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Statistical Analyses on Actual EV Shuttle Operation Service Data

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Abstract: In this paper, a model for estimation of EV's electrical consumption is discussed using actual EV shuttle operation service data which was acquired over a period of 21 months. Specifically, the focus of this paper is on the shuttle operation service between our 2 campuses. As a result, it was found out that there were 2 routes depending on the time of the day (i.e., peak-hour or off-peak-hour), and the variance of the travel time between the 2 campuses. In addition, the characteristics of the travel time for each direction and route were defined. The relationship of exogenous factors (e.g. the use of air conditioner and temperature, etc.) from the collected data was also confirmed. Finally, a formula is proposed for estimating EV's electrical consumption using a multiple regression model, taking into account the relationship of the aforementioned exogenous factors.

Keywords: Electric Vehicle（EV）, EV's electrical consumption, route choice

1. INTRODUCTION

In Japan, it has been over 5 years since Electric Vehicles（EV）have entered the market in 2009. During this period, many research institutions and general publications introduced the traveling characteristics of EV. One of the major concerns is EV's electrical consumption, which determines the travel distance, and the analysis of the factors that affect electrical consumption. Although this research also analyzed the factors that affect EV's electrical consumption, longer term, more stable and same section trip data was used, in contrast to conventional researches. The aim of this paper is to propose a new perspective for the estimation of EV's electrical consumption.

2. REVIEW OF RELATED LITERATURE

Davis & Figliozzi (2013) developed a model that examined the competitiveness of the latest generation of electric delivery trucks by integrating four models: (1) a vehicle ownership cost minimization model, (2) a model to calculate the power consumption and maximum potential range of an electric or conventional truck as function of velocity and weight, (3) a continuous approximation model to estimate fleet size, distance travelled, and ensure that practical routing constraints, and (4) a method to estimate the additional energy needed to follow real-world travel speed profiles. Results show that route feasibility, minimum fleet size, distance travelled, battery life, purchase costs, and planning horizon are among the most significant factors affecting commercial electric vehicle competitiveness (Davis & Figliozzi, 2013). The model developed by Davis & Figliozzi (2013) is comprehensive; however, due to its comprehensiveness a large varying collection of data is necessary in order to successfully apply the model. Thus, in the event that accurate data is not available, certain assumptions may need to be made which may decrease the accuracy of the model.

Lorf *et al.,* (2013) analyzed the energy consumption and CO_2 emissions of 40 electric, plug-in hybrid electric, hybrid electric and internal combustion engine vehicles using "tank-to-wheel" energy consumption as a reference unit in order to compare vehicles with varying power train types. The well-to-wheel and tank-to-wheel CO_2 emissions where also studied to determine the environmental impact of the participating vehicles. It was found that the vehicle's powertrain type has the largest impact on energy consumption and emissions. In this light, the new approach suggested in this paper tries to address the need for assumptions by estimating a model using actual EV shuttle operation service data.

Doucette & McCullcoch (2011) investigated the relative performance of high-speed flywheel (an emerging technology) against batteries and ultracapacitors as energy storage systems (ESS) in a fuel cell based hybrid electric vehicle (HEV). The comparative study was made on bases of cost and fuel economy. Computer models where employed to simulate a vehicle with a powertrain of a fuel cell based HEV and the results showed that when both cost and fuel economy are considered, high-speed flywheels are competitive with batteries and ultracapacitors as ESS (Doucette & McCullcoch, 2011). The potential of high-speed flywheel as ESS was revealed and the cost and fuel economy of different types of ESS and their relationship to their number (no. of units) and mass was also presented. However, given that only a simulation was conducted for the research, validation of the results is needed through data gathered from controlled experiments using actual fuel cell based HEVs. Likewise, Jeong & Oh (2002) conducted a comparative study of the fuel economy and life-cycle costs of a pure fuel cell vehicle as well as a fuel cell hybrid vehicle by establishing models for vehicle, fuel cells, battery and motor and simulated the overall design of the vehicles. The result suggested that with regards to fuel economy, the regenerative braking energy of a battery in a hybrid vehicle makes it more efficient. However, when the battery power is small, fuel economy decreases suggesting a need to determine an optimal battery size. On the other hand, it is possible to reduce the fuel cell cost through hybridization when the fuel cell cost is high (as is presently the case).

Hyodo *et al.* (2010) analyzed the EV's electrical consumption using an EV that was leased for research. It was proven that an EV's electrical consumption can be estimated accurately using a standard Geographical Positioning System (GPS) logger (Hyodo *et al.*, 2010). In addition, the unique eco driving style of an EV was determined and it was also demonstrated that the travelling characteristics of an EV can be evaluated by using it as probe car after test-driving it on Shin-Tomei Expressway (Hyodo *et al.,* 2013). It should be noted that the GPS logger used on the EV produces positional information with 1 second intervals. On the other hand, the battery consumption information acquired with 1 minute intervals by the EV itself was analyzed without considering other information that was gathered. Finally, the uniqueness of the new approach is that new factors are analyzed, which focuses on long-term actual travelling information, from actual EV Shuttle Operation Service Data that has been collected over a period of 4 years. Finally, given that most research on factors that influence fuel economy and life-cycle costs are experimental and theoretical (i.e. reliance on assumptions) as mentioned above, the estimated model in this paper introduces a new approach to forecasting the distance traveled per EV's electrical consumption (km/kWh) which is based on actual operational data. The new approach suggested in this paper is especially convenient and reliable compared to the research mentioned above because it allows forecasting for practical purposes.

3. THE CHARACTERISTICS OF ACTUAL EV SHUTTLE OPERATION SERVICE DATA

3.1 The Spec of EV and Actual EV Shuttle Operation Service Data

The electric vehicle (EV) used in this study is "i-MiEV" made by Mitsubishi Motors. The EV has come on the market in 2009, and the nominal travel distance of the EV in "10-15 mode", a Japanese standard test method, is 160km. It has 2 ways of charging its battery: first, is the "rapid charge" which uses a rapid charger, and second is the "normal charge" which uses a 200V or 100V plug from a standard home socket. The specification of the EV is shown in Table 1.

Table 1. Specification of the EV used in this study

Product name：i-MiEV(Mitsubishi Motors)
Weight：1,100kg
Battery size(Li-ion battery)：16kWh
Travel distance in 10・15 mode：160km

The EV used in this study has been used collectively for the purpose of basic research among many researchers in the university. The main use of the EV is for car sharing between Etchujima campus (Koto ward of Tokyo) and Shinagawa campus (Minato ward of Tokyo), so the usual users are determined and fixed. Also, long distance driving was performed a few times every year to analyze the EV's electrical consumption. The EV has also been used for a Shuttle Operation Service between the 2 campuses since 2012 by a driver from the university. Consequently, the number of times that the EV has been used has increased and therefore the distance traveled has become longer. As a result, the amount of data for analysis has increased dramatically (Figure 1, 2).

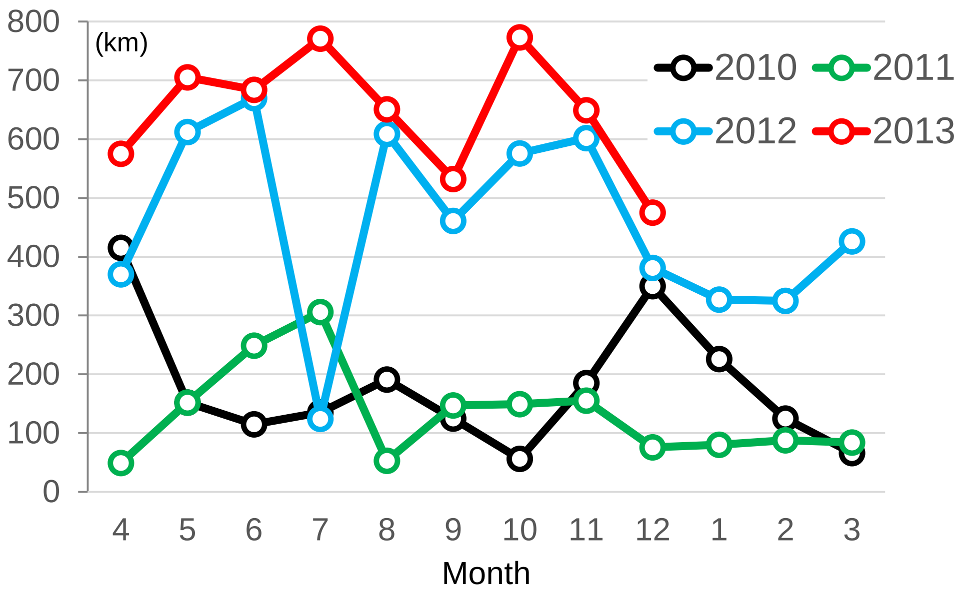

Figure 1. Comparison of travel distance per month, per year

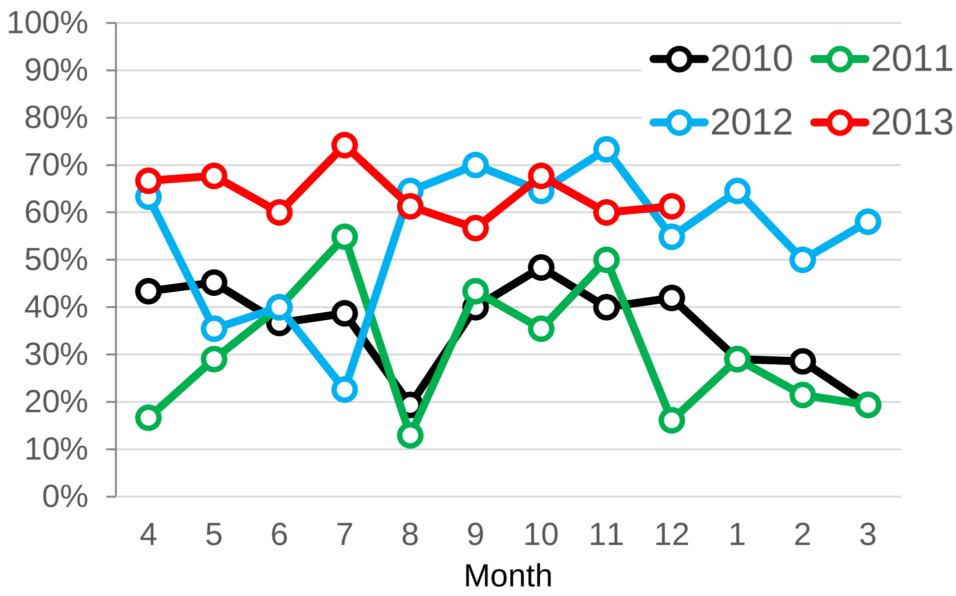

Figure 2. Usage rate per month

Thus, the analysis will start by focusing on the higher frequency EV's shuttle operation service data which was acquired for the same origin and destination.

The EV Shuttle Operation Service Data used in this study was acquired within a 21 month period between April 2 in 2012 and December 27 in 2013. The data was recorded every 1 minute, and consists of 37 data items such as the battery level, latitude, longitude, speed (max, average, and minimum speed every minute), outside temperature, distance traveled (i.e., measured by the odometer), use of the right/left winker, use of air conditioner (i.e., ON/OFF), drive shift (e.g., Drive, Ecology, Neutral etc.), the method of charging (i.e., rapid or normal), etc. The total number of data is 24,251 [minutes], and the total number of trips is 897 trips (1 trip is defined as one way between the 2 campuses).

3.2 The Characteristics of Actual EV Shuttle Operation Service Data

The route map of EV Shuttle Operation Service Data used in this study is shown in Figure 3. Based on the route map, there are 2 routes from Etchujima campus (Koto ward of Tokyo) to Shinagawa campus (Minato ward of Tokyo). According to Figure3, Route 1 is a straight line along a coastal road and Route 2 is a pass across Rainbow Bridge. Further, Table 2 shows an example of typical operation, which was recorded in the 2nd week of July, 2013. It shows the highest frequency of Shuttle Operation Service, and the graph represents a fixed departure time schedule. Based on the interview with the EV's driver, it was discovered that Route 2 was chosen during peak hours and Route 1 was chosen during off peak hours, depending on the time of the day and traffic conditions (e.g., traffic jams, traffic accidents, etc.).

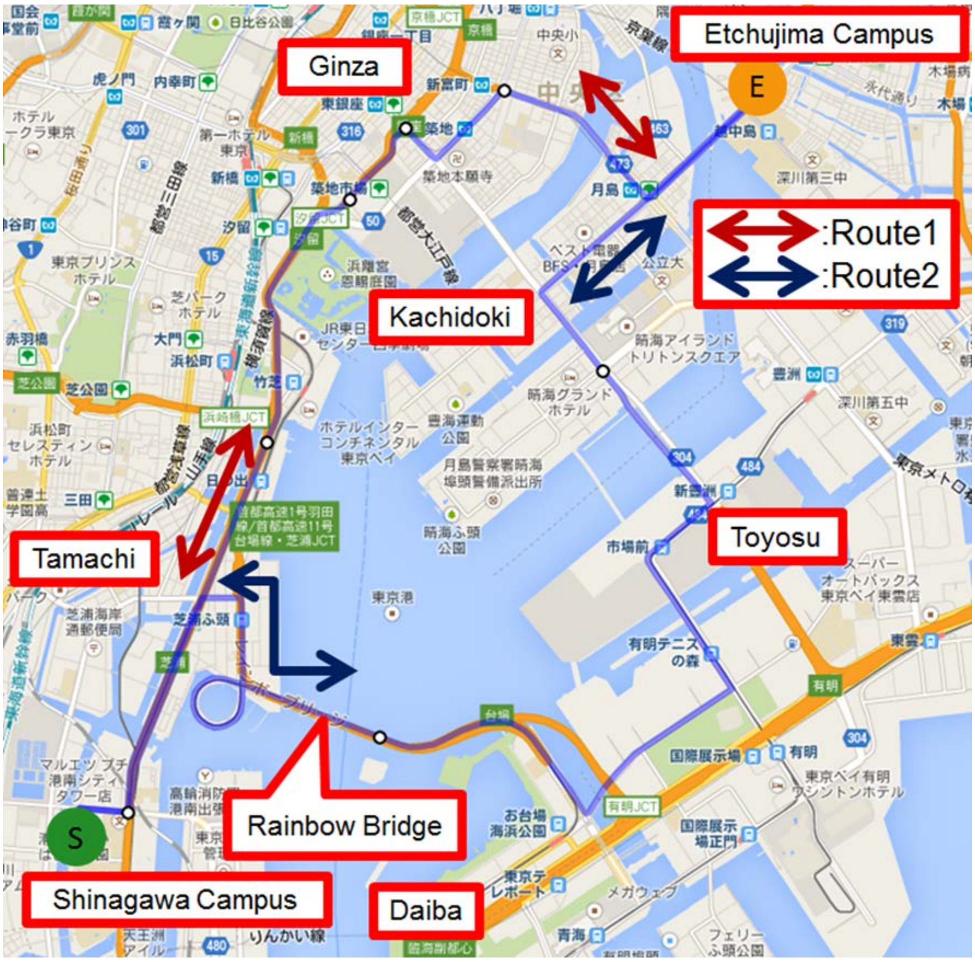

Figure 3. The route map of EV shuttle operation service

Table 2. Example of typical operation (2nd week of July, 2013)

Departure Time	Mon(2013.7/8)		Tue(2013.7/9)		Wed(2013.7/10)		Thu(2013.7/11)		Fri(2013.7/12)	
	Direction	Route	Direction	Route	Direction	Route	Direction	Route	Direction	Route
8:45	←	2	←	2	←	1	←	2	←	2
11:00	→	1	→	1	→	1	→	1	→	2
12:45			←	1					←	1
13:00	←	1			←	1	←	1		
13:27									→	2
13:54									←	2
16:30	→	1	→	2	→	2	→	1	→	2
					←	To Shinagawa		→	To Etchujima	

3.3 The Utilization Characteristic of EV

The Actual EV Shuttle Operation Service Data used in this study is characterized as long term, stable and OD trip data. Therefore, the data can cover the factors that affect EV's electrical consumption (e.g., outside temperature, use of light, etc.) in addition to normal traveling characteristics (e.g., acceleration, deceleration, etc.).

At first, to understand the utilization characteristic of EV, the usage ratios of air conditioner and light were calculated from a total of 24,251 [minutes] samples. Figure 4 shows that air conditioner is often used in summer. However, in this study, "air conditioner" means only the usage of cooler, not heater.

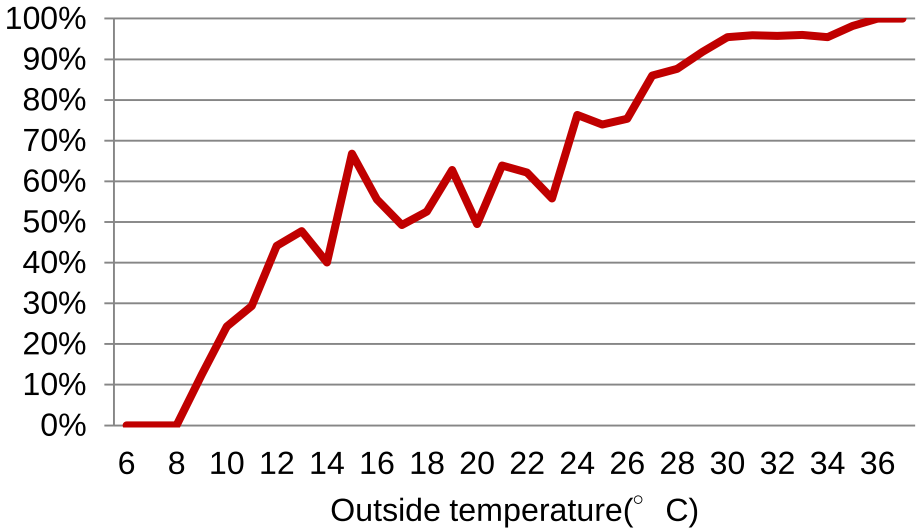

Figure 4. Rate of air conditioner usage

Also, Figure 5 shows that lights are often used starting from 16:00~17:00 during fall and winter due to the fact that it gets dark earlier in japan.

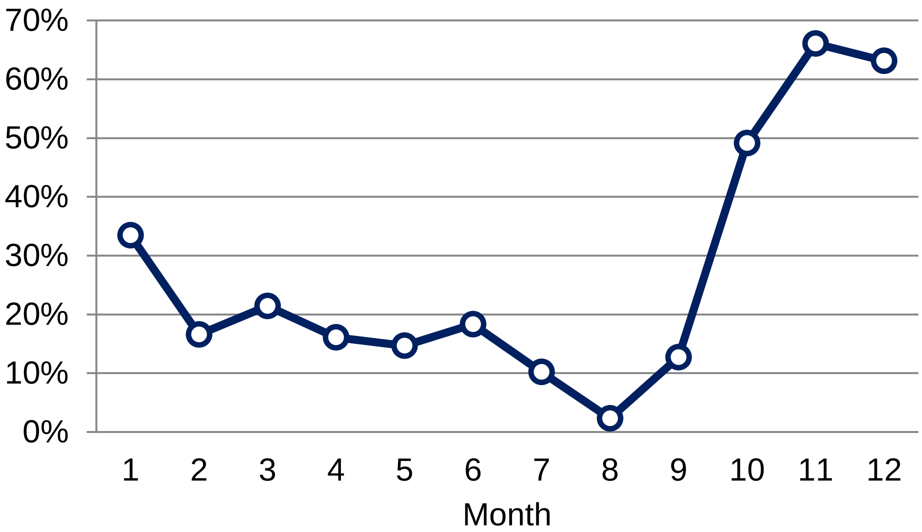

Figure 5. Rate of lights usage (during 16:00~17:00)

3.4 Analysis of the Characteristics of Travel Time

According to Figure 3 and Table 2, there are 4 patterns of EV Shuttle Operation Service, as follows:

1. From Etchujima campus to Shinagawa campus (Departure time; 8:45)
2. From Shinagawa campus to Etchujima campus (Departure time; 11:00)
3. From Etchujima campus to Shinagawa campus (Departure time; 13:00)
4. From Shinagawa campus to Etchujima campus (Departure time; 16:30)

Also, there are 8 cases of EV Shuttle Operation Service (4 patterns times 2 routes). To consider the reliability of travel time, the distribution of travel time of the 8 cases is shown in Figure 6.

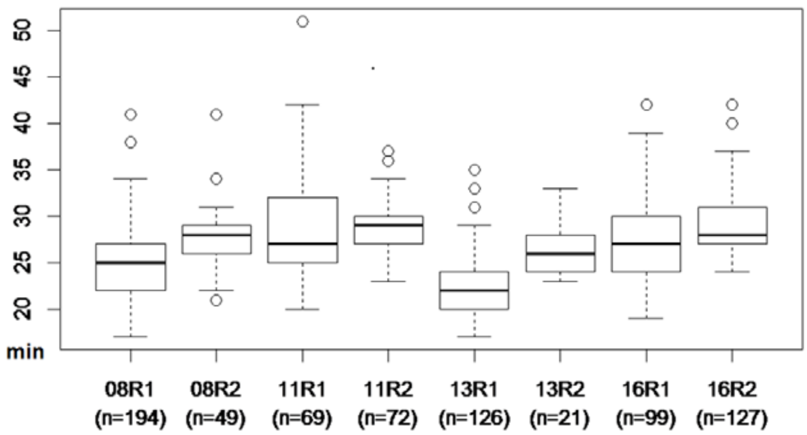

Figure 6. Boxplot of the distribution of travel time of the 8 cases
(Example: "08R1" is departure time 8:00, using Route 1)

As a result, it was confirmed that Route 2 is more often chosen in the late afternoon than Route1, and the dispersion of Route 2's travel time is smaller than Route 1's travel time. Thus, the EV's driver's route choice decision seems to be based on risk avoidance.

4. ESTIMATION OF EV'S ELECTRICAL CONSUMPTION MODEL

4.1 The Factors of EV's Electrical Consumption

EV's electrical consumption per distance traveled (kWh/km) can be estimated using the energy consumption equation with the speed and acceleration information that was calculated from the latitude and longitude information per 1 minute. However, the data used in this study which was recorded per 1 minute has speed information (i.e., max, average, and minimum speed every minute), but does not include acceleration information. Therefore, the relationship between the factors that affect the change of the speed and EV's electrical consumption is examined from a macro perspective of time.

More importantly, the data used in this study, that was acquired within a 21 month period, has enough factor diversity (e.g., use of light and air conditioner, etc.), to analyze possible relationships.

First, the characteristics of the speed information are considered. The distribution of the average speed and the maximum speed for a total of 24,251 minutes is shown in Figure 7. According to Figure 7, the frequency peak for the average speed is under 5 km/h, which shows that stops at traffic lights occurred quite often. Also, the frequency peak for the maximum speed is 60 km/h and the frequency of 0km/h is relatively low, which means that the EV was not often in traffic jams.

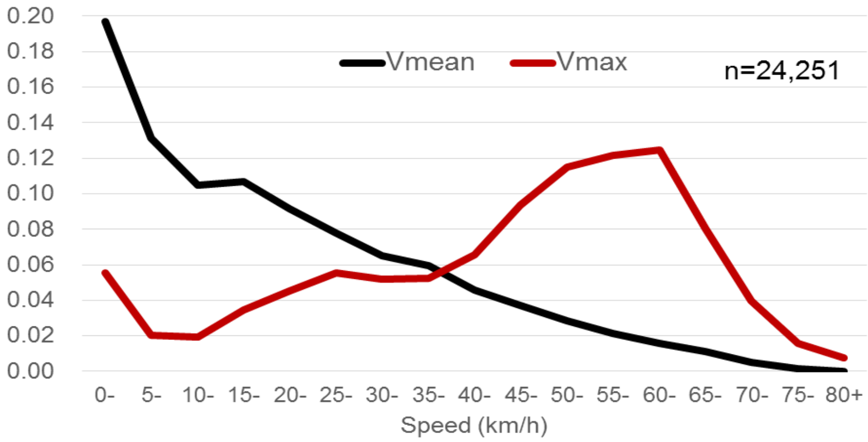

Figure 7. Distribution of Vmean (average speed) and Vmax (maximum speed)

The effect acceleration has on the energy consumption consists mostly of the influence of speed on the EV's electrical consumption. The gap between the maximum speed and the average speed (the minimum speed in the data is almost 0 km/h, so it is not considered) becomes bigger when the EV is accelerated. Also, when the EV travels at high speed, the EV's rate of electrical consumption efficiency, described in km/kWh becomes lower due to air resistance.

Considering the above, the 6 indices of the speed are shown as follows:

Max(Vmean) : maximum value of the average speed
Mean(Vmean) : mean value of the average speed
SD(Vmean) : standard deviation of the average speed
Max(Vmax) : maximum value of the maximum speed
Mean(Vmax) : mean value of the maximum speed
SD(Vmax) : standard deviation of the maximum speed

Starting to analyze the relationship between the speed and the EV's electrical consumption, first, their correlation is shown in Table 3. The correlation between the EV's electrical consumption and the mean value of the average speed is relatively high, but not sufficiently high. At this point, the correlation includes factors such as the use of light and air conditioner, but multiple regression analysis will be done in the next section to identify the influence of the use of light and air conditioner on the EV's electrical consumption.

Table 3. Correlation coefficient matrix of the relationship between the 6 indexes of the speed and the EV's electrical consumption

	1)	2)	3)	4)	5)	6)	7)	8)
1)Electrical consumption	1	0.025	0.237	0.079	-0.045	0.139	-0.159	-0.078
2)Max(Vmean)	0.025	1	0.695	0.879	0.760	0.525	0.366	0.315
3)Mean(Vmean)	0.237	0.695	1	0.765	0.584	0.857	0.062	0.251
4)SD(Vmean)	0.079	0.879	0.765	1	0.722	0.528	0.466	0.328
5)Max(Vmax)	-0.045	0.760	0.584	0.722	1	0.510	0.465	0.281
6)Mean(Vmax)	0.139	0.525	0.857	0.528	0.510	1	-0.131	0.376
7)SD(Vmax)	-0.159	0.366	0.062	0.466	0.465	-0.131	1	0.410
8)SD(Vmax-Vmean)	-0.078	0.315	0.251	0.328	0.281	0.376	0.410	1

4.2 Multiple Regression Analysis of EV's Electrical Consumption

Considering the determinant of EV's electrical consumption, there are 2 factors. Namely, speed and onboard device factors (e.g., light, air conditioner, etc.). Concerning the speed factor, the 6 indices of the speed shown in 4.1, are each used as the explanatory variable. When the 6 indices are used individually, Mean(Vmean), which is the mean value of the average speed, becomes the highest coefficient of determination among indices. Also, based on Mean(Vmean), when the other 5 indices were added, it was found that the combination of Mean(Vmax) and Mean(Vmean) produces the highest goodness of fit. In addition, since transformation of variable was applied to Mean(Vmax), the square root of Mean(Vmax) shows an even better fitness. As a result, Mean(Vmean) and Mean(Vmax) are used as parameters for multiple regression analysis.

On the other hand, the onboard device factor, specifically the factor of use of air conditioner, illustrates a cubic function. Generally, fuel consumption shows a non-linear, convex function in relation to outside temperature. The data used in this study does not have heater information. The use of air conditioner when the outside temperature is low seems to be primarily the use of the defrost function (it was considered in 3.3.). Therefore, when the air conditioner is not used, influence of heater needs to be considered. Thus, it is supposed that air conditioner use is illustrated by a cubic function, whereas heater use is illustrated by a linear function as follows:

$$U_a = \mathrm{AC} * (\beta_1 * t + \beta_2 * t^2 + \beta_3 * t^3) + (1 - AC) * \beta_4 * t \quad (1)$$

Where,

U_a: air conditioner usage,
AC: AC_ON (variable for turned on air conditioning),
t: outside temperature,
β_1,β_2,β_3,β_4: parameters.

First, the scatterplots of analyzed variables are shown in Figure 8. The peak of the EV's electrical consumption is 6 km. Different from Table 3, the correlation between the consumption and Mean(Vmean) is positive and the correlation between the consumption and Mean(Vmax) is negative.

The result of the multiple regression analysis is shown in Table 4. The effect of Mean(Vmax) is confirmed by comparing model 1 and model 3, also comparing model 2 and model 3, it is shown that a cubic function is more proper than a quadratic function for outside temperature when air conditioner is turned on.

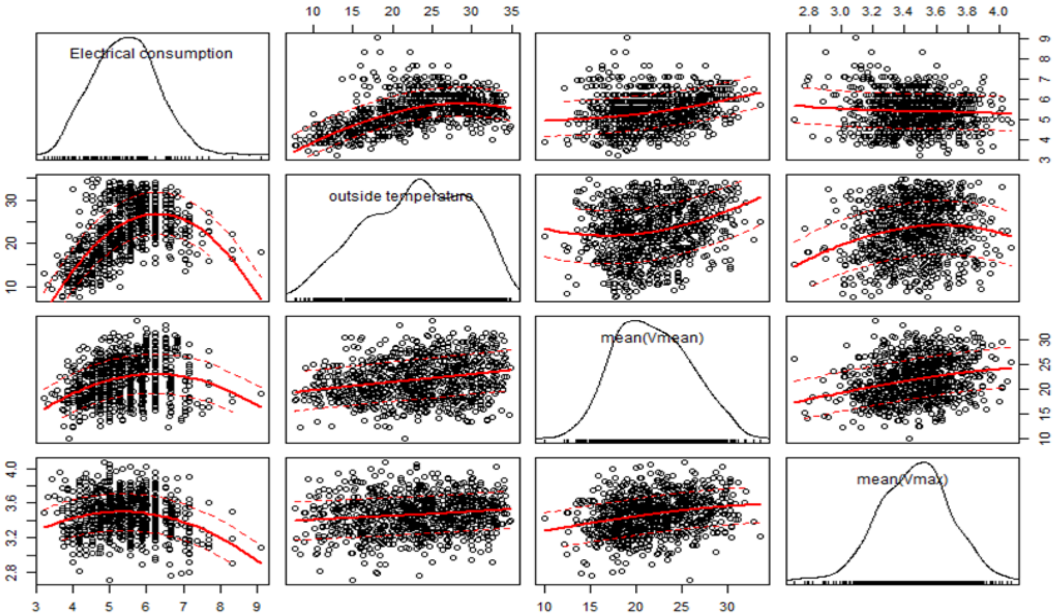

Figure 8. Scatter plot of the 2 speed indices, outside temperature and the EV’s electrical consumption

Table 4. Parameter estimation result of the multiple regression analysis

	model 1		model 2		model 3		model 4	
	parameter	t value	parameter	t value	parameter	t value	parameter	t value
R2 dummy	-0.4321	-6.5	-0.3738	-5.5	-0.4028	-6.2	-0.4108	-6.4
Rate of AC_ON×temp[℃]	-0.1923	-7.5	0.0205	2.5	-0.1919	-7.7	-0.2502	-10.8
Rate of AC_ON×temp[℃]^2	0.0145	7.3	-0.0026	-7.8	0.0145	7.5	0.0231	13.3
Rate of AC_ON×temp[℃]^3	-0.000322	-8.8			-0.000323	-9.0	-0.000442	-13.1
(1-Rate of AC_ON)×temp[℃]	0.1340	17.8	0.1579	22.1	0.1342	18.3		
(1-Rate of AC_ON)×temp[℃]×threshold D*							0.0734	18.9
Rate of lights usage	-0.3807	-3.8	-0.3983	-3.9	-0.4145	-4.3	-0.4146	-4.3
Mean(Vmean)	0.0673	8.9	0.0688	8.9	0.0729	9.9	0.0766	10.5
Mean(Vmax)$^{0.5}$			-0.6445	-6.5	-0.6480	-6.8	-0.6457	-6.8
Constant term	1.7850	8.8	3.4798	9.2	3.8810	10.6	5.1620	15.0
Adjusted R2	0.5033		0.4848		0.5274		0.5367	
Number of samples	897							

*"threshold D" is dummy variable. It takes value 0 under 15℃ or takes value 1 over 15℃.

At this point, the relationships between the EV’s electrical consumption and outside temperature when air conditioner is turned on, and between EV’s electrical consumption and outside temperature when air conditioner is turned off, will be reconfirmed. To achieve that, the effect of speed factor from the observation value of EV’s electrical consumption has to be removed. The residual value which shows that the constant term and the speed indices are removed from observation value of EV’s electrical consumption is shown in Figure 9. Also, samples when air conditioner is turned on and samples when air conditioner is turned off are shown separately in Figure 9. According to Figure 9, it is confirmed that the relation is illustrated by a cubic function when air conditioner is turned on, and a linear function when air conditioner is turned off and the EV’s rate of electrical consumption in km/kWh becomes high with the temperature in the range of 15°C to 23°C. Thus, when air conditioner is turned off, it is speculated that the range of heater’s influence remains the same as under constant temperature. Therefore, concerning the parameter “(1-AC_ON)×β_4 outside temperature”, the threshold of outside temperature is assumed, and the change of coefficient of determination within the range of 10°C to 20°C is tested. It is discovered that the multiple regression model acquired at the threshold of 15°C has the highest coefficient of determination, as shown in

Figure 10. Therefore, model 4 has the highest accuracy in this study.

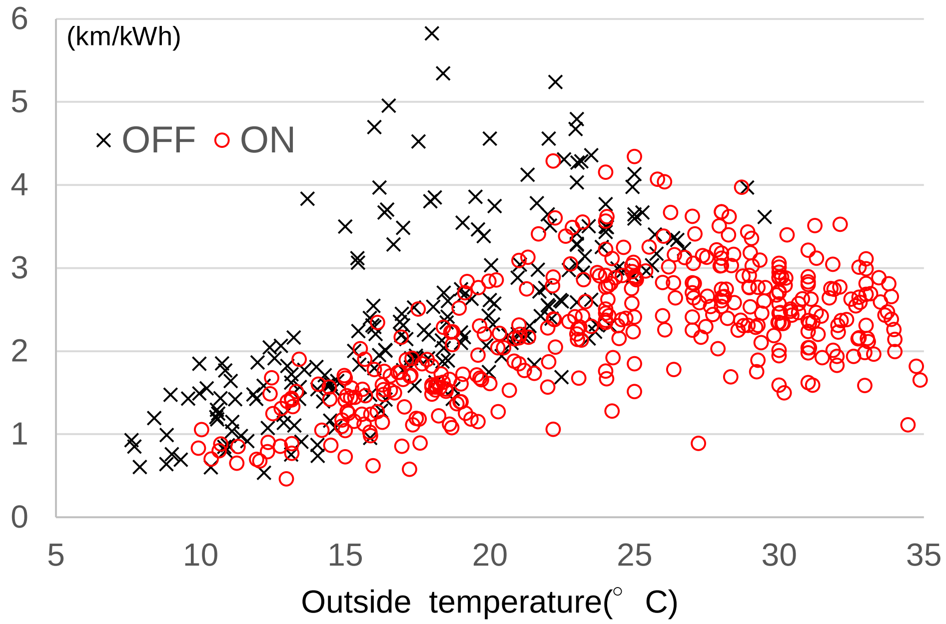

Figure 9. Scatter plot of relationship of EV's electrical consumption and air conditioner usage
(○: air conditioner ON; ×: air conditioner OFF)

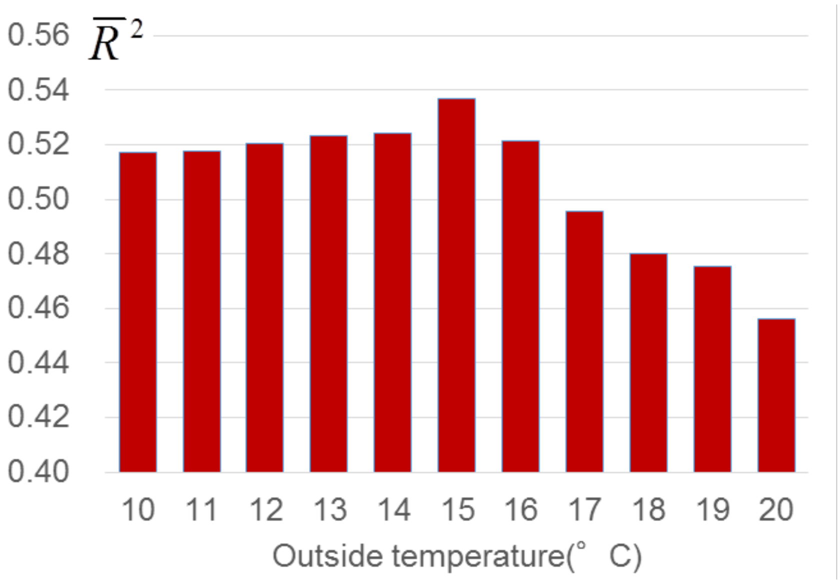

Figure 10. The coefficient of determination by threshold of outside temperature

To confirm the relationship between EV's electrical consumption and outside temperature based on model 4, the EV's average rate of electrical consumption in km/kWh was calculated using the average value of the explanatory variable of all trips, excluding the parameter of outside temperature.

Considering the parameter of outside temperature, the relationship between EV's electrical consumption and average outside temperature is shown in Figure 11. Since the parameter when air conditioner is turned on and the parameter when air conditioner is turned off are different, they are shown separately in Figure 11. According to Figure 11, the EV's rate of electrical consumption in km/kWh is highest when air conditioner is turned on, with outside temperature of around 28°C.

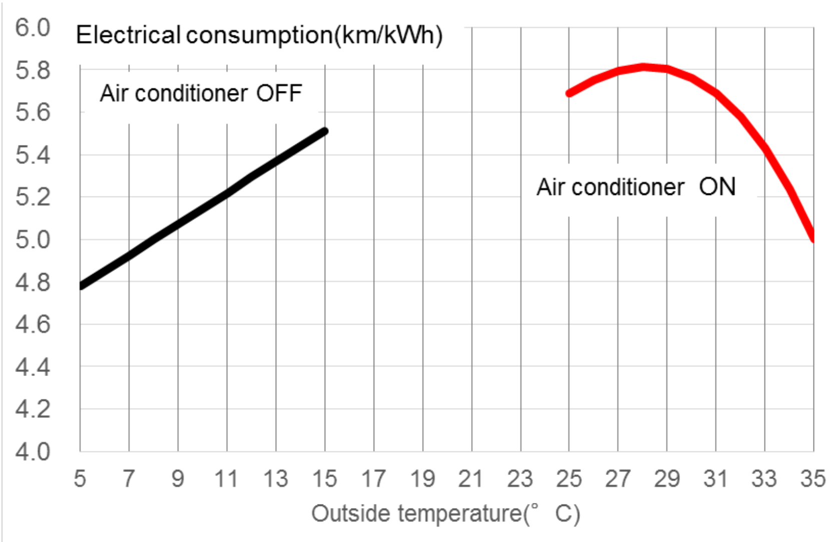

Figure 11. The relationship between EV's electrical consumption and average outside temperature

5. CONCLUSION

In this study, the influence of exogenous factors (i.e. the use of air conditioner and temperature, the use of light and time of the day and season) on EV's electrical consumption was analyzed.

The chief results are as follows:

1) The relationship between outside temperature and the distance traveled per EV's electrical consumption (km/kWh) becomes a non-linear cubic function at high temperature. It was also found that an EV's total electrical consumption during driving varies depending on the outside temperatures.

2) A formula that estimates EV's electrical consumption to a certain level intervals of accuracy can be found from the speed information of the data acquired with 1 minute intervals. For more accurate consumption model, GPS that can record longitude and latitude with 1 second accuracy is needed.

3) The distribution of travel time, which depends on directions and routes traversed by the EV, was illustrated from Actual EV Shuttle Operation Service Data. Based on this, it was confirmed that the route choice of EV's driver seems to be determined by the desire for risk avoidance.

According to 3), this study tried to formulate a route choice model as a behavioral model such as Logit model, but couldn't estimate it because of the difficulty of acquiring the required travel time of the route that was not chosen. As future steps, analysis of other information, observation of travel time from on-road devices, or the conduct of a Stated Preference (SP) survey can be considered.

6. POLICY IMPLICATIONS AND RECOMMENDATIONS

Based on the results of this research, the relationship between outside temperature and the distance traveled per electrical consumption was determined. This strengthens the understanding regarding the correlation between outside temperatures and an EV's total electrical consumption. Thus, this information can be used in the marketing and promotion of EVs specifically to demonstrate and explain to prospective EV users the benefits of using an EV. Further it can aid in making prospective EV users understand the mechanism of an EV.

Also, the resulting model/formula estimated using actual data may be used to forecast an EV's electrical consumption. This is especially important in estimating fuel economy and life-cycle costs which are important factors when analyzing characteristics of EV's.

Further, by being able to understand the factors that influence total electrical consumption of an EV (e.g., outside temperatures), optimal scheduling of EV operations for practical use such as shuttle operations may be done by considering such factors. Furthermore, by being able to understand the factors that affect distance traveled per EV's electrical consumption (km/kWh), the optimal allocation plan of EV chargers for EV systems such as EV sharing systems may be formulated.

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