (c) W/O coasting control style | 0.370 | −10.0% |
| (d) With coasting control style | 0.318 | −24.2% |

At this point, the three strategies of EV eco-driving can be confirmed again as follows: acceleration, regenerative braking, and coasting. Firstly, acceleration: At the same average speed, a faster acceleration can reduce the maximum speed/cruise speed of a trip, thereby reducing the energy required for acceleration and the air resistance loss of the entire driving trip. Secondly, regenerative braking: Using regenerative braking as much as possible can greatly improve the energy efficiency of the deceleration interval (without coasting control), convert kinetic energy into electrical energy, and reduce the energy loss of mechanical braking. Thirdly, coasting: The energy efficiency of coasting is very high. Therefore, using coasting to drive when allowed can effectively improve the energy efficiency of the vehicle, for example, cruising by repetition of acceleration and coasting or decelerating by coasting.

## 4. Verification of Derived Speed Change Pattern Optimization Based on the Public Road Driving Test Data

In this chapter, we verify the validity of the speed change pattern optimization derived in the previous chapter based on the public road driving test data. The optimization resulted in the following order (without coasting control): “acceleration interval with acceleration strongly”, “cruising interval with constant speed”, and “deceleration interval with maintaining the maximum regeneration and mechanical braking”. We compared the optimization result to the measured value for each interval.

### *4.1. Public Road Driving Test*

Our research group conducted a 12-month driving test in Tonomachi, Kawasaki City, Japan, using the electric bus WEB-3A (December 2015 to November 2016). This test was conducted four times daily covering a distance of ~5.5 km one way. The vehicle route is shown in Figure 9, and an illustration of the changes in vehicle speed and elevation along the route is shown in Figure 10. The route includes a bridge and the slope changes around it; however, the remainder of the route is flat. In the following test, we extracted various data from the verification test for analysis. We excluded areas with a change in slope. There was no change in the number of passengers, because it was a trial operation.

The driving test was conducted in Kawasaki City, which is in the Tokyo metropolitan area. This area is highly developed, with a high road density and traffic congestion. There are many occassions for acceleration and deceleration when driving a car and few situations for long-term cruising. Therefore, strategies related to acceleration and deceleration are more applicable, while strategies related to cruising are less applicable. If the traffic is smooth and there are more situations for free cruising in a city or road scene, the applicability of the above results may change. To maintain consistency with the optimal settings and to avoid a decrease in generality caused by road slope characteristics, we chose this relatively flat urban road to verify the optimization results. The maximum speed allowed on this route is 60 km/h, but due to the influence of traffic signals and traffic congestion, there are more instances of acceleration and deceleration when starting and stopping, and about one-third of the time is spent in a stationary state, resulting in a slow average speed of only about 15 km/h.

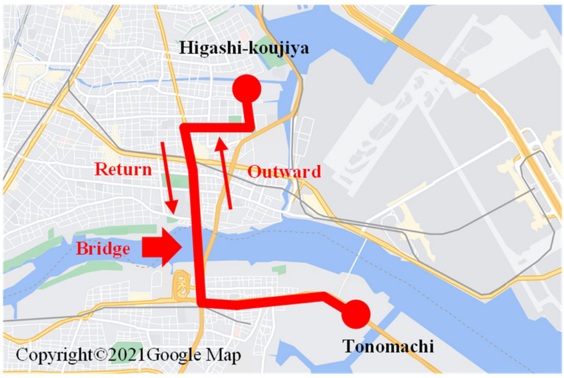



**Figure 9.** Route profile of Tonomachi/Higashi-koujiya shuttle route.

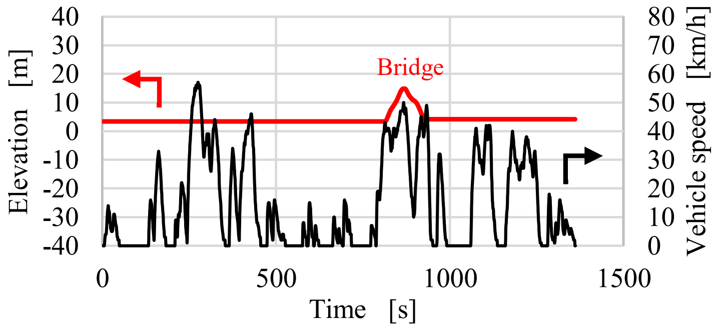
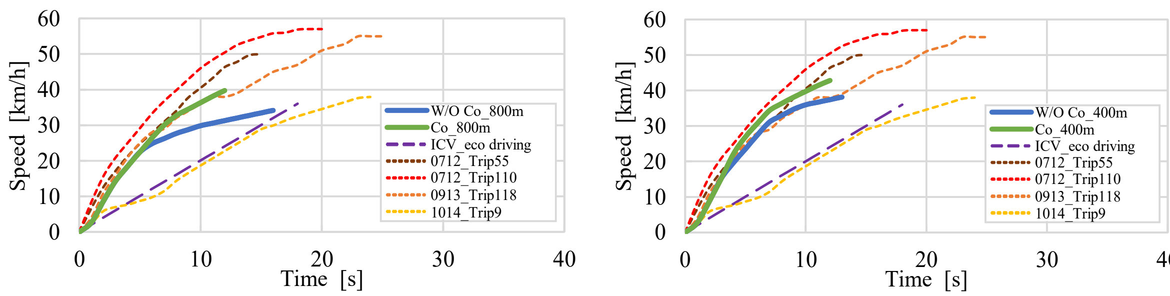



**Figure 10.** Running profile (from Tonomachi to Higashi-koujiya, 13 September 2016-2nd).

*4.2. Verification of Derived Speed Change Pattern Optimization*

4.2.1. Comparison of the Optimization Result and Measured Value in the Acceleration Interval

The optimization result was "acceleration interval with acceleration strongly". Figures 11 and 12 show the comparison with the measured value for the speed change pattern and motor operating point, respectively. The four types of values shown with a dotted line are the measured results (e.g., 0712_Trip55 is the 55th trip data from 12 July), the two types of optimization results are shown with a solid line (e.g., W/O Co means the optimization without coasting control), and the ICV eco-driving acceleration pattern is shown with break line. The most similar to the optimization results and ICV eco-driving acceleration pattern were extracted from the test data.




(**a**) (**b**)

**Figure 11.** Speed—time profile at acceleration interval: (**a**) 800 m; (**b**) 400 m.

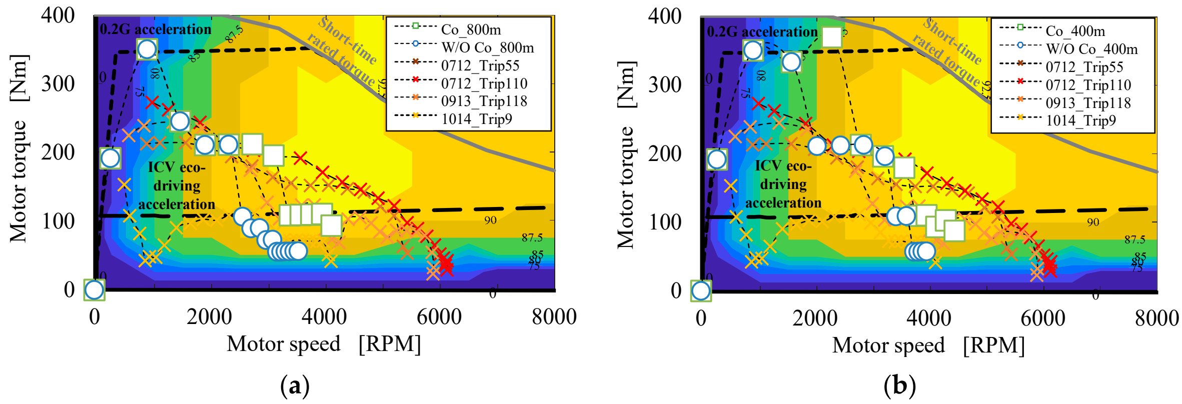



**Figure 12.** Motor torque—speed profile at acceleration interval: (**a**) 800 m; (**b**) 400 m.

Figures 13 and 14 compare the average motor efficiency (motor output/motor input) and the average vehicle efficiency (powertrain output/battery output). The figure shows 16 types of acceleration data, obtained on the same test day (12 July), as well as four different types of measured values to increase generality. The average efficiency was calculated from start to 30 km/h.

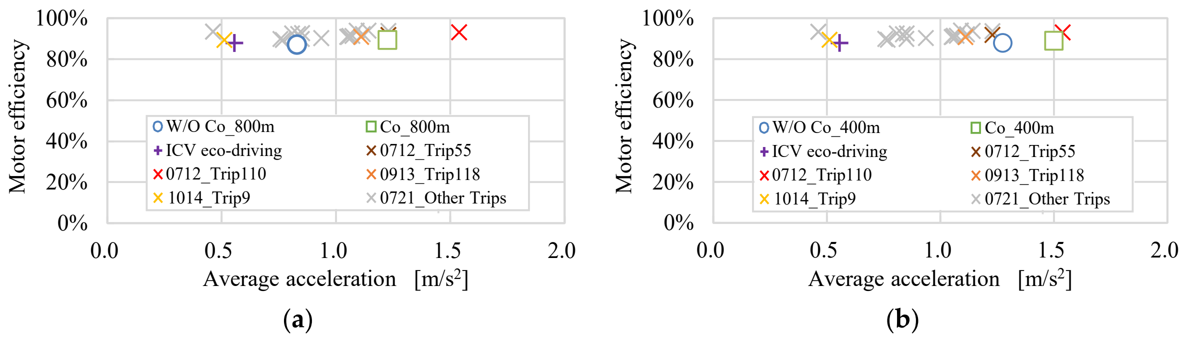



**Figure 13.** Relationship between motor efficiency and average acceleration: (**a**) 800 m; (**b**) 400 m.

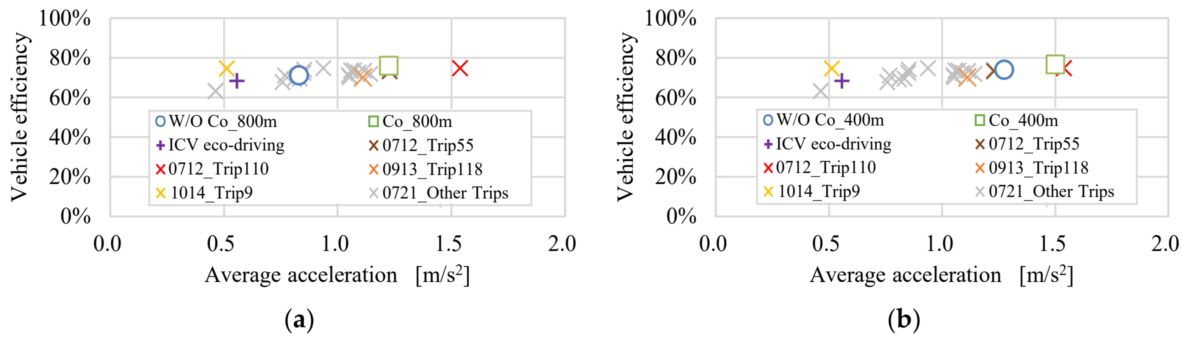
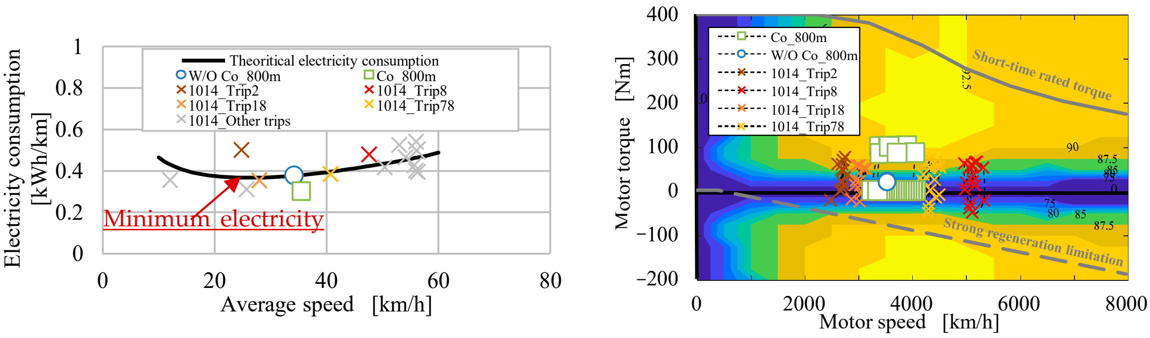



**Figure 14.** Relationship between vehicle efficiency and average acceleration: (**a**) 800 m; (**b**) 400 m.

The optimization result and the measured result were consistent. Specifically, efficiency remained rather constant regardless of acceleration, indicating that it is quite different from the property of internal combustion engine vehicles [19,20]. These results verify the previous optimization result: even if the electric vehicle performs strong acceleration, there will be no deterioration in efficiency.

#### 4.2.2. Comparison of the Optimization Result and Measured Values in the Cruising Interval

The WEB-3A adopts the "without coasting control" setting, so the optimization result for this type of control was "cruising interval with constant speed". Figure 15 shows the comparison of electricity consumption and motor operating point with the measured and optimized values. The figures illustrate 14 types of data obtained on the same test day (October 14), when the speed change was within ±2 km/h, and the acceleration was within ±1 km/h/s. In Figure 15a, the solid line represents the theoretical electricity consumption of a vehicle driven at a constant speed. The optimization result without coasting control is consistent with both the theoretical consumption and measured consumption. Furthermore, the conclusion of the previous section, "acceleration interval with acceleration strongly", has the effect of bringing the vehicle speed in the subsequent cruising interval closer to the theoretical minimum electricity consumption (about 30 km/h); thus, it was a valid optimization result.

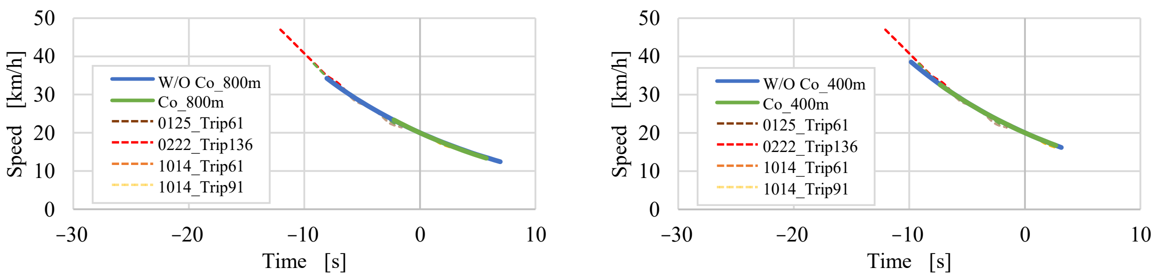



(**a**) (**b**)

**Figure 15.** Various comparisons of cruising interval: (**a**) relationship between electricity consumption and average speed; (**b**) motor torque—speed profile.

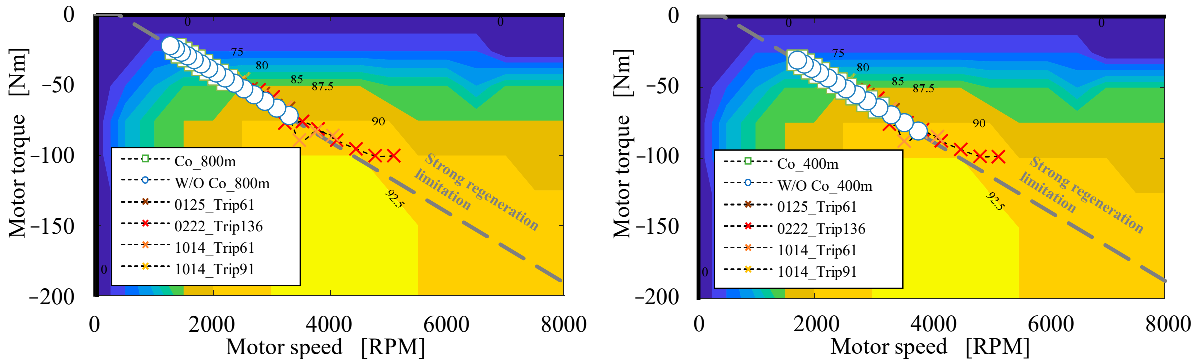
### 4.2.3. Comparison of the Optimization Result and Measured Value in the Deceleration Interval

The optimization result was "deceleration while maintaining the maximum regeneration". Here, we continue the comparison of "deceleration with maximum regenerative drive". Figures 16 and 17 show the comparison of the speed change pattern and motor operating point with the measured value, respectively. Figures 18 and 19 are comparisons of energy regeneration efficiency, with the former representing the average deceleration dependency and the latter representing the deceleration speed band notation. These are equivalent to the regenerative system efficiency (to the motor power generation unit) [32], which is derived by dividing the regenerative energy that was actually generated by the theoretically generatable regenerative energy. In order to broaden the scope, we collected 39 different types of deceleration data (other trips) in addition to the four measured values. Furthermore, for comparison, we included six different types of measured energy regeneration efficiency when using both regenerative and mechanical brakes. Overall, the optimization result and measured value were consistent, demonstrating the efficacy of "deceleration while maintaining the maximum regeneration" in electric buses. Additionally, the measured data showed that the energy regeneration efficiency (74–96% with a mean of 85%) improved significantly compared to using both regenerative and mechanical brakes (33–49% with a mean of 41%).



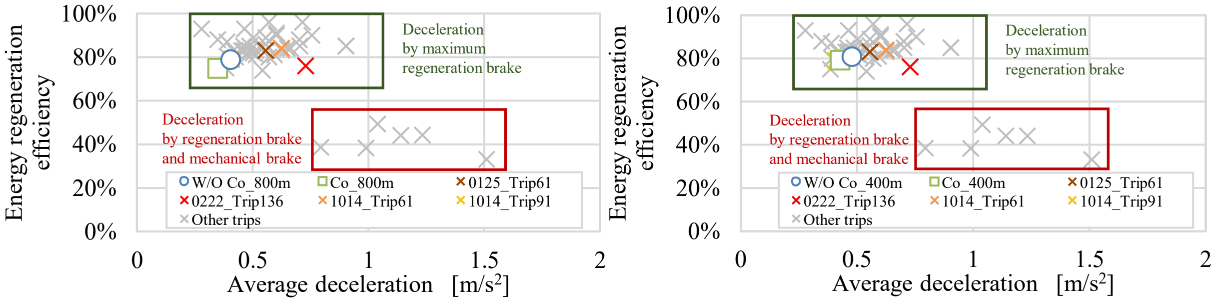

(**a**) (**b**)

**Figure 16.** Speed—time profile at deceleration interval: (**a**) 800 m; (**b**) 400 m.



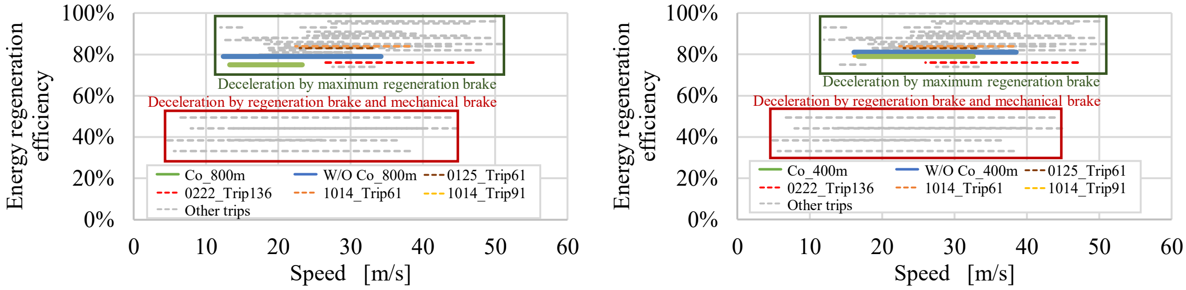

(**a**) (**b**)

**Figure 17.** Motor torque—speed profile at deceleration interval: (**a**) 800 m; (**b**) 400 m.




(**a**) (**b**)

**Figure 18.** Relationship between energy regeneration efficiency (up to the motor generator) and average deceleration: (**a**) 800 m; (**b**) 400 m.




(**a**) (**b**)

**Figure 19.** Relationship between energy regeneration efficiency (up to the motor generator) and speed zone: (**a**) 800 m; (**b**) 400 m.

## 5. Conclusions

We report an electric vehicle driving energy calculation simulator with a speed change optimization function that is proposed in this study. We were able to derive a speed change pattern that optimizes electricity consumption while performing various types of coasting controls using the designed simulator.

Based on the optimization calculation with the simulator, the optimal speed change pattern (EV eco-driving) was derived for electric buses "without coasting control" and "with coasting control" (assume "inverter off coasting control"). When the target vehicle is driven in the EV eco-driving speed change pattern, according to our trial calculation, this method can improve the electricity consumption by about 10–20% under the same average speed.

To confirm the validity of the optimization results of the speed change pattern derived, mentioned above, we used the object vehicle's road driving test data. The optimization result is in the following order (without coasting control): "acceleration interval with acceleration strongly", "cruising interval with constant speed driving", and "deceleration while maintaining the maximum regeneration". We verified these results by comparing them to actual measured data, which are the speed change in each interval, and found that they were consistent.

Specifically, we examined the details of the "acceleration interval with acceleration strongly", which was significantly different from that of internal combustion engine vehicles, and confirmed with our measured data that the previous optimization result is valid: even if an electric bus performs strong acceleration, there will be no deterioration in efficiency. Internal combustion engines have large variations in fuel consumption during acceleration, but the properties of an electric bus, whose efficiency does not depend on the pattern of acceleration change, contributes to eliminating variations in electricity consumption during acceleration.

Finally, we summarized the three eco-driving strategies that are applicable to EVs and mentioned above and anticipated their expected application scenarios in the real world: no need to limit acceleration, use regenerative braking, and use coasting. They are, respectively, suitable for city roads with frequent starts and stops and intercity roads (or highways) that are mainly for cruising.

No need to limit acceleration: EVs and ICVs have significant differences in their powertrain systems, so eco-driving methods based on ICVs may not be applicable to EVs. Limiting acceleration based on gentle acceleration and quick shifting up may improve the efficiency of the internal combustion engine but has no effect on the efficiency of the motor/inverter. At the same average speed, a faster acceleration can reduce the maximum speed/cruise speed of a trip, thereby reducing the energy that is required for acceleration and the air resistance loss of the entire driving trip. Therefore, from the perspective of eco-driving, there is no need to consider acceleration limits when driving EVs.

Regenerative braking: Using regenerative braking as much as possible can greatly improve the energy efficiency of the deceleration interval, convert kinetic energy into electrical energy, and reduce the energy loss of mechanical braking. Actively using regenerative braking can convert most of the deceleration kinetic energy into electrical energy for future driving. The mean energy regeneration efficiency is 85% when only using regenerative braking for deceleration, while the mean energy regeneration efficiency is 41% when using both regenerative braking and mechanical brakes. If regenerative braking is not used at all, all of this energy will be converted into the thermal losses of the mechanical brakes. When the two strategies mentioned above are applied to city road driving with frequent starts and stops, the effect is particularly significant, with an expected improvement of about 10% in electricity consumption.

Coasting: Coasting has already been widely used as a basic eco-driving method in railway transportation. The energy efficiency of coasting is very high. Therefore, using coasting to drive when allowed can effectively improve the energy efficiency of the vehicle, for example, by cruising by repetition of acceleration and coasting. Additionally, from the perspective of eco-driving, when road traffic conditions permit, coasting should be the first choice for deceleration, followed by regenerative braking. This method is particularly effective when driving on city-to-city roads or highways with fewer vehicles, with an expected improvement of about 10% in electricity consumption.

**Author Contributions:** Conceptualization, all authors; methodology, Y.F., W.-h.Y. and Y.K.; software, Y.F. and W.-h.Y.; validation, Y.F. and Y.K.; formal analysis, Y.F., W.-h.Y. and Y.K.; investigation, Y.F., W.-h.Y. and Y.K.; resources, Y.K.; data curation, Y.F. and Y.K.; writing—original draft preparation, Y.F.; writing—review and editing, Y.K., T.I., S.U. and M.K.; visualization, Y.F. and W.-h.Y.; supervision, Y.K.; project administration, Y.K.; funding acquisition, Y.K., T.I., S.U. and M.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References


1. Ho, S.H.; Wong, Y.D.; Chang, V.W.C. What Can Eco-Driving Do for Sustainable Road Transport? Perspectives from a City (Singapore) Eco-Driving Programme. *Sustain. Cities Soc.* **2015**, *14*, 82–88. [CrossRef]
2. Huang, Y.; Ng, E.C.Y.; Zhou, J.L.; Surawski, N.C.; Chan, E.F.C.; Hong, G. Eco-driving technology for sustainable road transport: A review, Renew. *Sustain. Energy Rev.* **2018**, *93*, 596–609. [CrossRef]
3. Xu, Y.; Li, H.; Liu, H.; Rodgers, M.O.; Guensler, R.L. Eco-Driving for Transit: An Effective Strategy to Conserve Fuel and Emissions. *Appl. Energy* **2017**, *194*, 784–797. [CrossRef]
4. Chen, Z.; Xiong, S.; Chen, Q.; Zhang, Y.; Yu, J.; Jiang, J.; Wu, C. Eco-Driving: A Scientometric and Bibliometric Analysis. *IEEE Trans. Intell. Transp. Syst.* **2022**, *23*, 22716–22736. [CrossRef]
5. He, M.; Lin, T.; Wu, X.; Luo, J.; Peng, Y. A Systematic Literature Review of Reverse Logistics of End-of-Life Vehicles: Bibliometric Analysis and Research Trend. *Energies* **2020**, *13*, 5586. [CrossRef]
6. Barkenbus, J.N. Eco-Driving: An Overlooked Climate Change Initiative. *Energy Policy* **2010**, *38*, 762–769. [CrossRef]
7. Wang, Z.; Wu, G.; Barth, M.J. A Review on Cooperative Adaptive Cruise Control (CACC) Systems: Architectures, Controls, and Applications. In Proceedings of the 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 4–7 November 2018; pp. 2884–2891. [CrossRef]
8. Caban, J.; Vrábel, J.; Šarkan, B.; Ignaciuk, P. About Eco-Driving, Genesis, Challenges and Benefits, Application Possibilities. *Transp. Res. Procedia* **2019**, *40*, 1281–1288. [CrossRef]
9. Caban, J. A Study of Eco-Driving Possibilities in Passenger Cars Used in Urban Traffic. *Arch. Automot. Eng.* **2021**, *91*, 37–48. [CrossRef]
10. Zhou, M.; Jin, H.; Wang, W. A Review of Vehicle Fuel Consumption Models to Evaluate Eco-Driving and Eco-Routing. *Transp. Res. Part D Transp. Environ.* **2016**, *49*, 203–218. [CrossRef]
11. Alam, M.S.; McNabola, A. A Critical Review and Assessment of Eco-Driving Policy & Technology: Benefits & Limitations. *Transp. Policy* **2014**, *35*, 42–49. [CrossRef]
12. Mongeon, P.; Paul-Hus, A. The Journal Coverage of Web of Science and Scopus: A Comparative Analysis. *Scientometrics* **2016**, *106*, 213–228. [CrossRef]
13. Gandia, R.M.; Antonialli, F.; Cavazza, B.H.; Neto, A.M.; de Lima, D.A.; Sugano, J.Y.; Nicolai, I.; Zambalde, A.L. Autonomous Vehicles: Scientometric and Bibliometric Review. *Transp. Rev.* **2019**, *39*, 9–28. [CrossRef]
14. Mata-Carballeira, O.; del Campo, I.; Asua, E. An Eco-Driving Approach for Ride Comfort Improvement. *IET Intell. Transp. Syst.* **2022**, *16*, 186–205. [CrossRef]
15. Čulík, K.; Štefancová, V.; Hrudkay, K.; Morgoš, J. Interior Heating and Its Influence on Electric Bus Consumption. *Energies* **2021**, *14*, 8346. [CrossRef]
16. Linkov, V.; Perůtka, J.; Zaoral, A.; Tučka, P.; Ťápal, A.; Zůvala, R.; Řezáč, P. The Speed Behavior of Czech Professional Drivers According to Ordinary vs. Variable Speed Limit Signs: An on-Road and Driving Simulation-Based Comparison. *Perner's Contacts* **2019**, *14*, 35–43.
17. The Golden Rules of Ecodriving. Available online: https://www.ecodrive.org/en/what_is_ecodriving/the_golden_rules_of_ecodriving/ (accessed on 20 December 2023).
18. 10 Recommendations for Eco-Driving. Available online: https://www.mlit.go.jp/report/press/sogo10_hh_000171.html (accessed on 22 December 2023).
19. Allen, R.W.; Rosenthal, T.J.; Park, G. An Overview of Eco-Driving Theory, Capability Evaluation, and Training Applications. *Sensors* **2021**, *21*, 6547.
20. Fleming, J.; Yan, X.; Lot, R. Incorporating Driver Preferences into Eco-Driving Assistance Systems Using Optimal Control. *IEEE Trans. Intell. Transp. Syst.* **2021**, *22*, 2913–2922. [CrossRef]
21. Mensing, F.; Trigui, R.; Bideaux, E. Vehicle trajectory optimization for application in ECO-driving. In Proceedings of the 2011 IEEE Vehicle Power and Propulsion Conference, Chicago, IL, USA, 6–9 September 2011; pp. 9–14. [CrossRef]
22. Sundström, O.; Guzzella, L. A generic dynamic programming Matlab function. In Proceedings of the 2009 IEEE Control Applications, (CCA) & Intelligent Control, (ISIC), St. Petersburg, Russia, 8–10 July 2009; pp. 1625–1630. [CrossRef]
23. Koch, A.; Bürchner, T.; Herrmann, T.; Lienkamp, M. Eco-driving for different electric powertrain topologies considering motor efficiency. *World Electr. Veh. J.* **2021**, *12*, 6. [CrossRef]
24. Maamria, D.; Gillet, K.; Colin, G.; Chamaillard, Y.; Nouillant, C. On the use of Dynamic Programming in eco-driving cycle computation for electric vehicles. In Proceedings of the 2016 IEEE Conference on Control Applications (CCA), Buenos Aires, Argentina, 19–22 September 2016; pp. 1288–1293. [CrossRef]
25. International Energy Agency. Global EV Outlook 2023. Available online: https://www.iea.org/data-and-statistics/data-product/global-ev-outlook-2023 (accessed on 20 December 2023).

26. Tokyo Metropolitan Bureau of Transportation. 2019 Transport Statistics Annual Report. Available online: https://www.kotsu.metro.tokyo.jp/about/information (accessed on 16 April 2022).
27. Koyano, S.; Okamura, H.; Miyagi, M.; Kokuryo, K. *Reduction Effect of $CO_2$ by Idling Stop in the Case of Route Buses*; Tokyo Metropolitan Research Institute for Environmental Protection: Tokyo, Japan, 2009; pp. 76–85.
28. Naoki, M.; Ikuma, S.; Tatsuya, S.; Keigo, A.; Yohei, N. e-Pedal system which provides simple driving by capacious throttle pedal controllability with electric brake control. In Proceedings of the JSAE Congress, Yokohama, Japan, 24–26 May 2017; pp. 217–222.
29. Volkswagen: Brake or Coast? The ID.4's Intelligent Energy Recuperation Concept. Available online: https://motor-fan.jp/article/photo/100003361 (accessed on 21 January 2021).
30. Kawai, H.; Sunohara, T.; Tasaka, Y.; Fukasawa, S. Permanent-Magnet Synchronous Motor Propulsion System for Tokyo Metro Ginza Line Trains. *Toshiba Rev.* **2008**, *63*, 45–49.
31. Hisanori, Y.; Sho, K.; Yoshinori, Y.; Kota, T. Development and Future Prospects of PMSM Drive Control Technologies for Railway Rolling Stock. *Mitubishi Denki Giho* **2016**, *90*, 513–516.
32. Fang, Y.; Xu, T.; Yang, W.; Ihara, Y.; Kamiya, Y. Detailed Analysis of Regenerative Energy When the Electric Bus Driving on Expressways. In Proceedings of the FISITA 2021 World Automotive Congress, Virtual, 14–16 September 2021; pp. 1–10.