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Developing a Simple Electricity Consumption Prediction Formula for the Pre-Introduction Prediction for Electric Buses

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Abstract: This study aims to develop a theoretical formula to help bus operators easily predict electricity consumption while introducing a certain type of electric bus on a predetermined route. The formula requires vehicle-side information (such as air resistance coefficient, rolling resistance coefficient, vehicle weight, powertrain efficiency, kinetic energy recovery rate, auxiliary equipment electricity consumption, and other vehicle-related data) for construction and road-/operation-side information (such as average driving speed, number of starts and stops, road gradients, and other road-/operation-related data) for prediction. First, herein, as a basic study to construct the theoretical formula, a developed electric bus and its vehicle electricity consumption simulator are employed. We then perform a comparative analysis considering the comparison of loss between the actual operation on public roads and the assumed constant velocity when running on flat roads. Next, we develop theoretical equations for the generalization of velocity and gradient changes and simplified modeling of electricity consumption prediction. Considering the burden of information collection on operators, we categorize it into three stages. In this paper, we first organize the minimum necessary road-/operation-side information (route/operational indicators). Next, we propose a theoretical formula for electricity consumption prediction constructed based on vehicle-side information. Finally, we validate the validity and accuracy of the constructed formula using electric buses and their on-road operational data that we developed earlier. The verification results showed that, after obtaining vehicle-side and road-/operation-side information, the theoretical formula constructed in this study achieved an electricity consumption prediction with an average error of 6% (high-accuracy method). This result demonstrates the practicality of using the theoretical formula to predict the electricity consumption/range of electric buses operating on specific routes.

Keywords: electricity consumption prediction; prediction formula; electric vehicle; simple method

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1. Introduction

Concerns about climate change (global warming) and the depletion of fossil fuels have prompted many countries and regions around the world to take active measures in reducing carbon dioxide emissions and saving energy [1,2]. The transportation sector consumes approximately 20% of global energy and accounts for about 25% of global carbon dioxide emissions, most of which come from the road transport sector [3,4]. Therefore, in order to achieve the emission reduction targets set out in the Paris Agreement under the United Nations Framework Convention on Climate Change in 2015, the road transport sector needs to make significant contributions [5,6]. Against this backdrop, the electrification of vehicles has been rapidly advancing in recent years across various regions of the world, including Asia, Europe, and the Americas [7–10].

Recently, we have seen an increasing number of electric buses and trucks [11–13]. However, owing to the difficulty of predicting the performance of electric buses during actual operation, many companies have ultimately been hesitant to act or have abandoned the idea of introducing electric buses by weighing this idea. In this study, we aim to develop a theoretical formula that enables operators to easily predict and calculate the most basic performance indicator, namely the electricity consumption of the vehicle(s) [kWh/km] [14,15].

Previous formulas for vehicle pre-introduction electricity consumption prediction include the following aspects. The most reliable method measures the electricity consumption data obtained through field test runs using the vehicles to be deployed. However, the implementation cost represents a major obstacle. As another method, there are cases where vehicle electricity consumption simulations are used [16]. Specifically, this method uses diesel vehicles that are already owned by the operator to test run the route to be introduced (to collect the velocity change data) and calculates the electricity consumption by simulating the process in combination with route gradient data collected from maps and other sources. However, vehicle simulation is a complex, interdisciplinary task involving multiple fields such as mechanical engineering, electrical engineering, control engineering, and computer science. Vehicle simulation requires skilled technical personnel with expertise and costly simulation tools (both hardware and software) [17,18]. At present, this approach is typically applied in automotive R&D departments or research institutions [19]. Therefore, while this method is effective in predicting electricity consumption, it requires specialized knowledge and technical capabilities, making it challenging to adopt.

Therefore, in this study, we developed a method (simplified method) that enables the operators to predict the electric power cost of vehicles to be introduced based only on the estimated average velocity information. Additionally, we shall look at measures that enable even better forecasts (medium- and high-accuracy methods) if additional information on acceleration/deceleration and the road gradient of the route to be introduced is available.

First, herein, as a basic study to construct the theoretical formula, a developed electric bus and its vehicle electricity consumption simulator are employed. We then perform a comparative analysis considering the comparison of loss between the actual operation on public roads and the assumed constant velocity when running on flat roads. Based on the approximate proportional relationship between the two electricity consumption values, we propose a simple electricity consumption prediction formula that requires only the average velocity for practical use. Next, we develop theoretical equations for the generalization of velocity and gradient changes and simplified modeling of electricity consumption prediction. Finally, we construct various methods and summarize the same.

2. Comparison and Discussion of Losses Between the Actual Operation on Public Roads and Constant Velocity Driving on Flat Roads

The purpose of this study is to develop a simplified method that will enable operators to predict the cost of electricity for the vehicles they plan to install. Here, it is desirable to use only the “average velocity” expected during operation for the input information when considering the burden on the operator. Therefore, we first consider the “electricity consumption when driving at a constant velocity on a flat road”, which can be easily obtained after determining the vehicle to be deployed. This uses the “average velocity” described above. Following that, we can construct a method that considers the effects of acceleration and deceleration that occurred during actual operation and overlay the "electricity consumption deterioration rate" on this value. This is positioned as a simplified method (using only average velocity information).

2.1. Various Information Obtained During Actual Operation of the Developed Electric Bus

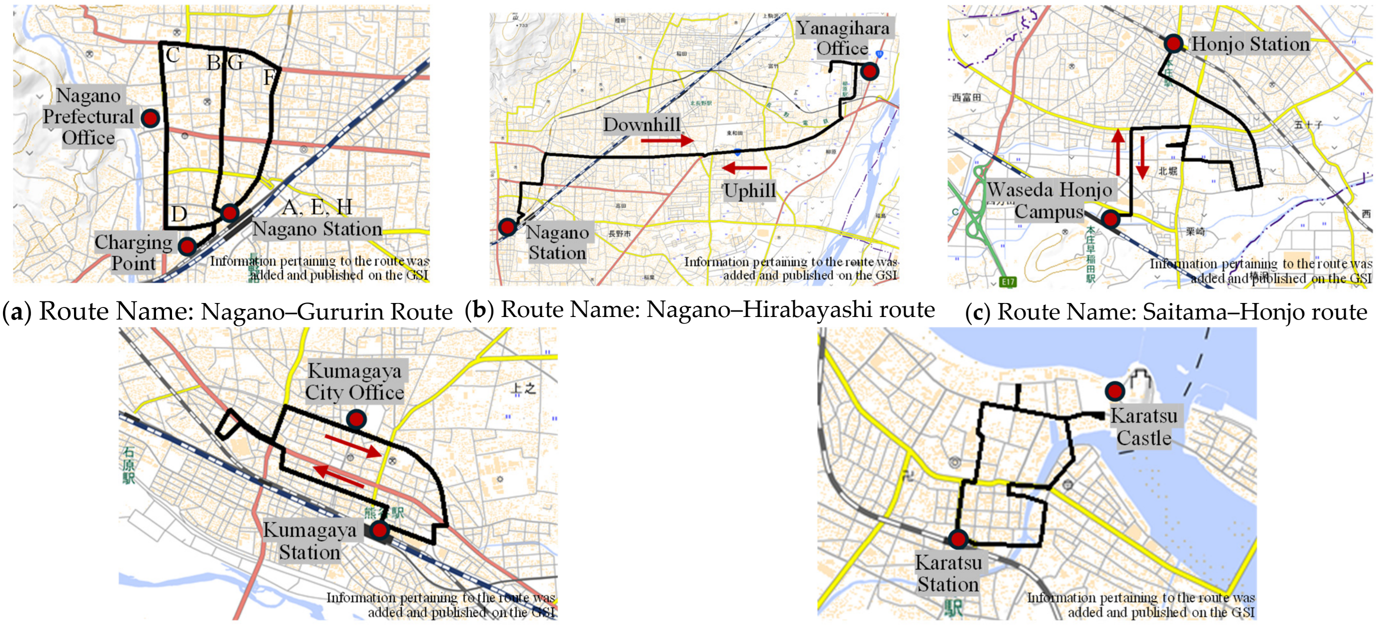
In this section, we proceed with the basic study for the electricity consumption prediction formula; here, the vehicle selected as an example was the Waseda Electric Bus-3 (WEB-3), a small electric bus previously developed by our research group [20]. This bus is based on a small diesel bus manufactured by Hino Motors, which was converted into an electric bus and equipped with a wireless battery charger. The basic vehicle specifications are shown in Table 1. WEB-3 has been used in various regions in the past. Consequently, we first used the measured velocity change, road slope, and electricity consumption obtained in these areas to derive the aforementioned "electricity consumption deterioration rate" coefficient.

Table 1. Waseda Electric Bus-3 basic vehicle specs.

Mass when empty	kg	5990
Equivalent inertial mass	kg	162
Max motor output	kW	145
Passenger capacity (average)	people	25 (10)
Front projected area	m^2	5.91
Auxiliary consumption power	W	600
Motor inverter average efficiency (when cruising)		85% (75%)
Gear efficiency		85%

Information related to the past operation using the same vehicle is summarized in Figure 1. Figure 1a is the Nagano–Gururin route, which is a community bus route that circles an 8.5 km route in the central city area in about 50 min, and travels in the order of A, B, . . . H. Points B, C, and G in the figure are the higher elevation points, with a difference in elevation of ~30 m. Figure 1b is the Nagano–Hirabayashi route. Shuttles are operated on this route of ~11.5 km one-way (~45 min) that links the stop in front of Nagano station to the Nagaden Bus Yanagihara office. As the Nagano station side is ~30 m higher in elevation than that of the Yanagihara office side, the trip from Nagano station is downhill, whereas the return from the Yanagihara office is uphill. Subsequent studies will be conducted on round-trip runs.

Figure 1c is the Saitama–Honjo route. This is an 11.2 km round-trip route that links Honjo station and the Waseda Honjo campus (~35 min), and it is virtually flat. Figure 1d is the Saitama–Kumagaya route, which is a 5.1 km circuit of the central city area that takes ~20 min to complete and is virtually flat. Figure 1e in the same figure is the Saga–Karatsu route, which is a 3.3 km circular circuit of the central city area that also takes ~20 min to complete.



(**a**) Route Name: Nagano–Gururin Route (**b**) Route Name: Nagano–Hirabayashi route (**c**) Route Name: Saitama–Honjo route

(**d**) Route Name: Saitama–Kumagaya route (**e**) Route Name: Saga–Karatsu route

Figure 1. Overview of actual operational routes to which WEB-3 was introduced. In this study, for each route, the authors attempted to use data that closely reflects typical traffic conditions, excluding cases of congestion from the analysis. The buses in this study do not operate on dedicated lanes but share lanes with general traffic. The energy consumption values presented for each route are final averages (Table 2).

Table 2. Basic information from each route in actual WEB-3 operation.

Route	Driving Distance	Driving Time	Actual Measured Average Electricity Consumption	Route/Operational Indicators				
				Average Velocity V	Start/Stop Times n	Stop Time Ratio α	Gained Uphill Elevation $\frac{\sum h^+}{X}$	Gained Downhill Elevation $\frac{\sum h^-}{X}$
	km	s	kWh/km	km/h	Times/km	%	m/km	m/km
Nagano–Gururin	8.5	2975	0.83	10.3	4.9	41%	6.5	−6.5
Nagano–Hirabayashi	23	5411	0.68	15.3	2.2	33%	2.7	−2.7
Saitama–Honjo	11.2	2210	0.74	18.2	2.0	20%	1.8	−1.8
Saitama–Kumagaya	5.1	1145	0.70	15.9	3.2	17%	2.4	−2.4
Saga–Karatsu	3.3	1185	0.72	10.1	3.9	32%	5.4	−5.4

Next, the basic information on each route obtained during actual operation is summarized in Table 2. Here, in addition to the measured electricity consumption values, the following five road/operational indicators that have a significant impact on the same values are included, such as average velocity, start/stop times, stop time ratio, and gained uphill/downhill elevation (Figure 2) [21]. This information shall be used in subsequent studies.

$$\frac{\sum \boldsymbol{h}^{+}}{\boldsymbol{X}} = \frac{h_1 + h_3}{X} \qquad \frac{\sum \boldsymbol{h}^{-}}{\boldsymbol{X}} = \frac{h_2 + h_4}{X} \; (negative\ value)$$

X: Driving distance

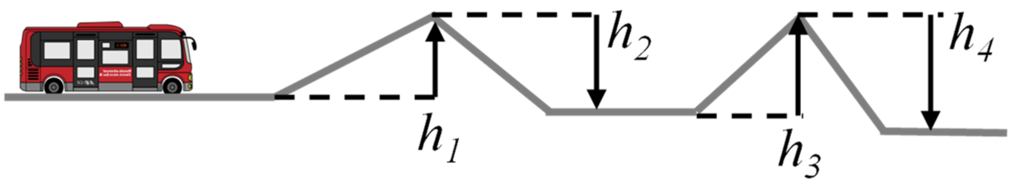


Figure 2. Image of derived gained uphill/downhill elevation value.

2.2. Vehicle Electricity Consumption Simulator Used in This Chapter

In the simplified method developed in this study, it is necessary to derive the "electricity consumption deterioration rate" as described above, and to acquire this value, a detailed comparison of the "power consumption values when running at a constant velocity on a flat road" and the "power consumption values during actual operation (acceleration/deceleration and hill climbing/descent)" is necessary. Therefore, we constructed a vehicle electricity consumption simulator [16] to derive these two values and analyze the contribution to electricity consumption deterioration. Figure 3 shows a conceptual diagram of the constructed backward simulator. This method, by inputting the vehicle velocity, can be used to obtain the final battery power consumption. The cost values derived by the constructed simulator and the measured cost values are shown in Table 3. The mean error is 2.4%, which was determined to be reasonable.

Table 3. Comparison of WEB-3 electricity consumption values for each route.

Route	Actual Measured Electricity Consumption	Vehicle Electricity Consumed Energy Simulator (Study in Section 2)		Electricity Consumption Prediction Formula (High-Accuracy Method) (Study in Section 3)	
		Electricity Consumption	Error	Electricity Consumption	Error
	kWh/km	kWh/km	%	kWh/km	%
Nagano–Gururin	0.83	0.80	3.6%	0.84	1.2%
Nagano–Hirabayashi	0.68	0.66	2.9%	0.72	5.9%
Saitama–Honjo	0.74	0.73	1.4%	0.67	9.1%
Saitama–Kumagaya	0.70	0.72	2.9%	0.68	2.9%
Saga–Karatsu	0.72	0.71	1.4%	0.66	8.3%
Mean error	-	-	2.4%	-	5.5%

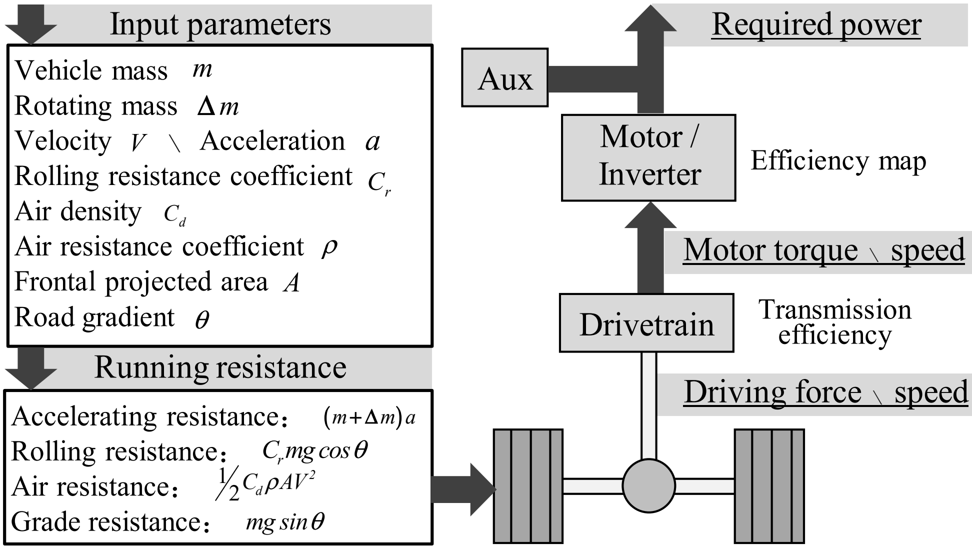


Figure 3. Constructed vehicle electricity consumption simulator, reprinted from Ref. [22].

2.3. Energy Analysis Using a Simulator When the Vehicle Is in Actual Operation and a Comparison Between It and When Driving on a Flat Road with a Constant Velocity

Using the vehicle consumed energy simulator constructed in this study, we calculated the loss breakdown that occurs during actual operation. The results are shown in Table 4. Considering the loss that occurs at a constant velocity over the flat road, the effects of acceleration/deceleration and uphill/downhill driving during actual operation are compared.

Table 4. Derivation of the loss that occurs during actual operation on each route using the constructed simulator and a comparison based on the assumption of running at a constant velocity on a flat road.

Route		**Nagano–Gururin**		**Nagano–Hirabayashi**		**Saitama–Honjo**		**Saitama–Kumagaya**		**Saga–Karatsu**	
Driving Situation		**Fixed Velocity**	**Actual Operation**	**Fixed Velocity**	**Actual Operation**	**Fixed Velocity**	**Actual Operation**	**Fixed Velocity**	**Actual Operation**	**Fixed Velocity**	**Actual Operation**
Average velocity	km/h	10.3		15.3		18.2		15.9		10.1	
Electricity consumption	kWh/km	0.42	0.80	0.41	0.66	0.41	0.73	0.41	0.72	0.43	0.71
Auxiliary equipment consumption	kWh/km	0.06	0.06	0.04	0.04	0.03	0.03	0.04	0.04	0.06	0.06
Rolling resistance	kWh/km	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Air resistance	kWh/km	0.00	0.04	0.01	0.05	0.01	0.05	0.01	0.03	0.00	0.02
Mechanical brake loss	kWh/km	0.00	0.24	0.00	0.14	0.00	0.20	0.00	0.21	0.00	0.20
Drive section loss	kWh/km	0.03	0.06	0.03	0.05	0.03	0.06	0.03	0.06	0.03	0.05
Motor loss	kWh/km	0.12	0.18	0.12	0.16	0.12	0.17	0.12	0.17	0.12	0.16
Electricity consumption deterioration rate (average value +74%)		+87%		+60%		+79%		+76%		+67%	

Mechanical brake loss only occurs during actual operation and has a high impact. The kinetic energy that decreases during deceleration and the potential energy that decreases during downhill driving are converted to calculate the same loss. Additionally, although the motor loss and drive loss worsen during actual operation, this phenomenon is caused by the increased load on the same component during acceleration/deceleration and uphill/downhill driving. There is also deterioration in the aerodynamic drag consumption. However, as this consumption is proportional to the square of the velocity, when the maximum velocity increases compared to the same average velocity during actual operation, this consumption also increases.

Figure 4 is a comparison of the loss breakdown of the Nagano–Gururin and Saga–Karatsu routes at approximately the same average velocity. Given the road/operational indicators for the two routes (Table 2), the former has a larger number of "start/stop times" and "gained uphill elevation" than the latter, and this leads to an increase in motor/drive unit/mechanical brake loss compared to the latter. These calculation results are considered reasonable. The former also has a higher "stop time ratio," which has the effect of increasing the maximum velocity and correspondingly worsening the aerodynamic drag. The electricity consumption deterioration rate for both lines is +87% and +67%, respectively.

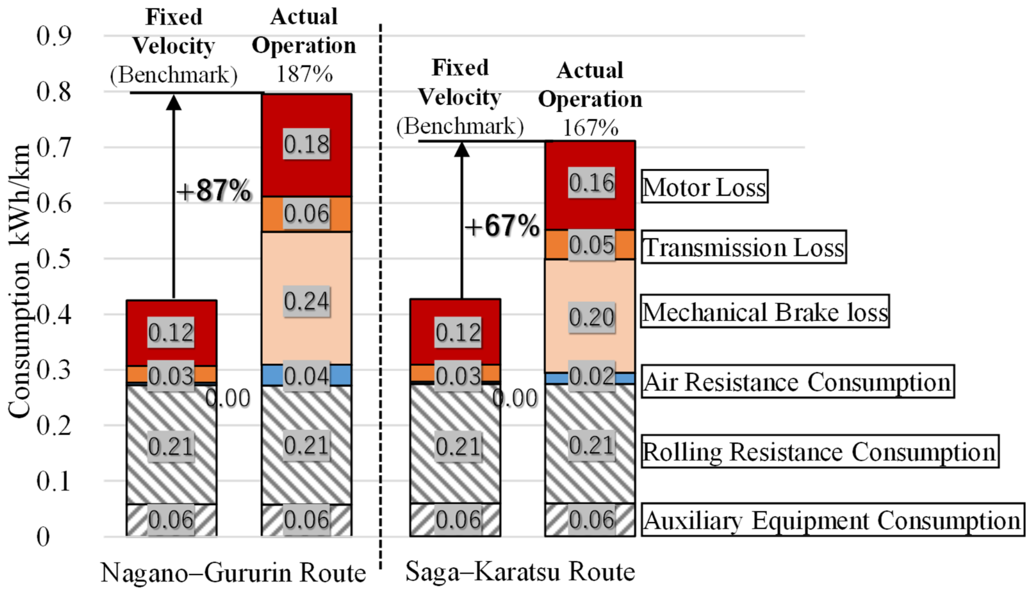


Figure 4. Comparison of loss between two routes at virtually the same average velocity.

Figure 5 is a graphical representation of the average velocity dependence of the various cost values listed in Table 4. The actual measured values are also shown, and the electricity consumption when driving at a constant velocity on a flat road is assumed to be a continuous line. Although the electricity consumption values during actual operation are greatly deteriorated compared to the continuous line of electricity consumption at a constant velocity, they converge relatively close to the continuous line. Thus, the continuous line for electricity consumption during constant-speed driving was adjusted by a constant multiplier so that it reflects the average rate of electricity consumption deterioration for the five routes analyzed in this study. The adjusted continuous line was then added to the figure. By using this corrected electricity consumption continuous line, it was possible to predict the electricity consumption to a certain degree when the average velocity information was provided by the operator. Therefore, for the "electricity consumption deterioration rate", which is a representative value for the subject vehicle, the average value (+74% in this study) was set, and a method for predicting electricity consumption based on the corrected electricity consumption continuous line is used as the "simplified method". The appropriateness of this method is discussed in Section 4 after constructing the theoretical formula.

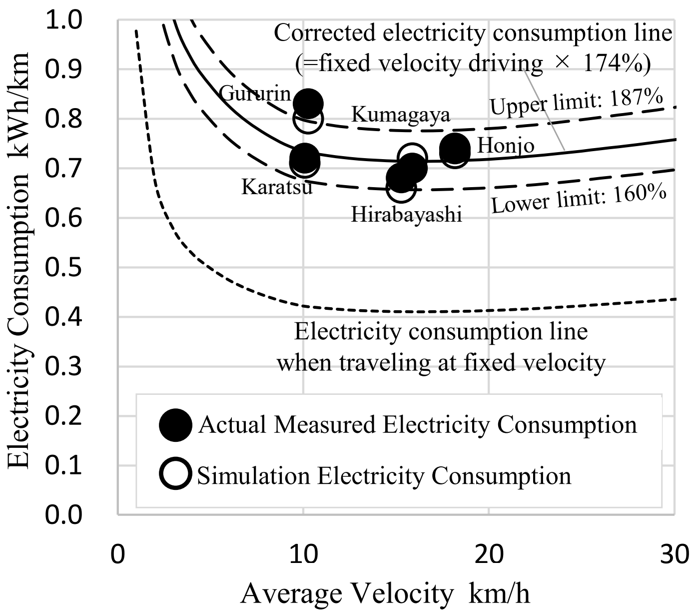


Figure 5. Attempt to predict electricity consumption using a corrected electricity consumption continuous line.

3. Construction of a Theoretical Formula for Simplify Modeling of Electricity Consumption Prediction

In the previous chapter, an attempt was made to derive a detailed comparison between the "electricity consumption values in actual operation" and the "electric power consumption at assumed constant velocity on flat roads" by analyzing various data obtained while the developed electric bus was running on the aforementioned five routes using a vehicle energy consumption simulator. Additionally, the "electricity consumption deterioration rate" representing the ratio between the two was calculated. We further generalize and simplify these studies in this chapter. Specifically, we use triangulated waveforms to generalize complex velocity changes in actual operations, substituting the effect of gradient changes with gained uphill/downhill elevation and adopting theoretical equations that simplify the modeling of electricity consumption estimation. Here, we shall investigate formulation strategies for regenerative energy that have been challenging in the past, and the results of this study should lead to the development of medium- and high-accuracy methods that can be used in situations where additional information on acceleration/deceleration and the road gradient of the route to be introduced can also be easily obtained.

First, we develop a theoretical formula for simplifying electricity consumption prediction monitoring. A generalized vehicle consumed energy theoretical formula [15] is described as follows:

$$E = E_{Air} + E_{Roll} + E_{Mech} + E_{Aux} \tag{1}$$

Here,

E	Vehicle consumed energy [J];
E_{Roll}	Rolling resistance consumed energy [J];
E_{Aux}	Auxiliary equipment consumed energy [J];
E_{Air}	Air resistance consumed energy [J];
E_{Mech}	Mechanical brake consumed energy [J]. (Mechanical braking directly consumes the vehicle's kinetic energy, and since this kinetic energy is supplied by the power system during acceleration, mechanical braking indirectly increases the vehicle consumed energy.)

This is a generalized formula established not only for electric vehicles but also for internal combustion engine vehicles, and we will proceed with our study based on this formula.

3.1. Construction of a Formula When Driving at a Constant Velocity on Flat Roads

In this section, we shall construct an electricity consumption prediction theoretical formula that assumes cruising at a fixed velocity on flat roads. As acceleration, deceleration, and stopping do not occur in this case, driving resistance only consists of air resistance and rolling resistance. Thus, the mechanical breaking term from Formula (1) does not exist and it becomes

$$E = E_{Air} + E_{Roll} + E_{Aux} \tag{2}$$

For the air resistance term, if we consider power system efficiency (gear efficiency/motor inverter efficiency), it becomes

$$E_{Air} = \frac{1}{\eta_G \eta_{Mot}} \int F_{Air} \boldsymbol{V} dt = \frac{1}{\eta_G \eta_{Mot}} \int \frac{1}{2} \rho A C_d \boldsymbol{V}^2 \boldsymbol{V} dt = \frac{1}{\eta_G \eta_{Mot}} \frac{1}{2} \rho A C_d \boldsymbol{V}^2 X \tag{3}$$

Here,

η_G Gear efficiency;
F_{Air} Air resistance [N];
t Time [s];
A Front projection area [m^2];
η_{mot} Motor inverter efficiency;
X Driving distance on the whole route [m];
ρ Air resistance [kg/m^3];
C_d Air resistance coefficient;
$\boldsymbol{V}$ **Average velocity [m/s]** (Table 2 Road/operational indicators).

In the same way, the rolling resistance term is described as

$$E_{Roll} = \frac{1}{\eta_G \eta_{Mot}} C_r (m_{Car} + m_{Pas}) g X \tag{4}$$

Here,

C_r Rolling resistance coefficient;
m_{Pas} Passenger vehicle mass [kg];
m_{Car} Vehicle mass [kg];
g Weight acceleration [m/s^2].

Finally, the auxiliary equipment consumed energy term is described as

$$E_{Aux} = P_{Aux} \cdot T \tag{5}$$

Here,

T Driving time on whole route [s];
P_{Aux} Auxiliary equipment consumption power [W].

Finally, the electricity consumption prediction formula is derived as

$$EC = \frac{E}{X} = \frac{1}{\eta_G \eta_{Mot}} [\frac{1}{2} \rho A C_d \boldsymbol{V}^2 + C_r (m_{Car} + m_{Pas}) g] + \frac{P_{Aux}}{\boldsymbol{V}} \tag{6}$$

3.2. Construction of a Formula When Accelerating/Decelerating on Flat Roads

For the theoretical formula constructed here, we added the "start/stop times" and "stop time ratio" to the "average velocity" used in the previous section, making variables of these three information points. These correspond to the road/operational indicators for each route used in Table 2. By introducing the same values, we can reflect the vehicle acceleration and deceleration, which were ignored in the study of the previous section. For generalization, the velocity change monitored in this study is assumed to be a "triangular wave velocity change" [23] (Figure 6). With the same triangular wave as the main trip, this is repeated for the entire route distance.

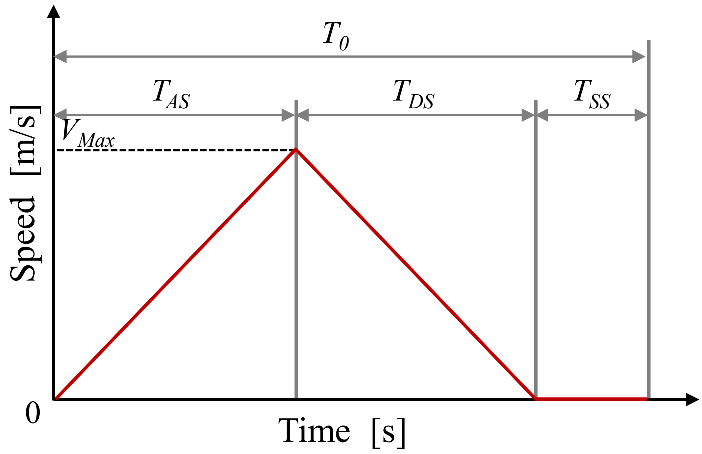


Figure 6. Triangular velocity change pattern basic trip.

We shall start by describing the method of determining the basic trip. The total time, acceleration time (=deceleration time), stop time, and maximum velocity for the basic trip are derived as follows.

$$T_0 = \frac{T}{N} = \frac{T}{\boldsymbol{n} \cdot X/1000} = \frac{1000}{\boldsymbol{n} \cdot \boldsymbol{V}},\ T_{AS} = T_{DS} = \frac{(1-\boldsymbol{\alpha})T_0}{2},\ T_{SS} = \boldsymbol{\alpha} T_0,\ V_{Max} = \frac{2\boldsymbol{V}}{(1-\boldsymbol{\alpha})} \quad (7)$$

Here,

T_0 Basic trip total time [s];
T_{DS} Basic trip deceleration time [s];
V_{Max} Maximum velocity [m/s];
T_{AS} Basic trip acceleration time [s];
T_{SS} Basic trip stop time [s];
N Number of start/stop times on the entire route [times];
$\boldsymbol{n}$ **Start/stop times (per unit driving distance) [times/km]** (Table 2 Route/operational indicators);
$\boldsymbol{\alpha}$ **Stop time ratio** (Table 2 Route/operational indicators).

Below, based on the basic trip velocity change patterns, as shown in Figure 6, we can construct the electricity consumption prediction theoretical formula based on Formula (1).

First, the air resistance term is

$$E_{Air} = E_{Air\_AS} + E_{Air\_DS} = 2E_{Air\_AS} = 2\frac{1}{\eta_G \eta_{Mot}} \int_0^{T_{AS}} F_{Air} v(t) dt = \frac{1}{\eta_G \eta_{Mot}} \cdot \frac{1}{4} \rho A C_d {V_{Max}}^2 X_0 \quad (8)$$

Here,

E_{Air_AS} Air resistance consumed energy (acceleration interval) [J];
E_{Air_DS} Air resistance consumed energy (deceleration interval) [J];
$v(t)$ Velocity time function [m/s];
X_0 Basic trip total driving distance [m].

In the same way, the rolling resistance term is

$$E_{Roll} = \frac{1}{\eta_G \eta_{Mot}} C_r (m_{Car} + m_{Pas}) g X_0 \quad (9)$$

Moving forward, we can formulate the energy consumed by the mechanical brake during deceleration, or "regenerative energy". When decelerating the vehicle (on flat roads), the operational energy possessed when deceleration starts is used effectively by the drive resistance in the beginning (rolling resistance, air resistance), and the remaining portion, excluding mechanical brake losses and power system losses, is the regenerated energy (to simplify the discussion here, rare cases of deceleration, etc., are ignored). Therefore, in this study, we consider this phenomenon as we define the operational energy usage rate η_K. The same value is the ratio of (iii) aerodynamic drag consumption (effective use)/(iv) rolling resistance consumption (effective use)/(vi) regenerative energy to (i) kinetic energy possessed at the start of deceleration and consisting of the sum of the three (Figure 7).

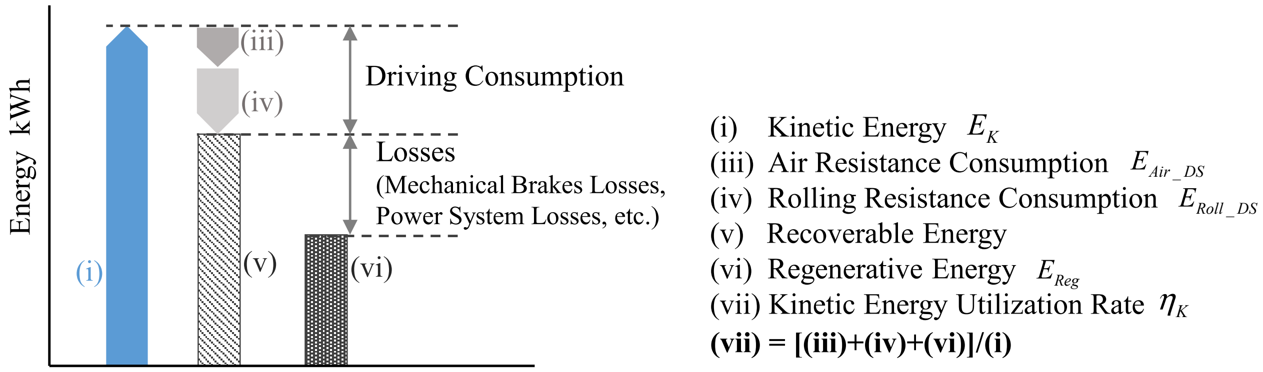


Figure 7. Definition of power energy usage rate when decelerating the vehicle (on flat roads).

It is shown below:

$$\eta_K = \frac{E_{Air\_DS} + E_{Roll\_DS} + E_{Reg\_K}}{E_K} \quad (10)$$

Here,

E_K Operational energy possessed at the start of deceleration [J];
E_{Air_DS} Air resistance consumed energy (deceleration interval) [J];
E_{Roll_DS} Rolling resistance consumed energy (deceleration interval) [J];
E_{Reg_K} Deceleration regenerative energy [J].

For ease of calculation, if we include the power system loss, etc., in the mechanical brake consumption, the mechanical brake consumption E_{Mech} based on the same figure is

$$E_{Mech} = \frac{1}{\eta_G \eta_{Mot}} E_K - (E_{Air\_DS} + E_{Roll\_DS} + E_{Reg\_K}) = \left(\frac{1}{\eta_G \eta_{Mot}} - \eta_K\right)(m_{Car} + m_{Pas} + m_{Rot}) a X_{AS} \quad (11)$$

When deriving the above formula, the relationship of

$$E_K = (m_{Car} + m_{Pas} + m_{Rot}) a X_{AS},\ a = \frac{V_{Max}}{T_{AS}} = \frac{\boldsymbol{n}\boldsymbol{V}^2}{250(1-\boldsymbol{\alpha})^2} \quad (12)$$

Here,

m_{Rot} Equivalent inertial weight [kg];
X_{AS} Driving distance (acceleration interval) [m];
α Acceleration (acceleration interval) [m/s^2].

Finally, there is the auxiliary equipment consumed energy term, which is

$$E_{Aux} = P_{Aux} T_0 \quad (13)$$

The final electricity consumption prediction formula is

$$EC = \frac{1}{\eta_G \eta_{Mot}}[\rho A C_d \frac{\boldsymbol{V}^2}{(1-\boldsymbol{\alpha})^2} + C_r(m_{Car} + m_{Pas})g] + (\frac{1}{\eta_G \eta_{Mot}} - \eta_K)(m_{Car} + m_{Pas} + m_{Rot})\frac{\boldsymbol{n}\boldsymbol{V}^2}{500(1-\boldsymbol{\alpha})^2} + \frac{P_{Aux}}{\boldsymbol{V}} \quad (14)$$

This formula is a "medium accuracy method" electricity consumption prediction formula.

3.3. Construction of a Formula When Accelerating/Decelerating on Gradient Roads

In the previous section, we constructed an electricity consumption prediction theoretical formula that assumed starting, accelerating/decelerating, and stopping on flat roads. In this section, to create a formula with a higher level of prediction accuracy, we shall add simple monitoring of situations where there is positional energy changes associated with uphill and downhill driving to the formula. Specifically, we shall consider ways to substitute the effect of gradient change with the gained uphill/downhill elevation.

Naturally, the increased positional energy amount becomes electricity consumption on uphill roads. If we consider power system efficiency, this becomes

$$E_{Up} = \frac{1}{\eta_G \eta_{Mot}}(m_{Car} + m_{Pas})g\sum h^+ \quad (15)$$

Here,

E_{Up} Consumption of positional energy related to going uphill [J];
$\sum h^+$ Total uphill elevation [m].

Next, we looked at a downhill road. First, we define the positional energy utilization rate η_P by considering the same phenomenon as the kinetic energy utilization rate η_K, as introduced in the previous section. As shown in Figure 8, this value is the ratio of (iii) air resistance consumption (effective use)/(iv) rolling resistance consumption (effective use)/(vi) regenerative energy to the (ii) position energy held at the start of the descent, which comprises the sum of the three. (To simplify the discussion here, rare cases of downhill driving, etc., are ignored.) As the same values are used, the reused amount (negative value) of the positional energy stored while driving uphill is

$$E_{Down} = \eta_P(m_{Car} + m_{Pas})g\sum h^- \quad (16)$$

Here, we have

E_{Down} Reused positional energy related to descent [J];
$\sum h^-$ Total downhill elevation [m] (negative value) [m].

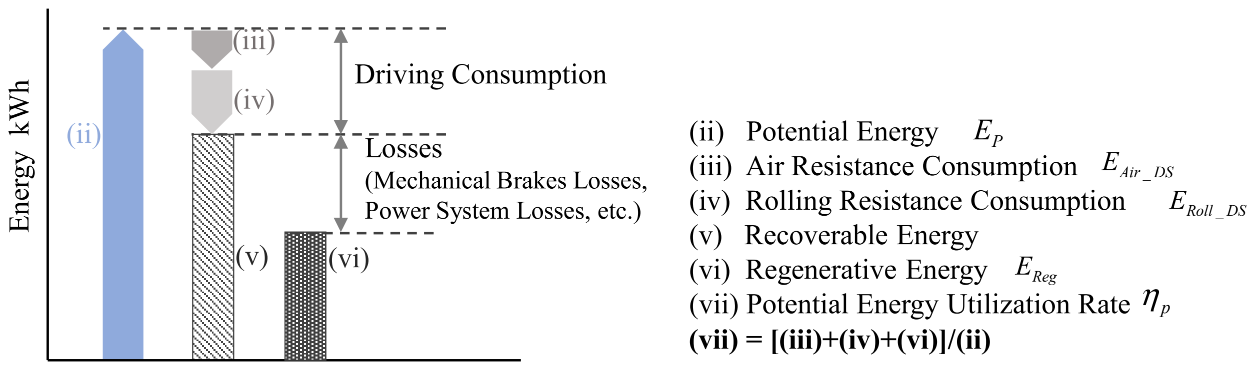


Figure 8. Definition of positional energy rate when driving downhill (cruise regenerative driving).

By summing the two terms described above, the electricity consumption amount change caused by the slope is derived as follows:

$$\Delta EC_{Slp} = \frac{E_{Up} + E_{Down}}{X} = (m_{Car} + m_{Pas})g(\frac{1}{\eta_G \eta_{Mot}} \frac{\sum \boldsymbol{h}^+}{\boldsymbol{X}} + \eta_P \frac{\sum \boldsymbol{h}^-}{\boldsymbol{X}}) \quad (17)$$

Here, we have

ΔEC_{Slp} Electricity consumption change amount when driving downhill [J/m];

$\frac{\sum \boldsymbol{h}^+}{\boldsymbol{X}}$ **Gained uphill elevation [m/m]** (Table 2 Route/operational indicators);

$\frac{\sum \boldsymbol{h}^-}{\boldsymbol{X}}$ **Gained downhill elevation (negative) [m/m]** (Table 2 Route/operational indicators).

By simply adding these formulas to the medium-accuracy method's cost prediction formula derived in the previous section, the following formula is finally achieved. The same formula is used as the cost prediction formula for the "high-accuracy method".

$$\begin{aligned} EC = {} & \frac{1}{\eta_G \eta_{Mot}}[\rho A C_d \frac{\boldsymbol{V}^2}{(1-\boldsymbol{\alpha})^2} + C_r(m_{Car} + m_{Pas})g] + (\frac{1}{\eta_G \eta_{Mot}} - \eta_K)(m_{Car} + m_{Pas} + m_{Rot})\frac{\boldsymbol{n}\boldsymbol{V}^2}{500(1-\boldsymbol{\alpha})^2} + \frac{P_{Aux}}{\boldsymbol{V}} \\ & + (m_{Car} + m_{Pas})g(\frac{1}{\eta_G \eta_{Mot}} \frac{\sum \boldsymbol{h}^+}{\boldsymbol{X}} + \eta_P \frac{\sum \boldsymbol{h}^-}{\boldsymbol{X}}) \end{aligned} \quad (18)$$

3.4. Application of the Formula to the Developed Vehicle and Verification of Its Accuracy

In this section, we apply the theoretical formula for predicting electricity consumption that we developed earlier to a developed electric bus running on an actual operational route, as was studied in a previous chapter. We also investigate the accuracy of this formula.

Regarding the electricity consumption prediction theoretical formula assuming constant velocity on flat roads (Formula (7)), accelerating/decelerating on flat roads (Formula (14)), and accelerating/decelerating on a slope (Formula (18)), the theoretical formulas for the subject vehicle obtained by substituting the various coefficients listed in Table 1 are summarized below:

$$EC = 0.00091\boldsymbol{V}^2 + 0.35 + \frac{0.17}{\boldsymbol{V}} \text{ [kWh/km]} \quad (19)$$

$$EC = \frac{0.0016\boldsymbol{V}^2}{(1-\boldsymbol{\alpha})^2} + 0.31 + \frac{(0.0052 - 0.0022)\boldsymbol{n}\boldsymbol{V}^2}{(1-\boldsymbol{\alpha})^2} + \frac{0.17}{\boldsymbol{V}} \text{ [kWh/km]} \quad (20)$$

$$EC = \frac{0.0016\boldsymbol{V}^2}{(1-\boldsymbol{\alpha})^2} + 0.31 + \frac{(0.0052 - 0.0022)\boldsymbol{n}\boldsymbol{V}^2}{(1-\boldsymbol{\alpha})^2} + \frac{0.17}{\boldsymbol{V}} + (25 \cdot \frac{\sum \boldsymbol{h}^+}{\boldsymbol{X}} + 11 \cdot \frac{\sum \boldsymbol{h}^-}{\boldsymbol{X}}) \text{ [kWh/km]} \quad (21)$$

Here, based on driving results obtained until now, the power energy usage rate and positional energy usage rate were set to 60%. Here, the medium-accuracy method was obtained from Formula (20) and the high-accuracy method was obtained from Formula (21). Next, as shown in Table 2 for Formula (21), the predicted electricity consumption obtained by inputting the road and the operational indicators for each route were enlisted in the previously discussed Table 3. The mean error when compared with actual measured values was found to be 5.5%, which is considered sufficient accuracy for practical use.

Figure 9 is a graph that can be used to confirm the differences between the actual measured values/calculated values from the vehicle electricity consumption simulator (studied in Section 2) and the values calculated using the constructed theoretical formula (Formula (21)). In the same figure, the continuous line of electricity consumption and the corrected continuous line of electricity consumption (derived using the same process as the previous chapter) for constant-velocity running on a flat road derived by Formula (19) are also compared with those obtained by the vehicle electricity consumption simulator. The generalized and simplified studies performed in this chapter (triangulation for generalization of velocity change, adoption of a strategy to substitute gained uphill/downhill elevation for gradient change, and adoption of a theoretical formula to simplify the modeling of electricity consumption prediction) were all considered to be appropriate.

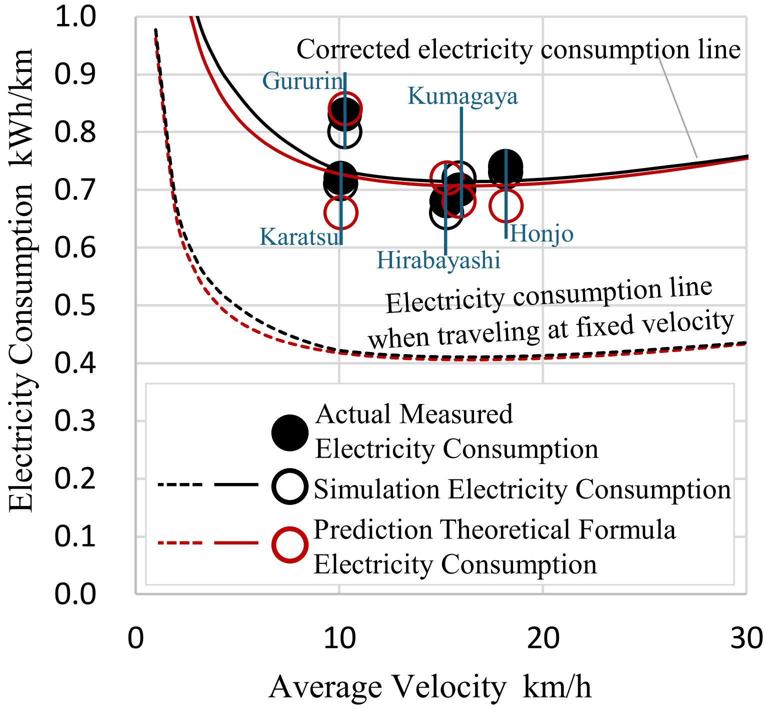


Figure 9. Derivation of various electricity consumption values using constructed formulas.

4. Discussion on the Appropriateness of a Simplified Method Using Only Average Velocity Information Using a Theoretical Formula

The simplified method we developed previously corrects the continuous line of electricity consumption of the vehicle at a constant velocity through the average of the deterioration rate of electric consumption over the five routes used in this study (introduction of a corrected continuous line of electricity consumption) and thus enables us to forecast electricity consumption only from average velocity information. In this chapter, we discuss the validity of our method using the cost prediction formula for the high-accuracy method developed previously. Additionally, even when driving at the same average velocity, the same high-accuracy formula can be used to predict the variation range of electricity consumption that can be expected in other areas with different road and operational conditions.

To prepare for this study, we first generalize the road/operational indicators (start/stop times, stop time ratio, and gained uphill/downhill elevation) and clarify the range of variation. To guarantee its accuracy, the target vehicles should be operated in a large number of regions and the distribution of these indicators should be determined before starting the study. However, as the main goal of this study is method establishment, only the information on the abovementioned five routes will be used.

The distribution status of the "start/stop times" indicator and the status of the "stop time ratio" are summarized in Figure 10a,b, respectively. Given the average velocity dependence of the two values, usually they have a negative first-order correlation [24], and the same tendency can be read from the information on the five aforementioned routes.

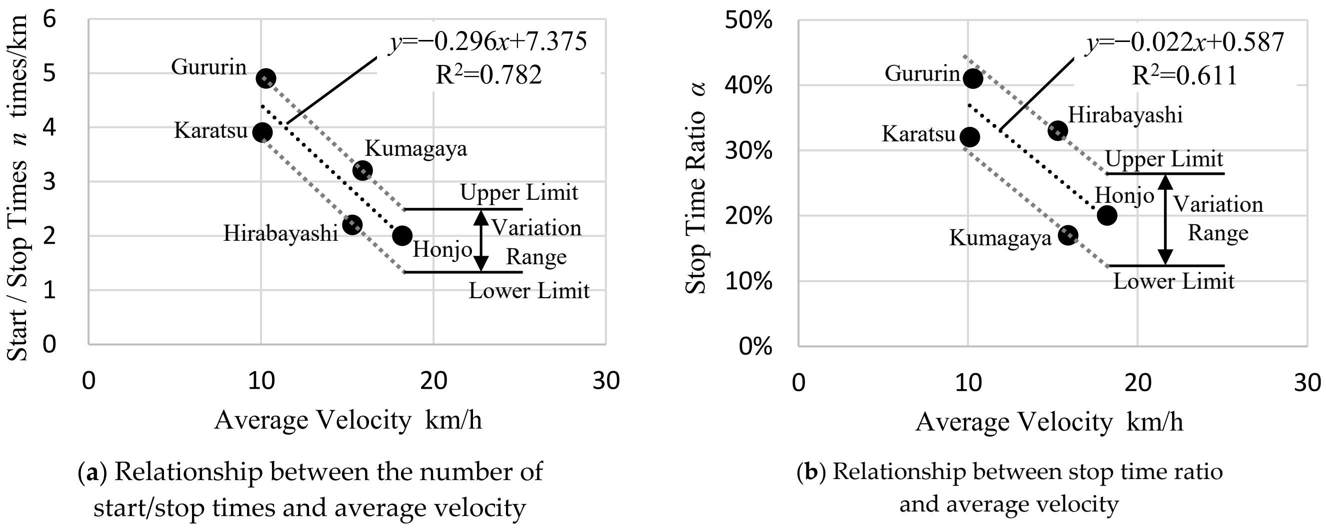


Figure 10. Generalization of road/operational indicators and clarification of the variation range during WEB-3 actual operation.

Additionally, from the same figure, estimates of the upper and lower limits for each average velocity for both values, that is, the variation range of the indicators assumed when operating, can be predicted to a certain extent. Given the fact there is no average velocity dependence for the gained uphill/downhill elevation, the variation range discussed below is from the highest to the lowest value of the information in Table 2 (6.5–1.8 m/km).

Next, in the same way as the previous study, we took the Nagano–Gururin route and the Saga–Karatsu route to be traveling at virtually constant velocity for our example routes, and we discussed in detail based on this. Figure 11 is an expansion of the area around an average velocity of 10 km/h in Figure 9. As mentioned above, the electricity consumption value based on the prediction theoretical formula (high-accuracy method) is obtained by substituting the road and operation indicators for each route into Formula (22), and the following equation is used to calculate the electric cost value. This value is obtained by substituting the road/operational indicators for each route into Formula (22).

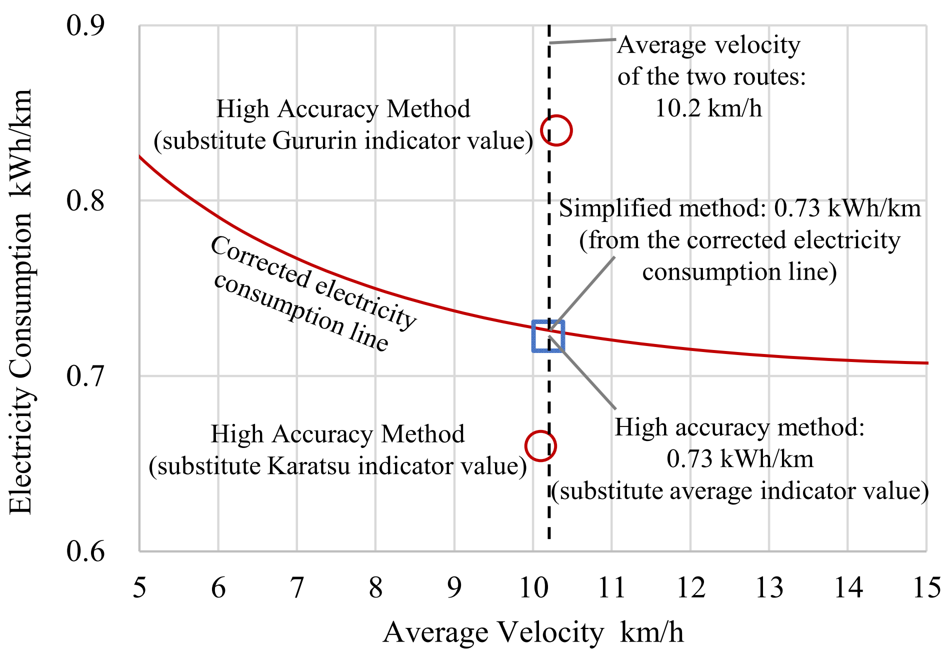


Figure 11. Study using the high-accuracy method regarding the electricity consumption values derived from the simplified method.

The electricity consumption value (high-accuracy method), as previously described, was obtained by substituting the respective road/operational indicators for each route into Formula (22) (Gururin: 0.84 kWh/km, Karatsu: 0.66 kWh/km) and was found to be 0.73 kWh/km by the simplified method by taking the value on the corrected electricity consumption continuous line. The ideal situation would be obtained if the latter electricity consumption values were representative of the consumption values obtained under the standard road and operating conditions at the same average velocity. Hence, to confirm this situation, we compared the average values of the indicators for the five routes in this study to the consumption values obtained by substituting the average values into the same equation. The electricity consumption value using the same method was 0.72 kWh/km, achieving a good match with the value obtained from the simplified method. This suggests that the electricity consumption values obtained for the average state of the five roads and operations are equivalent to those obtained by the simplified method, thereby demonstrating the utility of the method.

Next, we tried to predict the range of electricity consumption values that would occur in the case of operation in other regions with similar average velocity but where the road and operating conditions were different. Specifically, we first derived the best and worst values for electricity consumption obtained in Formula (22) and then arbitrarily moved the values within the variation range of each of the indicators assumed from the results of the previous study, as shown in Figure 10. Figure 12 shows the results of the study for the three average velocity groups (Gururin and Karatsu routes, Kumagaya and Hirabayashi routes, and Honjo route). The variation range is distributed almost symmetrically in the upward and downward directions of the electricity consumption values obtained from the corrected electricity consumption continuous line; thus, this can be considered appropriate. Furthermore, this range matches that of the maximum error range expected when using the simplified method.

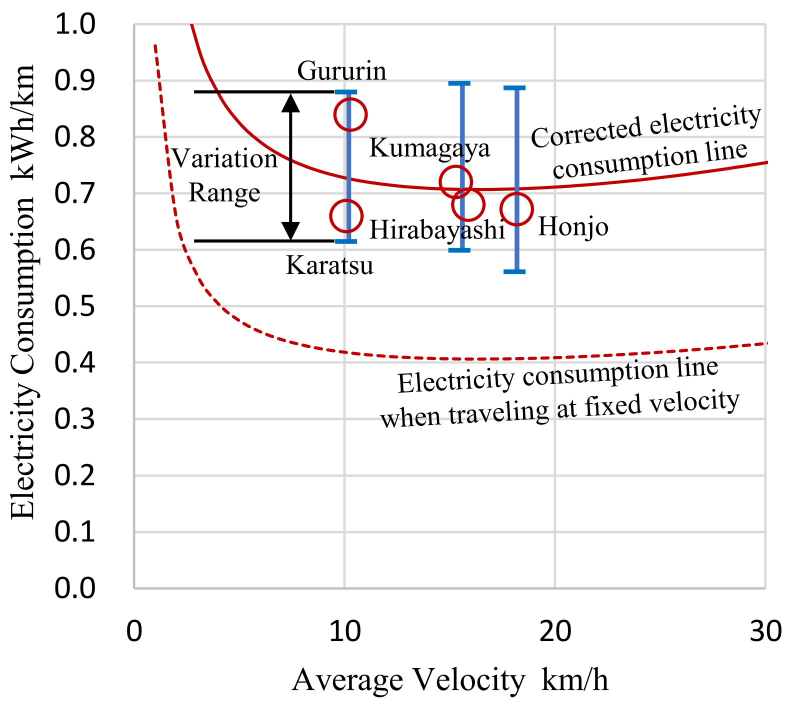


Figure 12. Prediction of the range of expected electricity consumption variation when driving in other regions with different road and operational conditions.

Therefore, a simplified method can be used to obtain approximate values for electricity consumption prediction provided that road/operational indicators do not deviate considerably from the standard ones. However, when predicting electricity consumption for routes with specific values for the start/stop times, the stop time ratio, and the gained uphill/downhill elevation, it is preferable to use medium- or high-accuracy methods once the necessary information has been achieved.

5. Summary

In this study, we have developed a range of methods that enable operators to easily predict the electricity consumption of electric buses and trucks to be introduced on new routes. This is achieved using only basic information on the planned routes and operation methods.

First, we have constructed a simplified method. This is a method that uses only one type of road and an operational indicator (average velocity) to make a power cost prediction. This is based on the power consumption of the vehicle that is planned to be introduced when driving at a constant velocity on a flat road. The approach considers the effects of acceleration/deceleration and uphill/downhill driving that occurs during actual operation by multiplying the "power cost deterioration rate" by the power cost. We discussed the reasonability of the method based on the theoretical formula using a separately developed high-accuracy method. It was pointed out that approximate electricity consumption values can be obtained for routes where road/operational indicators do not deviate substantially from the standard ones.

Next, we have developed a medium-accuracy method. It is capable of predicting electricity consumption based on three types of road/operational indicators (average velocity, start/stop times, and stop time ratio) while assuming triangular-wave velocity changes. Notably, the same formula should be used after additional information on the operational status of the proposed installation site is obtained from the operator.

Finally, we have constructed a high-accuracy method. This is based on the medium-accuracy method and is capable of predicting electricity consumption using four types of road/operational indicators, with gained uphill/downhill elevation. Moreover, the appropriateness and validity of the method are verified based on the electricity consumption prediction simulator and actual measurements using the test vehicle.

In this study, the WEB-3 electric bus developed by our research group have been used as a specific example for a wide variety of studies. Notably, the equations and methods developed here can be applied to other electric vehicles if the relevant constants that are used are replaced. Herein, we have attempted to develop a method based on information from only five routes that have been operated in advance. However, in the future, we plan to increase the sample size to better align with the diverse operational conditions in different regions. Additionally, regarding future directions for this research, we believe that a more detailed discussion on the calculation method for kinetic energy recovery could be beneficial. Kinetic energy recovery significantly impacts the energy consumption of electric vehicles. The medium-accuracy and high-accuracy formulas we proposed consider kinetic energy recovery at a certain ratio based on measured data. However, to improve the accuracy of electricity cost predictions for different vehicles, adopting varying ratios for different vehicle types or establishing new calculation terms for kinetic energy recovery based on the braking system could be effective. Of course, detailed calculations for kinetic energy recovery might become complex, and balancing the complexity of the formulas with prediction accuracy will be key when developing new calculation terms for kinetic energy recovery.

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References

1. Lacal Arantegui, R.; Jäger-Waldau, A. Photovoltaics and wind status in the European Union after the Paris Agreement. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2460–2471. [CrossRef]
2. Foley, A.; Smyth, B.M.; Pukšec, T.; Markovska, N.; Duić, N. A review of developments in technologies and research that have had a direct measurable impact on sustainability considering the Paris agreement on climate change. *Renew. Sustain. Energy Rev.* **2017**, *68*, 835–839. [CrossRef]
3. 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]
4. Alshehry, A.S.; Belloumi, M. Study of the environmental Kuznets curve for transport carbon dioxide emissions in Saudi Arabia. *Renew. Sustain. Energy Rev.* **2017**, *75*, 1339–1347. [CrossRef]
5. United Nations. Summary of the Paris Agreement. Available online: http://bigpicture.unfccc.int/#content-the-parisagreemen (accessed on 9 January 2025).
6. United Nations. Paris Agreement—Status of Ratification. Available online: http://unfccc.int/paris_agreement/items/9444.php (accessed on 9 January 2025).
7. Li, Z.; Fan, H.; Dong, S. Electric Vehicle Sales Forecasting Model Considering Green Premium: A Chinese Market-based Perspective. *arXiv* **2023**, arXiv:2302.13893.
8. Forsythe, C.R.; Gillingham, K.T.; Michalek, J.J.; Whitefoot, K.S. Technology advancement is driving electric vehicle adoption. *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2219396120. [CrossRef] [PubMed]
9. Jung, F.; Schröder, M.; Timme, M. Exponential adoption of battery electric cars. *PLoS ONE* **2023**, *18*, e0295692. [CrossRef] [PubMed]
10. Bryła, P.; Chatterjee, S.; Ciabiada-Bryła, B. Consumer Adoption of Electric Vehicles: A Systematic Literature Review. *Energies* **2023**, *16*, 205. [CrossRef]
11. World Resources Institute. Accelerating Electric Bus Adoption in Colombia. Available online: https://www.wri.org/initiatives/accelerating-electric-bus-adoption-colombia (accessed on 9 January 2025).
12. World Resources Institute. TUMI E-Bus Mission. Available online: https://www.wri.org/initiatives/tumi-e-bus-mission (accessed on 9 January 2025).
13. World Resources Institute. STATEMENT: EPA Makes Nearly $1 Billion in Funding Available for Clean Heavy-Duty Vehicles Including Electric School Buses and Trucks. Available online: https://www.wri.org/news/statement-epa-makes-nearly-1-billion-funding-available-clean-heavy-duty-vehicles-including (accessed on 9 January 2025).
14. Imoto, S. Electric Power Consumption Performance of Battery Electric Vehicles. *JARI Res. J.* **2019**, 1–4. https://img.jari.or.jp/v=1641526914/files/user/pdf/JRJ20190402_q.pdf (accessed on 10 January 2025).
15. Chen, Y.; Wu, G.; Sun, R.; Dubey, A.; Laszka, A.; Pugliese, P. A review and outlook of energy consumption estimation models for electric vehicles. *arXiv* **2020**, arXiv:2003.12873.
16. Nozawa, T.; Mimuro, T.; Takanashi, H. Electric Mileage Simulation for Introducing EV in Akita Prefecture. In Proceedings of the Tohoku Branch of the JSME, Sendai, Japan, 14 March 2014; Volume 49, pp. 165–166. [CrossRef]
17. Ansible Motion: Looking Down the Road: Harnessing the Benefits of Driving Simulator Technology. Available online: https://www.ansiblemotion.com/driving-simulator-technology-and-how-automotive-manufacturers-will-benefit#download (accessed on 9 January 2025).
18. Beck, J.; Huff, S.; Chakraborty, S. Diagnosing and Predicting Autonomous Vehicle Operational Safety Using Multiple Simulation Modalities and a Virtual Environment. *arXiv* **2024**, arXiv:2405.07981.

19. MathWorks, Vehicle Dynamics Blockset. Available online: https://www.mathworks.com/products/vehicle-dynamics.html (accessed on 9 January 2025).
20. Kyodo News Prwire, High-Frequency Wireless Electric Bus Cuts CO_2 by 40 to 60%. Available online: https://kyodonewsprwire.jp/release/201703220146 (accessed on 9 January 2025).
21. Hinkoji, R.; Inohae, T. Difference in User Satisfaction Factor and Construction of Satisfaction Model of Driving Environment for Cycling Route, -Case study of the main route of the Shimanami Kaido. *J. City Plan. Inst. Jpn.* **2021**, *56*. [CrossRef]
22. 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. [CrossRef]
23. Hyodo, T.; Watabe, D.; Hashimoto, T. Research Note on "Ecological Drive" for Electric Vehicle Based on Electricity Consumption. *Traffic Eng.* **2012**, *47*, 72–79.
24. Koyano, S.; Okamura, H.; Miyagi, M.; Kokuryo, K. *Reduction Effect of CO_2 by Idling Stop in the Case of Route Buses That Met New Exhaust Emission Regulations*; Annual Report of the Tokyo Metropolitan Research Institute for Environmental Protection; Tokyo Metropolitan Research Institute for Environmental Protection: Tokyo, Japan, 2009; pp. 76–85.