Estimation of Energy Consumption Equation for Electric Vehicle and Its Implementation

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1. ABSTRACT

To realize a low-carbon society, electric vehicles are gathering more momentum. In recent years, products have advanced into the market. Therefore, the specific of electric vehicles' proper user market and the process of infrastructure construction like plug-in station etc. are drawing increasing attention. To discuss the measures and policies, the measurement of electric vehicles' mileage is an extremely important work because of the capacity of battery. And accurate estimating method of electrical consumption instead of fuel consumption is desired. Compared with gas vehicles, the energy demand mechanism of an electric vehicle is simple. So a new estimating formula differing from existing one is necessary. The positional measurement technology like GPS has evolved, the improvement of a higher capture accuracy of moving objects is expected, which is indispensable for the estimation of electrical consumption.

According to the background above, we discuss the estimating formula of electric vehicles' electrical consumption using actual data taken by a high accuracy positional measurement technology in this study.

Keywords: electric vehicle, energy consumption, expressway

2. Measurement condition of data

2.1 Parameters of the electric vehicle

The electric vehicle (EV) used in this study is "i-MiEV" made by Mitsubishi Motors. The parameters of the EV is shown in Table 1, the nominal travel distance in "10-15 mode", Japanese standard test method, is 160 km. In a simply calculation, the electric consumption is 10 km/kWh. But in a normal travel, there are more energy consumption factors which lead to a higher electric consumption. We discuss about the estimating formula in this study.

2.2 Measurement item

Considering the resolution and accuracy of location and time, we applied two kinds of measuring methods for a comparison examination[1] (Table 2). In Method 1, we used a compact sized GPS logger to measure the latitude, longitude and altitude by seconds. In Method 2, we use the RTK (Real Time Kinematic) – GPS device which is made by the satellite navigation engineering laboratory, Tokyo University of Marine Science and Technology. The RTK-GPS compares the GPS data with data taken by 1200 electronic reference points in Japan to estimate the location. With this method, we can get a high accuracy of location. And the accuracy (standard deviation) of it is about ten centimeters in all latitude, longitude and altitude. In contrast, the receiving condition of it is strict, effect of the buildings or trees, the correct location data cannot be taken in the measurement of moving object like an EV used in this study.

Table 1 Parameters of the EV used in this study

Product name: i-MiEV Weight: 1100kg Battery capacity: 16 kWh Travel distance in 10-15 mode: 160km

The Method 1 is more portable and convenient; the Method 2 is more accurate but more missing data. Considering all these characters, we discuss a proper estimate method of EV's location.

Table 2 Measuring methods of traveling path

Method	Content
1	Equipment: wbt-202 made by Wintec, measuring latitude, longitude and altitude in seconds, accuracy (S.D.) is around ten meters
2	Equipment: RTK-GPS made by the satellite navigation engineering laboratory, Tokyo University of Marine Science and Technology, measuring latitude, longitude and altitude in seconds, accuracy (S.D.) is around ten centimeters

3. Summary of the measurement result

The position data in this chapter is taken on March 15th, 2010 at a round trip from Etchujima campus of Tokyo University of Marine Science and Technology to Urayasu, Chiba prefecture where the electronic reference mark point is set. The travel time is about from 13:00 to 15:00, and the total travel distance is about 70 km. To define a clear relationship between travel conditions and electrical usage, the light and heater is not used. First, we consider the estimate method of location information (latitude, longitude and altitude).

3.1 The GPS measurement result

The travel data is taken during about 2.5 hours. 5,918 seconds data is recorded correctly by Method 2, RTK-GPS, in 8,941 seconds; the recording rate is about 66%. Because the GPS radio disturbance is especially notable for moving objects. In this analysis of location estimate, we choose a typical time zone (13:42'57" to 13:48'18", total 322 seconds) when almost all of the data is taken by all two methods, however, it includes few missing seconds by Method 2. The velocity records in this time zone are shown in Figure 1. And the velocity is calculated by the moving distance of latitude and longitude by second for two methods.

As shown in the figure, the data recorded by Method 2 is much smoother than by Method 1 without two seconds lost data. The high accuracy is confirmed. And for the two seconds' lost data, we use linear interpolation for the following analysis.

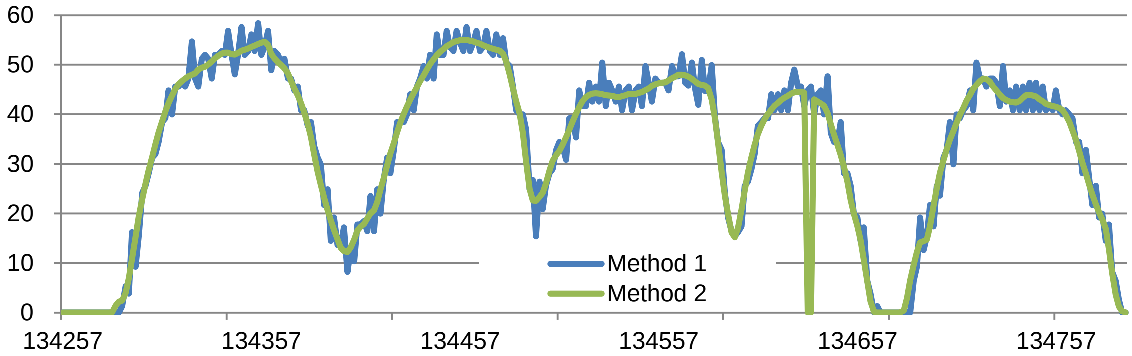

Figure 1 Comparison of the velocity measurement result in two methods
(Vertical axis: velocity [km/h]; horizontal axis: time [h m s])

3.2 The smoothing processing of GPS measurement result

As shown in Figure 1, since there is more than ten meters deviation in the GPS data by Method 1, compared to that by Method 2, a distinguished noise in the data of estimated velocity is observed. On the other way, although the accuracy of Method 2 is higher, acquisition probability is less than 66%. The data by Method 2 is not enough to meet the analysis purpose of this study which is to estimate the electrical usage of the entire travel. If there was a way to reduce the error in Method 1, the measurement taking advantage of the portability and high acquisition probability is possible. We can use the data by Method 2 with high accuracy to verify the data by Method 1. So we make a comparative review of the data after a smoothing process for Method 1 and the data directly taken by Method 2.

We use an algorithm of simple moving average. The moving average of *K* seconds on the time point *p* is shown as following equation. Since this is a centering moving average, the equation is different for odd K and even K.

$$MA(p,K) = \frac{\sum_{k=1}^{K} x_{p-(K+1)/2+k}}{K}, \qquad \text{if } K \text{ is odd} \qquad (1)$$

$$MA(p,K) = \frac{\dfrac{\sum_{k=1}^{K} x_{p-K/2+k}}{K} + \dfrac{\sum_{k=1}^{K} x_{p-K/2+k+1}}{K}}{2}, \qquad \text{if } K \text{ is even} \qquad (2)$$

We calculated the moving average of 3 seconds (MA(3)) to 9 seconds (MA(9)). The result of MA(3), MA(6) and MA(9) are shown in Figure 2.

From Figure 2, the error is not eliminated enough in MA(3) Method 1, by contraries, the change of real velocity is obtusely estimated in MA(9), an excess of effect is shown. Since the evaluation of a proper moving average interval is used for the estimating formula of electrical usage, we leave it to next chapter.

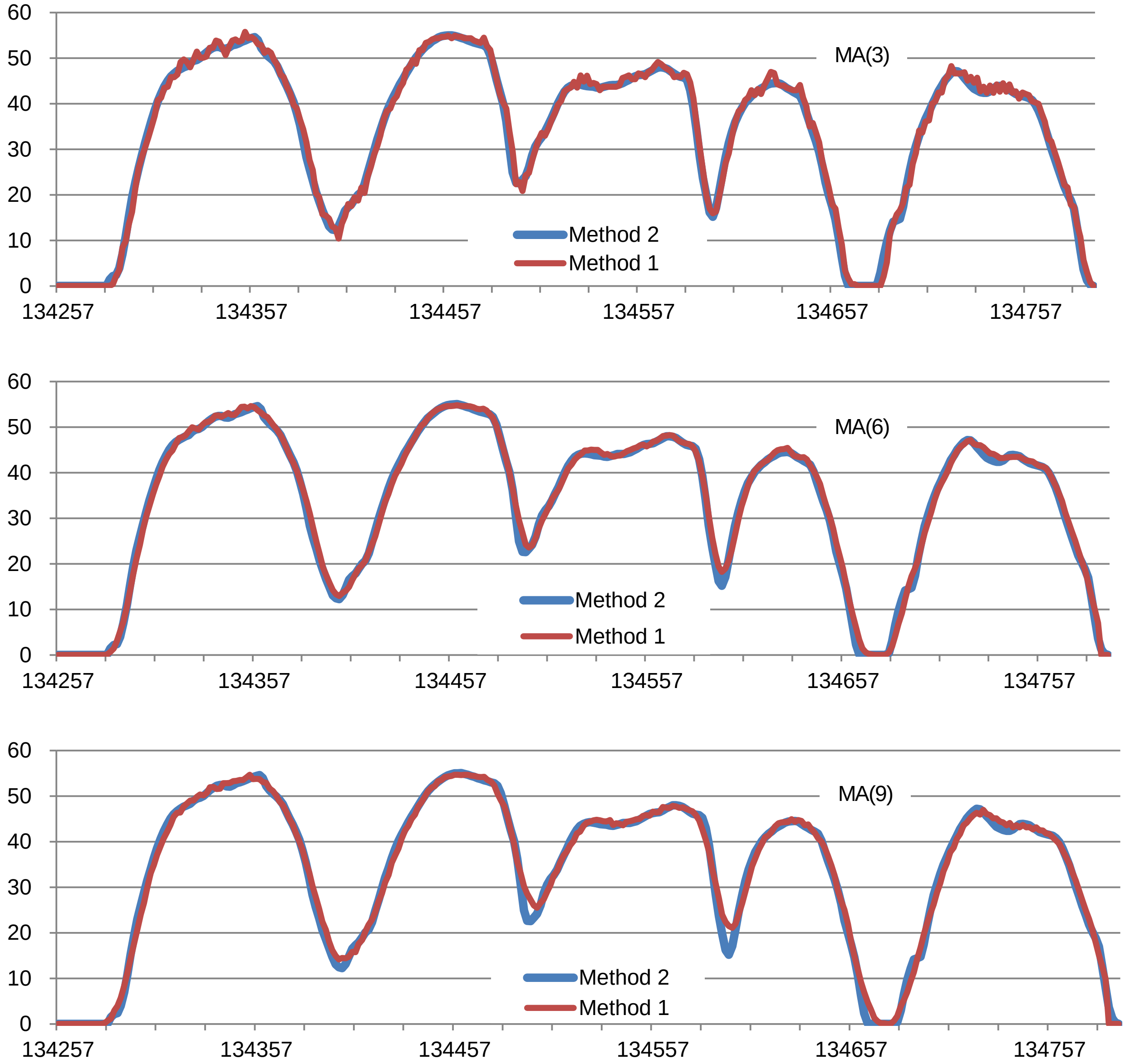

Figure 2 Comparison of velocity estimating result in moving average interval
(Vertical axis: velocity [km/h]; horizontal axis: time [h m s])

4. An estimating formula of electrical usage

4.1 The basic formula of energy consumption of vehicles

The estimating formula of fuel consumption of vehicles is proposed in many previous papers and texts [2),3)]. Here we use the conventional formula discussed by many researches. Specifically, the energy consumption consists of 1) accelerating resistance, 2) air resistance, 3) gradient resistance and 4) rolling resistance. The electric consumption in one second E_s [Ws] can be written like the following equation.

$$E_s = M \cdot v \cdot \alpha + \frac{1}{2}\rho \cdot C_D \cdot A \cdot v^3 + M \cdot g \cdot \Delta h + \tau \cdot M \cdot g \cdot v \tag{3}$$

M : mass [kg], v : velocity [m/s], α : acceleration [m/s^2], ρ : air density 1.24 [kg/m^3] (10℃), C_D : air resistance coefficient, A : projected area of the EV [m^2], g : G-forces 9.8 [m/s^2], Δh : difference of elevation in 1 second [m] (absolute value), τ : rolling resistance coefficient

Since the equivalent mass of rotation acceleration is unspecified in the formula, which is difficult to measure, we assume it is included in the adjustment parameter discussed after. And the gradient resistance is only considered for upward slope, for downward slope (Δh<0), we considered the gradient resistance to be zero. On the other hand, we consider the regeneration energy generated on the down-grade in the electrical consumption estimating formula, and it is discussed at chap. 5.

In Section 3.2 we use moving average formula as a proper estimating formula of velocity, and discuss about MA(3) to MA(9). As shown in the estimating formula of electrical usage, because of the measurement error of velocity in Method1 (Figure 1), the estimating error of accelerating resistance is large. As a result, the accelerating resistance is over estimated. So to value the moving average of velocity, we calculate the accelerating resistance by MA(0) to MA(9).

The result is shown in Figure 3. If we assume the data taken by Method 2 using RTK-GPS is true value, the result of MA(0) is 3.5 times to the true values. But after MA(6), the result becomes acceptable. In this paper, we use MA(6) in the following analysis.

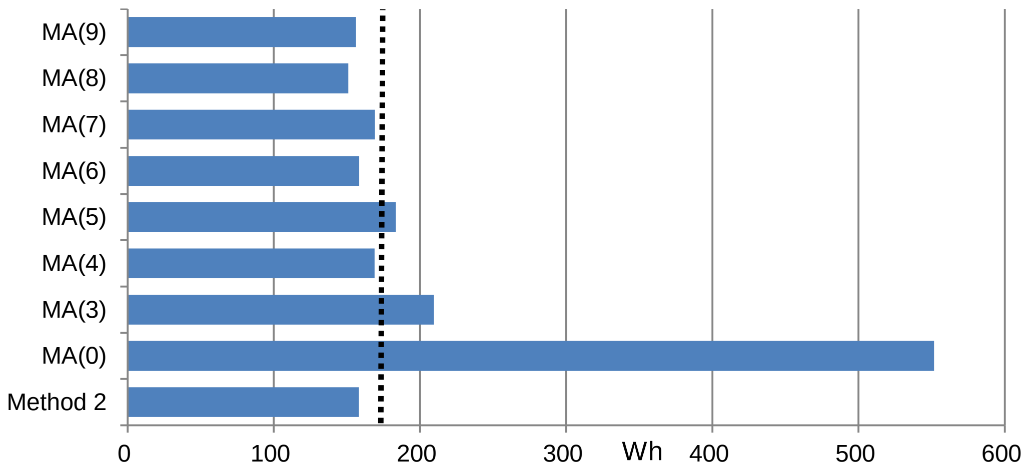

Figure 3 Estimated value of accelerating resistance in moving average interval

4.2 Comparison between the theoretical formula and observation result

Referring the parameters of EV, we set the parameters in the theoretical formula as follows:

M=1200［kg］, C_D=0.37, A=2.14［m^2］, τ =0.015

The value of C_D or A is published by Mitsubishi Motors, and a representative value of the rolling resistance coefficient for asphaltic pavement is used.

In the data used for this comparison taken on 28th Feb. 2010. On that day, we traveled from university to Makuhari and Urayasu. The positional data is only recorded by Method 1.

And the observation value of electrical usage, the CAN (Controller Area Network) data, is obtained using i-MiEV exclusive on-vehicle equipment. Since this data is recorded by minute, the result of the theoretical formula of electrical usage counted by seconds needs to be added up to minute. As the result, the observation value and estimated value in 131 minutes are obtained. First, substitute the velocity and acceleration using MA(6) into the theoretical formula of electrical usage indicated before, and the estimated results for the four resistance terms can be indicated in Figure 4. Because the altitude changed mightily, we use an average value in 9 seconds. From the result, the interval with a sharp inclination (49~62min, 103~123min), using expressway, a noticeable electrical usage caused by air resistance can be seen. During the traffic jam interval (25~50min), since the travel distance is small, energy consumption is almost zero.

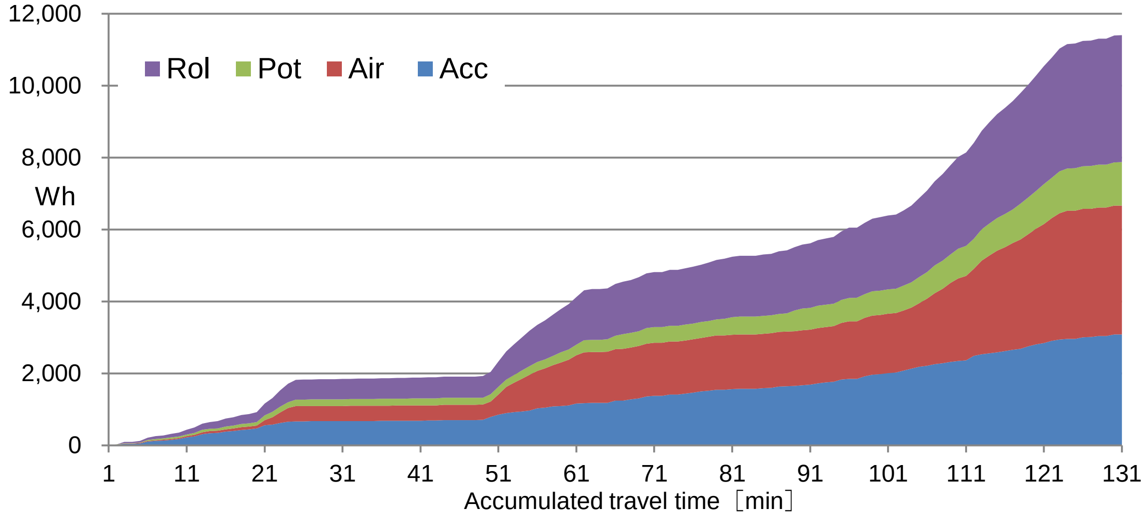

Figure 4　Estimated value of electrical consumption in terms

“Acc”: accelerating resistance, “Air”: air resistance, “Pot”: gradient resistance, “Rol”: rolling resistance

The same estimated value and observation value of electrical usage calculated by minute are shown in Figure 5. Since the observation value is by minute and the minimum recorded value is 80 Wh, the curve of observation value shown discretely. The observed error caused by this reason is inescapable.

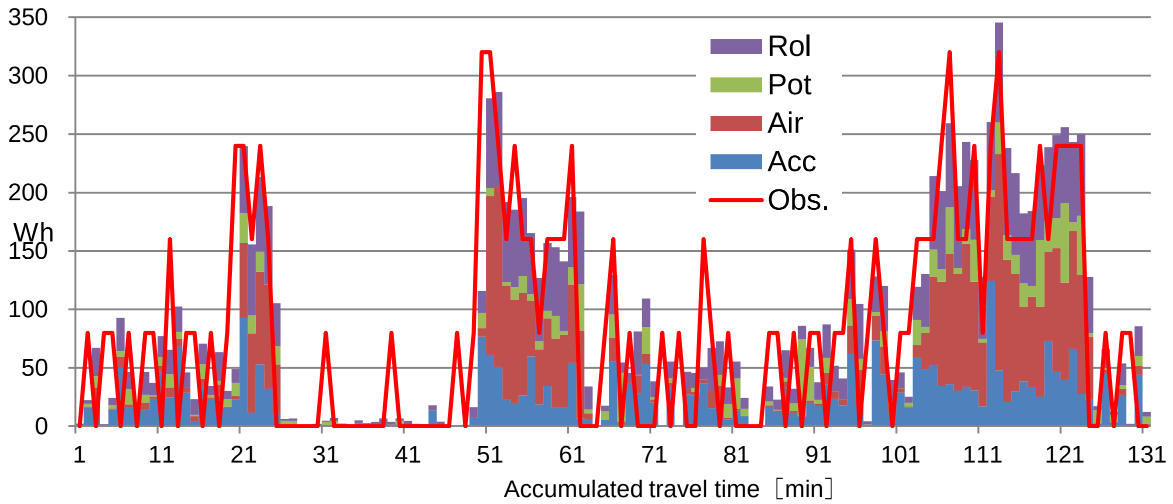

Figure 5　Comparison of estimated value and observation value of electrical consumption

Compare the estimated value and observation value calculated above by cumulative value in Figure 6. In this cumulative figure, the consumption of observation value is 11.2 KWh, which is almost same as the estimated value. But if we compared the value on expressway ((1) 20~24min, (2) 49~62min, (3) 103~123min), the estimated value in (1) and (2) is under estimated, and the estimated value in (3) is overestimated. For the same expressway travel, the difference of acceleration and deceleration frequency caused this results. And the total travel distance of this data is 72.3km; the average electrical consumption is estimated to be 6.5 km/kWh.

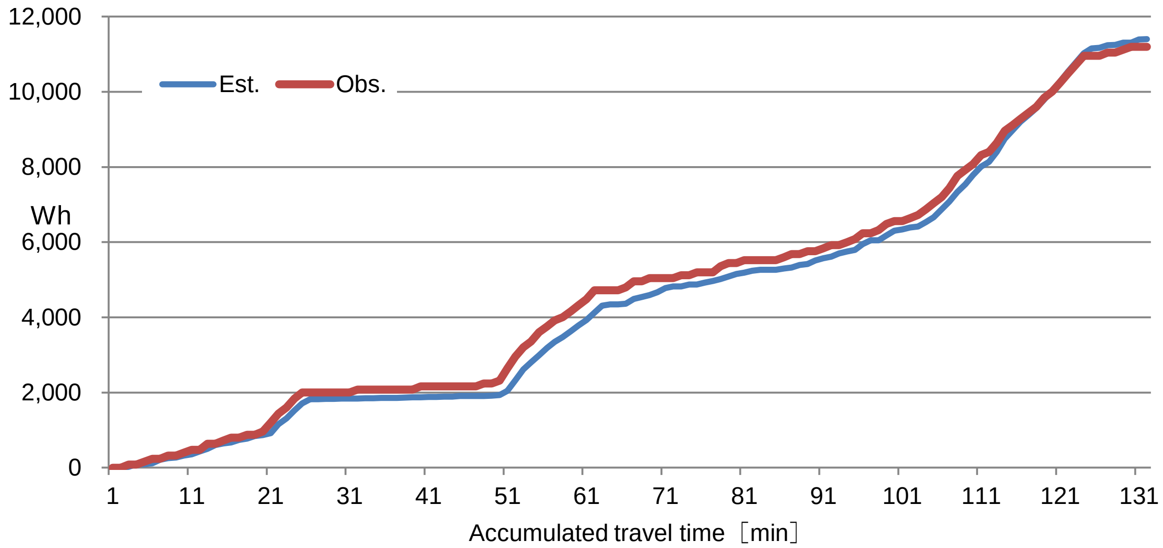

Figure 6　Accumulated electrical consumption

The correlation coefficient matrix of observation value and four resistance value is shown in Table 3. During the expressway travel, the correlation between the high air resistance, rolling resistance proportionated to velocity and observation value is high. The correlation between air resistance and rolling resistance is high because these two terms can be formulated by velocity variable.

Table 3　Correlation coefficient matrix of observation value and each term

	Obs.	Acc	Air	Pot	Rol
Observation value	1				
Accelerating resistance	0.595	1			
Air resistance	0.750	0.465	1		
Gradient resistance	0.402	0.262	0.433	1	
Rolling resistance	0.733	0.588	0.939	0.483	1

Since in the estimating formula defined in this study, “the equivalent mass of accelerate rotation” is not included in *M*, larger *M* should be used. And there are some undetermined factors in the air resistance term. To fit the observation value, we try to estimate the following correction coefficients using regression analysis.

$$E_s = \theta_1\left(X_1 + X_3 + X_4\right) + \theta_2 X_2 + \theta_0 \qquad (4)$$

X_1 : accelerating resistance, X_2 : air resistance, X_3 : gradient resistance, X_4 : rolling resistance

The estimated result is as follows（t-value in brackets）.

$E_s = 0.9661(X_1+X_3+X_4) + 0.8085X_2$　　Compensation formula 1　　(5)
(7.8)　　(4.1)　　R^2=0.7916

$E_s = 0.7545(X_1+X_3+X_4) + 0.9246X_2+15.16$　　Compensation formula 2　　(6)
(4.5)　　(4.5)　　(1.9)　　R^2=0.617

Since the observation value is discrete, the correction coefficient is below one, we use the moving average of both explanatory variables and explained variables in 3 minutes to estimate correction coefficient again.

$$E_s = 1.091(X_1+X_3+X_4) + 0.7000X_2 \quad \text{Compensation formula 3} \quad (7)$$
$$(14.0) \qquad (5.6) \qquad R^2=0.9295$$

A relatively good value is obtained. The result of cumulative electrical usage using these three correction coefficients is shown in Figure 7. Although the explanation of the constant term is not clear, the electrical usage estimation using compensation formula 3 is confirmed with enough accuracy.

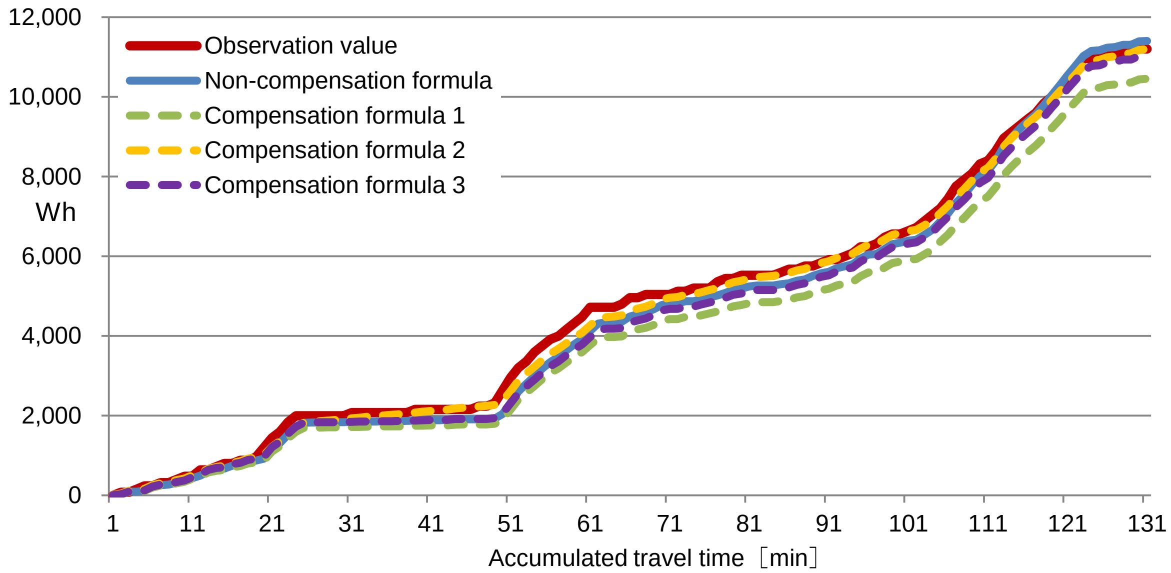

Figure 7　Comparison of correction accumulated electrical consumption
(The non-correction in this figure is same with the estimating value in Figure 6)

5. The analysis of road quality by energy consumption formula

The New Tomei expressway from GOTENBA junction (JCT) to MIKKABI JCT opened on April 14th, 2012 [4]. The distance between GOTENBA JCT and MIKKABI JCT by New Tomei expressway is 157.4km, which is about 10km shorter than by (conventional) Tomei Expressway.

Figure 8　Map of New Tomei Expressway and Tomei Expressway

The New Tomei expressway built using the up-to-date road design is great for the environment. The bends and slopes are gentler than that in Tomei Expressway. Since the road is straighter, people can drive more comfortably and safely. The minimal curve radius in New Tomei expressway during the interval opened this time is 3,000[m], which in Tomei Expressway is 300[m]. And the maximum gradient in New Tomei expressway is 2%, which is 5% in Tomei Expressway. Since a composite pavement combined the concrete pavement which is advantaged for durability and the asphaltic pavement which is advantaged for travelling performance is used in the New Tomei expressway, New Tomei expressway is flatter than Tomei Expressway.

To compare the difference of electrical consumption between driving on New Tomei expressway and Tomei Expressway, we made two test drives on May 9th and June 25th in 2012. May 9th is from Tomei to New Tomei, and June 25th is from New Tomei to Tomei (Figure 9).

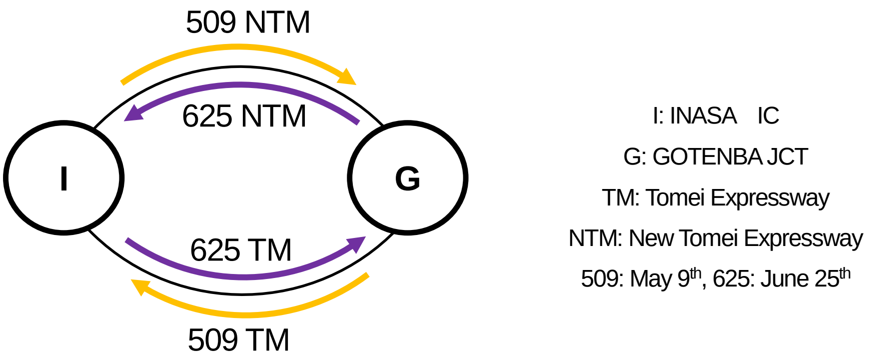

Figure 9 Drive routes on May 9th (509) and June 25th (625)

Table 4 Variation coefficient of each term

	Tomei expressway		New Tomei expressway	
	↘ (green)	↗ (red)	↗ (red)	↘ (green)
	509	625	509	625
ACC	0.452	0.587	0.658	0.643
Air	0.266	0.328	0.290	0.244
Pot	1.352	1.285	1.022	1.079
Rol	0.171	0.209	0.219	0.176
Reg	1.248	1.481	1.234	1.040

The red arrow stands for the direction from low altitude to high altitude; the green arrow stands for the opposite, from high altitude to low altitude.

The estimated value and observation value of electrical demand calculated by minute are shown in Figure 10. The yellow columnar part in each figure stands for the regeneration energy generated on the down-grade.

The variation coefficients are shown in Table 4. The result in the coefficient of variance table is the absolute value of the ratio of standard deviation to average. As shown in this table, the coefficient of variance in New Tomei expressway is larger than that in Tomei expressway. Since there are more sloping roads in Tomei expressway, the accelerations are occurred many times by the sags or crests. The frequency of acceleration is high but the change of each acceleration is small, which causes a small dispersion. Since there are less sloping roads in New Tomei expressway, the number of acceleration is small, and it is easy to keep on a constant velocity compared to Tomei expressway. But the acceleration increases from zero when the vehicle speeds up. Compared to the high frequency of acceleration but small changes of acceleration in Tomei expressway, the dispersion is high in New Tomei expressway. Beside this, we can also find that the variation coefficient of gradient resistance in Tomei expressway is larger than that in New Tomei expressway in this table. That is because there are more sags or crests in Tomei than New Tomei expressway.

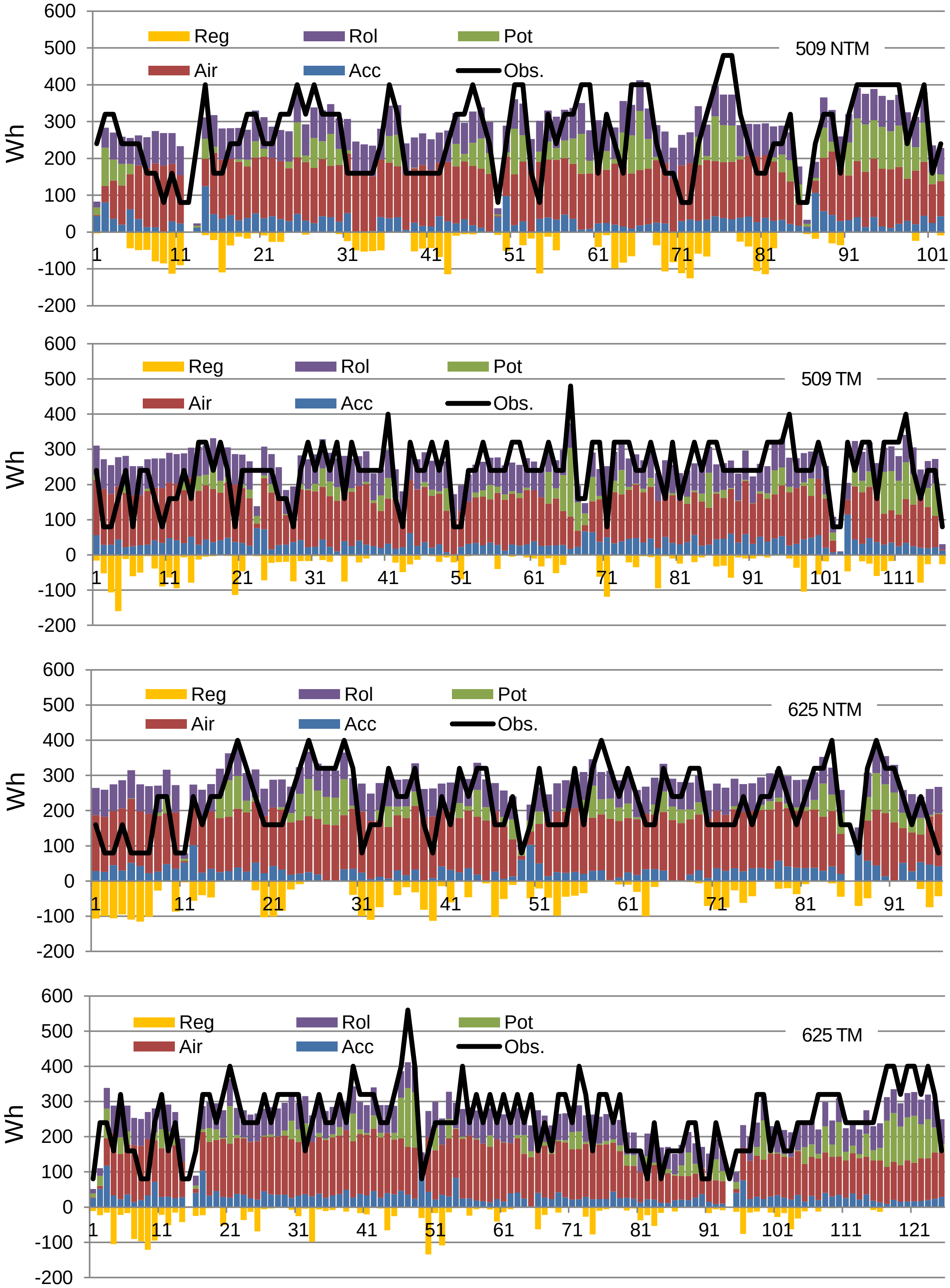

Figure 10 Comparison of estimated value and observation value of electrical consumption

In this study, the equivalent mass of accelerate rotation is not included in *M*, larger *M* should be used. And there are some undetermined factors in the air resistance term. Because the altitude difference could not be ignored in the expressway, we consider the regeneration energy generated on the down-grade in the electrical consumption estimating formula. The road surface condition of New Tomei Expressway is better than Tomei Expressway because of the new technology used. This caused the difference of rolling resistance coefficient between two expressways. To fit the observation value, we try to estimate the following correction coefficients using regression analysis.

$$E_s = \theta_1(X_1 + X_3) + \theta_2 X_2 + \theta_4 X_4 + \theta_5 X_5 + \theta_6 X_6 \qquad (8)$$

X_1 : accelerating resistance, X_2 : air resistance, X_3 : gradient resistance, X_4 : regeneration energy, X_5 : rolling resistance (Tomei Expressway), X_6 : rolling resistance (New Tomei Expressway)

The estimated result is shown as follows (t-value in brackets).

$$E_s = 1.317(X_1 + X_3) + 0.573X_2 + 1.062X_4 + 1.498X_5 + 1.487X_6 \quad \text{May 9}^{th} \text{ (509)} \qquad (9)$$

(11.6) (1.9) (8.3) (2.6) (2.4) R^2=0.956

$$E_s = 1.179(X_1 + X_3) + 0.975X_2 + 1.151X_4 + 1.123X_5 + 0.703X_6 \quad \text{June 25}^{th} \text{ (625)} \qquad (10)$$

(10.5) (4.1) (9.4) (2.2) (1.3) R^2=0.955

The rolling resistance coefficient of New Tomei Expressway is smaller than Tomei Expressway in the compensation formula, which means the road surface condition of New Tomei Expressway is better and good for vehicle running.

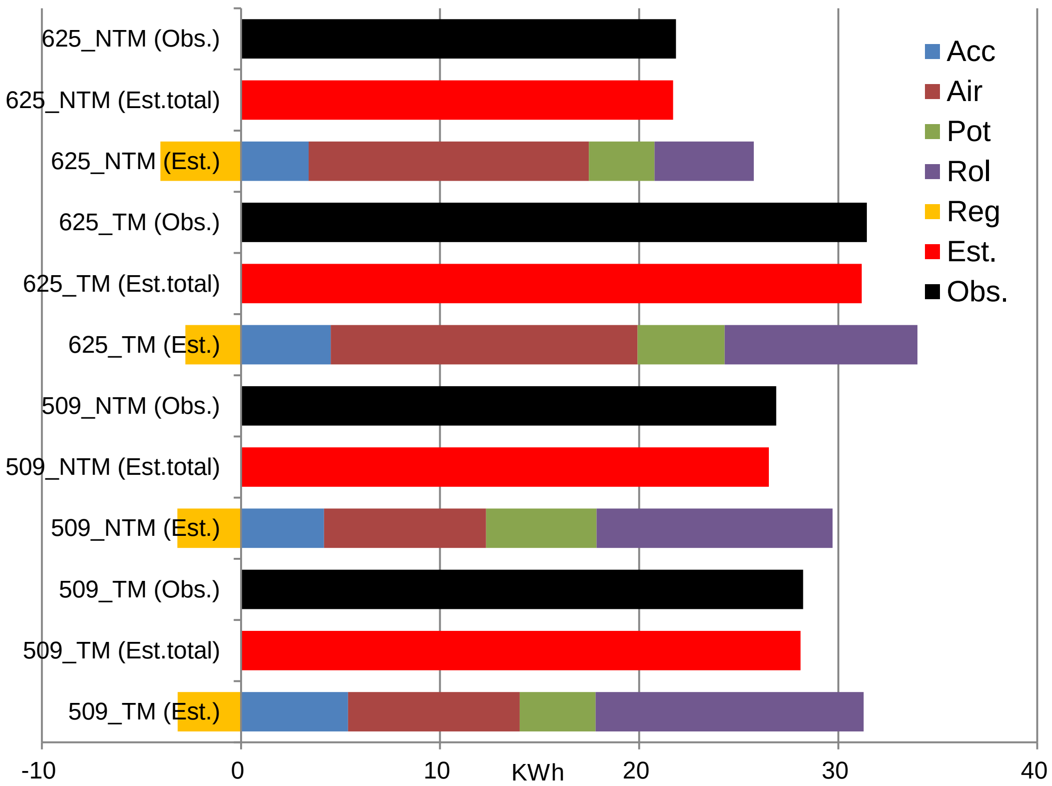

Figure 11 Cumulative electrical consumption and observation values

As shown in the figure of compensating cumulative electrical consumption and observation values (Figure 11), the compensating values are almost same with observation values. In the test driving on May 9th, the electrical consumption in New Tomei Expressway is smaller than Tomei Expressway. In the test driving on June 25th , we had a same result. And we also compared the electrical consumption from Gotenba JCT to INASA IC by New Tomei Expressway on June 25th with Tomei Expressway on May 9th; the electrical consumption from INASA IC to Gotenba JCT by New Tomei Expressway on June 25th with Tomei Expressway on May 9th. The result is same, the electrical consumption in New Tomei Expressway is lower. In summary, the New Tomei Expressway can realize less energy consumption.

6. Conclusions

In this study, we discussed the electrical consumption estimating equations of EVs. The estimated value is almost same with the observation value. And we also found that the road friction coefficient of New Tomei Expressway is smaller than Tomei Expressway; the electrical consumption of New Tomei Expressway is lower than Tomei Expressway too. Although the heater and light were not used in the drive, the action of heater and light should be considered in the further research.

It is one of the important findings of this study that the energy consumption can be calibrated accurately by a simple GPS logger. And it also means that EV can measure the road conditions such as smoothness or effects of sags or crests. We will test EV probe system to clarify the road conditions in many fields.

References:

1) Tetsuro HYODO, Daisuke WATANABE, Taimu HASHIMOTO, Kenichiro SAWAKI (2010), The electrical consumption estimating formula of EVs, Journal of Traffic Engineering (in Japanese)
2) Shigeru KASHIMA, Hisashi IMANAGA, Syohei KOGANEI (2010), Fuel consumption estimation model for gasoline vehicles based on trip segment unit and manner of utilization for eco-drive evaluation, Traffic Engineering, Vol.45, No.2, pp.53-63 (in Japanese)
3) Masayuki MORIMOTO (200) , *Electric vehicle*, Morimoto Press
4) http://www.c-nexco.co.jp/shintomei/ , (accessed in 2012, September)